Dear Steven Morley Editor of the Journal Space Weather,

I am submitting the changes made to our Paper #2025SW004363, according to major revisions requested by both referees.

The changes are numerous and, trying to satisfy all their questions and doubts we decided to change the structure of the paper. Besides the restructuration of the sections in the document, we added in appendix A with the description of the electronics built to read the signals, and the data taking process.

We also added sections with more analysis of the Forbush Decrease events observed, for example we introduced the morphology of both events. We also introduced in the Appendix B a comparison of our results with the Mexico neutron detector data, where we found that we are totally correlated with their findings, even for events registered that is hard to explain that could be generated by geomagnetic storms

We are pleased to submit the revised version of our manuscript (Paper #2025SW004363), in response to the comments and suggestions provided by the referees. We sincerely appreciate the time and effort they dedicated to reviewing our work, as their feedback has significantly improved the quality of our paper.

In addressing the major revisions requested, we have implemented the following key changes:

1. **Restructured Content**: We have reorganized the paper to enhance clarity and flow, ensuring a more coherent presentation of our research.
2. **Expanded Analysis**: Additional sections have been included to provide a deeper analysis of the Forbush Decrease events observed, including a detailed examination of their morphology.
3. **New Appendices**:
    - **Appendix A**: A comprehensive description of the custom-built electronics used for signal readout, along with the data acquisition process.
    - **Appendix B**: A comparative analysis of our results with data from the Mexico neutron detector, confirming a strong correlation between our findings and theirs—even for events whose origins are challenging to attribute to geomagnetic storms.

We are confident that these revisions have fully addressed the referees' concerns while enhancing the scientific robustness of our study. Below, we provide a detailed point-by-point response to each of the reviewers' comments, highlighted in bold for clarity.

Associate Editor Evaluations:
Recommendation (Required): Return to author for major revisions
Accurate Key Points: Yes

Reviewer #1 Evaluations:
Recommendation (Required): Return to author for major revisions
Significant: The paper has some unclear or incomplete reasoning but will likely be a significant contribution with revision and clarification.
Supported: Mostly yes, but some further information and/or data are needed.
Referencing: No
Quality: The organization of the manuscript and presentation of the data and results need some improvement.
Data: Yes
Accurate Key Points: No

Reviewer #1 (Formal Review for Authors (shown to authors)):

Referee Report - Space Weather Journal
Title: Measurements of Forbush decrease events at the centre of the South Atlantic Magnetic Anomaly with Muon detectors'

I have carefully reviewed the manuscript submitted for publication in Space Weather. The topic-investigating cosmic-ray-induced variations through muon detection-falls well within the journal's scope and is particularly timely, given the increasing interest in muon-based proxies for heliospheric modulation. However, in its current form, the manuscript does not meet the standards expected for publication in this journal.

While the subject is relevant and potentially valuable to the Space Weather readership, the work lacks the necessary depth, rigour, and clarity. In particular, the paper would benefit from a more thorough and self-contained presentation of the instrumentation, a stronger connection to the existing body of literature on muon flux variations and Forbush Decreases, and a more detailed justification and evaluation of the proposed TTS method. Moreover,

the English language usage throughout the manuscript requires substantial revision for readability and precision.

To enhance the clarity and depth of our analysis, we expanded the discussion of the TTS method and relocated it to a dedicated section: 4.2.1 Dst Comparison – Statistical Methodology. This restructuring ensures a more systematic presentation of our statistical approach.

Regarding the comment on *"English language usage throughout the manuscript requires substantial revision for readability and precision,"* we note that the manuscript was thoroughly reviewed for grammar and style by one of the co-authors, Dr. Euan Richards, a native English speaker. We acknowledge that certain technical aspects of the manuscript may benefit from further refinement. In this revision, we have made a concerted effort to enhance precision by incorporating discipline-specific terminology and clarifying key methodological descriptions.

Additionally, the manuscript would greatly benefit from a deeper and more critical physics-based discussion, especially concerning the underlying mechanisms that link space weather phenomena to muon flux variations. This would help anchor the results within a stronger theoretical framework and enhance the scientific impact of the study.

We incorporated an analysis of the Forbush Decrease using data from magnetometers installed within the South Atlantic Magnetic Anomaly (SAMA) region. Specifically, we added a dedicated section (5.2.2 *Magnetic Field X-Component*) comparing our muon detector measurements with the *X*-component of the geomagnetic field recorded at the Vassouras Observatory (Rio de Janeiro, Brazil). This comparison provides additional insights into the arrival time and structure of the interplanetary coronal mass ejection (ICME), particularly its associated magnetic cloud.

Furthermore, we discuss prior studies conducted within the SAMA by other experiments, contextualizing our findings within the broader understanding of geomagnetic and cosmic-ray variations in this region.

I recommend that the authors undertake substantial revisions before the manuscript can be evaluated further. Specifically, I encourage the authors to:
+ Please provide a detailed and self-contained description of the detector and its electronic architecture, including the influence of environmental variables such as pressure and temperature on the count rate.

This was done introducing all the different components of the amplification system, the data read and their processing. In section 2 the Detection system is described with the topics of Physical construction, signal processing and data acquisition are explained. The schematics and details of each of those topics are in Appendix A.

The influence of environmental variables is explained in subsection 3.2 where a specific topic was created to treat this problem. This part provides a comprehensive treatment of environmental variable influences, incorporating: (1) atmospheric pressure corrections, (2) temperature corrections based on the mass-weighted temperature approach (Mendonça et al.), and (3) analysis of temperature-dependent SiPM gain variations.

+ Incorporate a comprehensive and critical review of prior work, particularly the numerous studies linking muon flux to solar modulation effects, including Forbush Decreases.

We introduced in section 1.1 the works that has been done with the measurements inside the SAMA with all the reference about the Forbush decreases found, and for other type of measurements as well

+ Clarify the novelty and implementation of the TTS method and benchmark it against established techniques.

As we put it above, in subsection 4.2.1 Dst Comparison – Statistical Methodology, we introduced lot of information about this novel technique whit its benefits, and why we chose it over the usual one.

+ Thoroughly revise the manuscript for language, grammar, and structural coherence.
I look forward to reviewing a substantially improved version of the manuscript.

Below, I detail my main concerns:

+ Insufficient description of instrumentation. The manuscript offers only a minimal and incomplete description of the instrumentation. It relies heavily on references to prior works -in Spanish- without presenting clear, self-contained explanations. Essential components such as schematics, block diagrams, or concise system

architecture summaries are missing. A thorough and accessible description of the electronic design and overall setup -including the acquisition chain, signal processing stages, triggering mechanism, and data storage workflow- would significantly enhance the reader's understanding of the detector's capabilities and limitations. Additionally, the manuscript lacks a rigorous analysis of how environmental variables, such as atmospheric pressure and temperature, influence the muon count rate. This superficiality is critical, as such correlations are fundamental to the reliable interpretation of flux variations in space weather studies.

As stated before, this was done introducing all the different components of the amplification system, the data read and their processing. In section 2 the Detection system is described with the topics of Physical construction, signal processing and data acquisition are explained. The schematics and details of each of those topics are in Appendix A.

The influence of environmental variables is explained in section 3.2, is explained above.

+ Lack of engagement with prior literature. The manuscript shows little engagement with the extensive body of research accumulated over nearly two decades on the modulation of muon flux by Forbush Decreases. Notably, the authors do not reference or discuss early pioneering studies conducted in the South Atlantic Anomaly region (e.g., https://doi.org/10.1590/S0102-261X2007000600018). To properly situate their work within the broader scientific context, the authors should incorporate a more comprehensive and critical review of the existing literature. A more profound synthesis is essential to highlight the study's relevance and demonstrate how it advances or complements the current understanding in the field.

We did this and include two more analysis methods besides the TTS study. The are the correlation with the X component of the magnetic field, and then the comparison with data taken by the Mexico neutron detector, a place chosed because the rigidity is close to ours.

Unclear Novelty and Insufficient Justification of the TTS Method. The manuscript introduces a Time-Tagging System (TTS) as a novel temporal muon flux analysis approach. However, quantitative evidence does not clearly articulate or support this method's conceptual motivation and practical advantages over well-

established techniques, such as conventional time binning or flux smoothing. Key questions remain unanswered: What specific value does TTS add to space weather analysis? How does it perform regarding calibration, timing resolution, or reliability when compared to standard methods? Without addressing these aspects or providing benchmarks and validation data, the claimed methodological innovation lacks clarity and scientific justification.

+ Language and style require substantial editing. Although the manuscript is generally comprehensible, the quality of the English requires significant improvement. Numerous grammatical errors and stylistic issues negatively affect both readability and the scientific tone. Several sections are marked by wordiness, vague phrasing, and ambiguous sentence structures, sometimes obscuring the intended meaning. A thorough language review is necessary to enhance the text's clarity, precision, and professionalism. Examples include:
+ Verb tense inconsistencies (e.g., using present tense to describe results from a previous calculation/analysis/measurements)
+ Lines 190-191. The present tense ("is") describes results from a previous calculation.
+ Lines 235-240. Present tense verbs "show" and "indicate" are mixed with past events ("was being prepared", "occurred ", "added").
+ Lines 241-244. Present tense ("can be seen", "is", "gives") describing results of past analysis.
+ Ambiguous phrasing and syntax hinder clarity.
+ Lines 235-240. "overlay" is casual terminology; it is unclear whether it is a plot, comparison, or mathematical operation. "with r = 50 and l = 2" needs contextualization (e.g., define r and l).
+ Lines 254-257. The phrase "can be used to detect muon flux changes related to space weather events" is redundant given the prior context and lacks precision regarding what types of events or data features it refers to.
Thank you for considering our resubmission. We look forward to your feedback and hope that the revised manuscript now meets the journal's standards for publication.

All reviewer suggestions were implemented, including those pertaining to English language refinement. These comprehensive revisions have resulted in a significantly improved final manus

Answers to referee #2

Reviewer #2 Evaluations:
Recommendation (Required): Return to author for major revisions
Significant: There are major errors or gaps in the paper but it could still become significant with major changes, revisions, and/or additional data.
Supported: Yes
Referencing: Please Select
Quality: Yes, it is well-written, logically organized, and the figures and tables are appropriate.
Data: Yes
Accurate Key Points: Yes

Reviewer #2 (Formal Review for Authors (shown to authors)):

Review of "Measurements of Forbush decrease events at the center of the South Atlantic Magnetic Anomaly with Muon detectors", by Jorge Molina et al.

General remarks
I greatly enjoyed reading the manuscript "Measurements of Forbush decrease events at the center of the South Atlantic Magnetic Anomaly with Muon detectors" by Jorge Molina et al. It is a nicely written, succinct account of a newly-placed and simple but effective muon detector in the South Atlantic Anomaly: its construction, testing, data analysis and with initial results that indicate that it is working well. There are sufficient references and the figures are good. However, having read the Aims and Scope of AGU Space Weather, I am concerned whether the current manuscript meets the remit of the journal, but I think that it has potential to do so.
I think that I can recommend publication if you modify the paper to make a better and more detailed link to forecasting. In addition, the TTS test is not fully introduced and described. In summary, I feel that the paper needs a major revision, but I hope that you are expert enough that this should not take too much time. Here I describe how I reacted to the paper.

Section 1, the introduction describes what a Forbush decrease in cosmic ray flux is, and states (to possibly justify being published in Space Weather) that Forbush decreases can potentially be used in the forecasting of geomagnetic storms. The Global Muon Detector Network is mentioned and then the paper describes the

South Atlantic Anomaly, one reason why the new detector is placed there, and the precise location of the detector.

In section 1 we introduced more studies concerned to previous measurements done inside SAMA, specially the Forbush events reported by those experiments

Section 2 gives sufficient detail about the hardware of the detector and how data is acquired and stored. Importantly, it mentions that there is further detail about this particular detector in an IEEE conference proceedings by Bertoli at al. (2023) entitled "Optimization of a muon detection system with silicon photomultiplier sensors (Sipm)" so it seems that this is not the first time that details of the detector's hardware have been published. Also, the abstract mentions that "The detector is of standard construction".

By request of one referee, we extended the explanation about the electronics used. Now the Detection system is described with subtopics about the Physical construction, signal processing and data acquisition. The schematics and details of each of those topics are in Appendix A.

Section 3 describes important details about how bad data is excluded, and how simultaneous corrections are made for atmospheric temperature and pressure, and temperature effects on the silicon photomultiplier sensors.

In response to reviewer requests, we have expanded our description of the data correction procedures in this revision. These include not only standard data cleaning processes but also comprehensive atmospheric and environmental adjustments applied to the dataset.

Section 4 shows mathematically how to obtain the measured flux. Much of this is standard but is applied to this new detector. The paper then compares the index Dst to the muon detector values for two storms using statistical method called the Truncated Time-Shift (TTS) test which is very recent [Yuan et al. (2024, 08). A rigorous and versatile statistical test for correlations between stationary time series. PLOS Biology]. The paper describes the benefits of this new test, which sound good. Then the test is applied, having first checked that the datasets meet the requirements needed to apply the TTS test. The text mentions the TTS test r

value but does not explain what it is, then mentions the l value and sets it to l=2. However, the TTS test itself is not presented in detail. For instance, the correlation value, u is calculated but not discussed.
The results of the TTS test as applied to two Forbush decreases in 2024, one in May and one in October, are discussed in section 4.2.2. Figs. 5 and 6 show the muon flux and Dst index values for the two storms. The figures show a similarity between the muon flux and Dst, but not total correspondence. Interestingly for the readers of Space Weather, the authors mention that hardware issues caused by the storm create an electrical blackout, one of the many issues that experimentalists must deal with!

The text again mentions the r and l values of the TTS test, and indicates that this gives a certain u value, as if the reader would have a feel for what it represents, but the reader has not been given a background about the TTS test.

On top of the analysis done with the TTS method, we significantly enhanced the study through two additional data processing methods, enabling: (1) more detailed investigation of Forbush decreases, (2) interaction type characterization via spectral morphology analysis, and (3) comparative studies with Mexico neutron monitor data, selected due to its similar geomagnetic rigidity to Asunción.

Major concerns
A. The paper may not meet the remit of the journal Space Weather. The Aims and Scope as stated on the website are:

Aims and Scope

Space Weather: The International Journal of Research and Applications (SWE) is devoted to understanding and forecasting space weather. The scope of understanding and forecasting includes: origins, propagation and interactions of solar-produced processes within geospace; interactions in Earth's space-atmosphere interface region produced by disturbances from above and below; influences of cosmic rays on humans, hardware, and signals; and comparisons of these types of interactions and influences with the atmospheres of neighbouring planets and Earth's moon. Manuscripts should emphasize impacts on technical systems including telecommunications, transportation, electric power, satellite navigation, avionics/spacecraft design and operations, human spaceflight, and other systems. Manuscripts that describe models or space environment climatology should clearly state how the results can be applied.

Papers include original research articles as well as feature articles, and commentary.

Space Weather publishes:
• peer-reviewed articles presenting the latest engineering and science research in the field, including studies of the response of technical systems to specific space weather events, predictions of detrimental space weather impacts, and effects of natural radiation on aerospace systems;
• news and feature articles providing up-to-date coverage of government agency initiatives worldwide and space weather activities of the commercial sector;
• letters, policy and opinion articles offering an exchange of ideas; and
• editorial comments and highlights on current community issues.

My concern is that the paper itself does not obviously contribute to the "understanding and forecasting space weather", although the detector will do so in the future. To meet the remit of the journal, the authors could connect the results of the muon detector in a more detailed way to the issue of forecasting by adding some of these topics to the paper:
1. How and why do Forbush decreases offer a chance of forecasting? Give references. What is the community trying to forecast and why?
2. Having validated the data using Dst, this paper could move on to the forecast potential of the detector. Can you relate the muon flux results to other muon and non-muon datasets quantitatively? Or can you describe how that might be done in future studies?
3. Can the muon detector network be used to start to build a means of forecasting? How would that be done or is it already happening? Are there references?
4. Does this new detector fill a critical hole in that network? Can you give further evidence or a line of argument to show that? Given that the detector is simple and cheap, do the authors have plans for more detectors in the SAMA, and where might they place them, and why?
5. Rockenbach et al. (2014) is cited, but perhaps more up-to-date references about the network, and its use, could be added as well, to illustrate the power of muon detectors.
6. Can you collaborate with people who use other muon detectors or satellites to detect Forbush decreases for forecasting, and extend the current paper, so that it is more suitable for the journal Space Weather? Perhaps other teams have examined/tried to forecast these two particular events? A comparison of the ability of your detector to forecast and (other detectors in) the network to forecast would

be interesting, as would a comparison between your detector and a satellite forecast. I realise that this might be a step too far, but maybe you can do this relatively easily?
In summary, how (and why) would you now forecast events, given the results of this paper so far presented? This is my main concern.
B. My second concern is there may not be anything novel enough in the paper, very interesting though it is. The hardware for the detector seems to have been published and its design may not be novel. Or am I wrong - the detector was presented and published as part of an engineering conference, not a space weather symposium? So perhaps that makes it novel enough for the Space Weather audience, and also these are indeed first results from an interesting sector of Earth's magnetic field.
C. My third concern is that the TTS test is new, but the authors do not describe the TTS test in any detail. This means that the u values might easily have no meaning to the reader. I would welcome a more detailed presentation of the TTS test, as is done in Section 4 for the derivation of the muon flux measurements from the raw data.

To better align our study with the journal's focus on space weather forecasting, we have made the following additions and clarifications:

- **New Subsection 5.1: "Utility of Muon Detectors"**
  We've added a dedicated discussion on the role of muon detectors in forecasting Forbush Decrease (FD) events, referencing recent studies by Ali et al. (2025) and Munakata et al. (2020) that explore CME arrival predictions (Lines 320–335).

Complementarity with Existing Observations
We highlight how our detector complements other systems through:

- **Cross-validation with the Mexico City neutron monitor (Appendix A)**
- **Morphological comparisons with the Vassouras magnetometer (Fig. 7)**
- **Temporal correlation with the Dst index, with reported significance (u = 0.0196 / 0.0392)**

Integration into Global Networks
We emphasize our detector's strategic location in the South Atlantic Magnetic Anomaly (SAMA), referencing Saito (2023), and discuss how it can help

address geographic coverage gaps in the Global Muon Detector Network (Lines 95–105, 340–355).

Pathway Toward Operational Forecasting
We now outline specific future steps, including:

- **Plans to deploy additional detectors across the SAMA region Real-time data integration with CALLISTO spectrometers**
- **Potential collaboration with balloon and LEO satellite missions to monitor low-energy particle fluxes**

B. Clarifying the Novel Contributions

To better communicate the originality of our work, we have emphasized the following points:

- **First Muon Detector Installed in Paraguay/SAMA Core**
  Our station's unique geomagnetic cutoff rigidity (R = 9.63 GV) offers a new window into particle precipitation processes in this under-observed region
- **Cost-Efficient, Scalable Instrumentation**
  We describe our compact, SiPM-based system with a cost below $5,000 USD, and detail its modular design that enables future expansion into a broader network (Section 2).
- **New Scientific Insights**
  We report the first observations of FDs in the SAMA core (May and October 2024) and demonstrate a clear 2-hour precursor signal relative to the Dst index (Figs. 5–6).

C. Expanded Description of TTS Test Methodology

We have revised this section to provide a clearer and more complete explanation of the statistical framework:

- **Parameter Definitions**
  We now specify the time shift (ℓ = +2h), consistent with physical delays reported by Baral (2023), and set a truncation radius of r = 50h .
- **Interpretation Guidance**
  We explain that the u-value provides a conservative bound for the p-

value under α = 0.05 and benchmark our results against neutron monitor data (u = 0.059).

- **Validation of Robustness**
  We confirm the stationarity of the time series using the Augmented Dickey-Fuller test ($p < 0.01$) and demonstrate reproducibility across two independent FD events (May/Oct 2024).

Additional Revisions

- **We have expanded the Open Research statement and now provide direct links to Zenodo and GitHub repositories.**
- **Appendix A Electronic Design Description**
- **Appendix B includes additional cross-comparisons with neutron monitor data.**
- **Citation formatting issues throughout the manuscript have been corrected.**
- **All figures have been standardized to use consistent date formats.**

These changes directly address all of the reviewer's comments, while reinforcing the manuscript's scientific rigor and relevance to operational space weather forecasting. We are truly grateful for your insightful suggestions—they have meaningfully improved the manuscript.

Minor points
a. Are there 2 or 3 Key Points? There are 2 keypoints in the manuscript [#1: Commissioning of a compact muon detector in Paraguay; #2: Correlation with Forbush decrease using Truncated Time Shift statistical test.]
But there are 3 keypoints in the online description:
[Main point #1: We construct a compact particle detector made with scintillators read by SiPMs for continuos monitoring of photons and muons independently;
Main point #2: We demonstrate that the detector works correctly through the measurements of the muon angle distribution and with the flux measurement;
Main point #3: We were able to observe two Forbush decreases and correlate them with the Dst index using the Truncated Time- Shift (TTS) test].
I prefer the 3 keypoints, which are superior to the 2 keypoints. However, again there

seems to be no mention of forecasting or some other requirement made by the journal for publication (see Aims and Scope above). Having extended the paper to show how the new detector (or muon detectors) assists with forecasting, then perhaps make one of the keypoints about forecasting.

On top of the three keypoints we added two more now by introducing two new analysis of our data as cited above.

b. Quite a lot of work needs to be done on the referencing. There are many instances of incorrect style of citation. An example of the kind of errors include:
(i) Line 94: "...implementations described in (Benitez Montiel et al., 2019)". [Brackets in wrong place]
(ii) Augusto, C., Navia, C., Tsui, K., Shigueoka, H., Miranda, P., Ticona, R., . . . Saavedra, O. [the dots are not needed]
(iii) Schuch, N. J. (2013). The global muon detector network - gmdn the brazilian contribution for space weather forecasting. In 33rd international cosmic ray conference (p. 0946). [Lack of use of capital letters where needed]
(iv) Detailed reference is missing from both the main text and the reference section: Rockenbach, M., Dal Lago, A., Schuch, N.J. et al. Global Muon Detector Network Used for Space Weather Applications. Space Sci Rev 182, 1-18 (2014). https://doi.org/10.1007/s11214-014-0048-4
(v) Yuan, A., & Shou, W. (2024, 08). [only year needed].

c. Fig. 5 does not mention the date of the storm but Fig. 6 does, and this is not ideal.
d. Line 135: typo? 1 ~ 3%

This minor errors were solved in the new version, most of them were ocassionated by an overleaf bug.