A Comparative Study on the Correlation of Geomagnetic Variations dB/dt between Low-Latitude Stations

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A Comparative Study on the Correlation of Geomagnetic Variations dB/dt between Low-Latitude Stations

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Abstract: *Understanding geomagnetic variation (dB/dt) in low-latitude regions is crucial for predicting geomagnetically induced currents (GICs) that threaten ground infrastructure. However, long data gaps in geomagnetic observations can hinder comprehensive analysis. This study explores the correlation between geomagnetic time series data from eight low-latitude stations: Huancayo (HUA), Kourou (KOU), Mbour (MBO), Tamanrasset (TAM), Addis Ababa (AAE)Alibag (ABG), Muntinlupa (MUT), and Guam (GUA). The primary objective is to identify highly correlated station pairs that could potentially allow data substitution to fill long gaps in observations. Using geomagnetic field variation data from March 30, 2001, to April 2nd, 2001, we conducted a correlation analysis between the time series of these stations. Pearson correlation coefficients were calculated for each station pair across different magnetic field components. Results revealed strong correlations (r > 0.8) between certain station pairs, particularly TAM-MBO and ABG-GUA.*

Keywords: Geomagnetic Variations, Low-Latitude, dB/dt Correlation, Geomagnetically Induced Current, Solar Cycle.

1. INTRODUCTION

Geomagnetic variations in low-latitude regions play a crucial role in understanding and predicting geomagnetically induced currents (GICs), which pose significant threats to ground infrastructure [1], [2]. These variations, often quantified as dB/dt, are particularly important during geomagnetic storms, which represent the rapid changes in the Earth's magnetic field [3], [4]. Continuous and reliable geomagnetic data from low- latitude regions are essential for studying space weather phenomena, developing geomagnetic models, and understanding the Earth's magnetic field dynamics. Maintaining uninterrupted data records is challenging due to instrument malfunctions, environmental disturbances, or operational issues, leading to significant data gaps [5]. This limitation can lead to incomplete understanding of geomagnetic behavior in these critical areas, potentially impacting our ability to forecast and mitigate GIC-related risks [6]. While interpolation techniques exist for short-term data gaps [6]–[9], addressing long-term missing data remains a challenge [10].

Research has also demonstrated the need to take into account long-term changes and their influence on geomagnetic phenomena, with the help of models [11]. In addition, the effects of magnetic fields on different geophysical measurements such as muography images also present the necessity of accurate data processing and calibration methods to eliminate the distortions in the gathered data [12].

To address these limitations, this work conducts a comparative study on the correlation of geomagnetic dB/dt variations between eight low-latitude stations spanning different continents. By analyzing geomagnetic field variation data over a certain period, this work aims to identify highly correlated station pairs that could potentially allow for data substitution during observational gaps. This work looks at the problem of data deficiency in geomagnetic observations, and by this, highly correlated low-latitude stations can be established to employ data substitution for record continuity. This approach increases the dependability of geomagnetic observation and refines the forecasts for preventing the consequences of geomagnetically induced current (GIC). The methodology includes data visualization, correlation analysis, and time series analysis to provide a comprehensive understanding of the relationships between these stations. This approach not only enhances our ability to maintain continuous geomagnetic monitoring in low-latitude regions but also contributes to improving predictive models for GICs.

The paper is structured as follows: Section 2 describes the datasets used, Section 3 outlines the research methodology, Section 4 presents the results and analysis, and Section 5 concludes with a discussion of the findings and their implications for future research and space weather forecasting.

2. DATASETS

This work uses two days of collected geomagnetic data with 2,880 data points for every parameter at a frequency of one minute. The data came from the SC23, maximum phase between 31 March 2001 00:13 UTC and 2nd April 2001 00:12 UTC. Eight low-latitude magnetometers provide the geomagnetic data utilised here are Huancayo

(HUA), Kourou (KOU), Mbour (MBO), Tamanrasset (TAM), Addis Ababa (AAE), Alibag (ABG), Muntinlupa (MUT) and Guam (GUA) and depicted in Fig. 1 with its geomagnetic latitude and longitude tabulated in Table 1. The geomagnetic field components dbnnez and dbenez, which stand for the northward and eastward components, are used to calculate the total magnetic field, or dB/dt. The SuperMAG database is where these data were taken from [13]. The SuperMAG repository (https://supermag.jhuapl.edu/) contains the data from the SuperMAG ground magnetometer station used in the current investigation. On the other hand, the values for the symmetrical H index (Sym/H) and heliospheric magnetic field (HMF) were obtained from the OMNI database using the OMNIWeb service (http://omniweb.gsfc.nasa.gov).

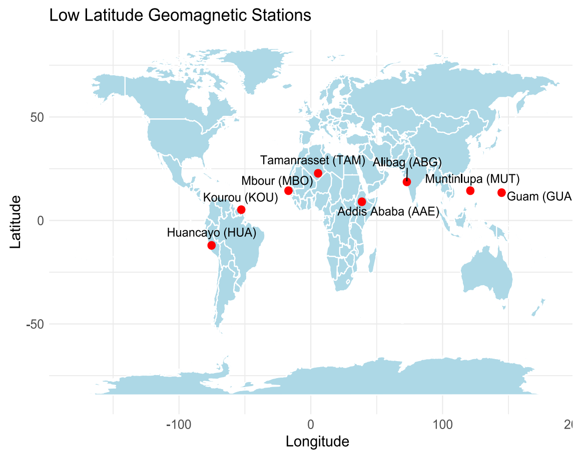

Fig. 1 Geographic locations of the geomagnetic stations involved in this study.

Table 1.List of magnetometer stations and its geomagnetic latitude involved in this study.

Low-latitude Locations			Geomagnetic	
Code	Station	Country	Lat	Long
HUA	Huancayo	Peru	0.4	-3.57
KOU	Kourou	France	9.45	23.5
MBO	Mbour	Senegal	1.33	57.8
TAM	Tamanrasset	Algeria	9.47	78.3
AAE	Addis Ababa	Ethiopia	5.45	112.55
ABG	Alibag	India	12.09	145
MUT	Muntinlupa	Philippines	7.21	-167
GUA	Guam	Senegal	1.33	57.8

3. METHOD

The research method employed in this study follows a systematic approach as illustrated in Fig. 2 beginning with data selection and collection, where relevant data are identified and gathered to ensure appropriateness and sufficiency for addressing the research questions.

This is followed by data visualization, which provides a clear understanding of the data's characteristics through the identification of patterns, trends, and anomalies. Subsequently, correlation analysis is performed to determine the nature and degree of association between different data variables as a means of understanding existing links.

At the same time, the analysis of data points which have been registered at a certain time interval is carried out using methods of time series analysis, therefore, temporal features and characteristics, as well as future values are predicted using the results of previous periods.

Interpretation and conclusion are the last step, where the result got after correlation and time series analysis is going to be interpreted as well as conclusion will be drawn based on the finding towards the research objectives to cover up all the objectives in a comprehensive manner. This integrated approach of the method ensures that the analysis is based on strong data, leading to well-supported conclusions.

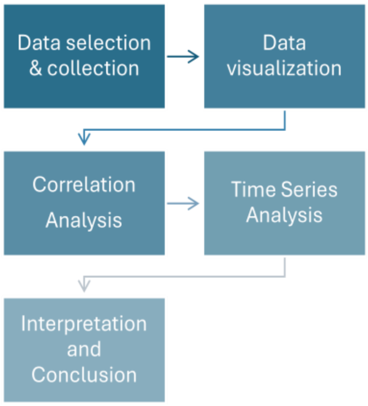

Fig. 2 Flowchart of the Research Methodology. This diagram illustrates the systematic approach employed in the study, comprising data selection and collection, data visualization, correlation analysis, time series analysis, and the final interpretation and conclusion.

4. RESULTS

This section will explain the results following the method applied.

4.1 Data Visualization

The provided Fig. 3 and Fig. 4 represents the geomagnetic variations recorded across multiple stations from March 30 to April 2, 2001, offering critical insights into the impact and propagation of geomagnetic storms. It illustrates geomagnetic variations in dB/dt (nT/m) over the local time for eight different stations. The heliospheric magnetic field (HMF) Bz component is a measure of the southward component of the heliospheric magnetic field. The HMF is the magnetic field that is embedded in the solar wind, the stream of charged particles that flows out from the Sun. When the HMF is southward, it can connect with the Earth's magnetic field and cause a geomagnetic storm. The Sym/H index is a measure of the strength of the geomagnetic field at the Earth's surface. It is a global index that is based on the measurements from a network of ground-based magnetometers. The Sym/H index is used to track the development of geomagnetic storms. The geomagnetic storm that occurred on March 30-31, 2001, was categorized as medium to major intensity, marking a significant event in space weather research. The impact on Earth began in the early hours of March 31, as Coronal Mass Ejections (CMEs) from events on March 29 reached our planet. These CMEs, initially predicted by model runs to arrive late on March 30, demonstrated the challenges in precisely forecasting space weather phenomena. At 2100 UT on March 30, the Advanced Composition Explorer (ACE) satellite detected a gradual increase in energetic proton levels, signaling the approaching disturbance [14].

This early warning system provided crucial data, allowing researchers to anticipate the storm's arrival and intensity. The storm's effects were observed across multiple ground stations in the low latitude regions, where at the initial stage of Sym/H = 105nT, with at some points, the variation exceeded the harmful GIC value of > 30 nT/m, with particularly notable disturbances recorded in the Sym/H index, which showed a significant negative excursion reaching approximately -400 nT/m. In low-latitude region, from the 8 locations, this impact arrived as early as 7:52 PM on 30th March at HUA, while KOU was at 9:52 pm, MBO at 12:52 am and TAM was at around 1:52 AM. as depicted in Fig. 3. The geomagnetic storm, as evidenced by the data presented in the geomagnetic variations plot in Fig. 4, indeed proved to be of medium to higher intensity with readings more than 50 nT/m.

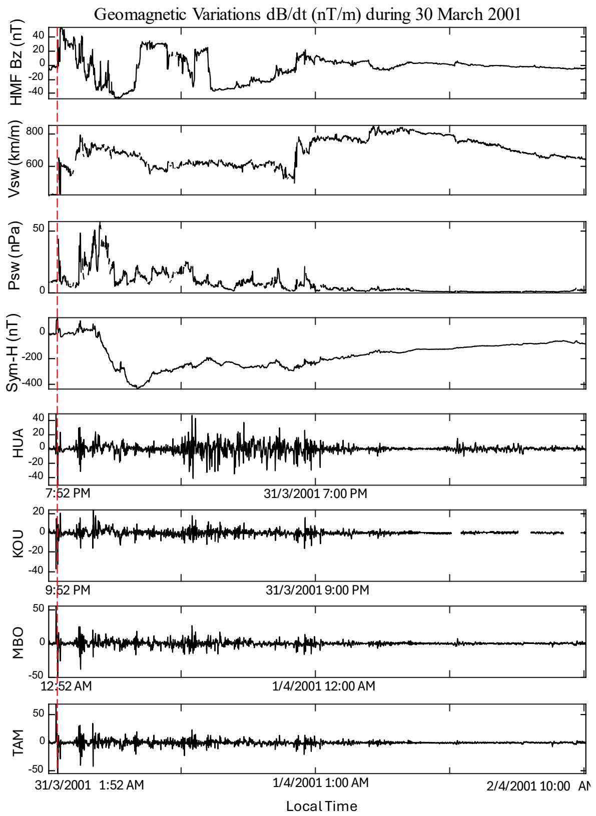

Fig. 3. The geomagnetic storm event on 31st March 2001, consists of the heliospheric magnetic field (HMF) Bz component, solar wind, solar wind dynamic pressure, Sym-H index, and followed by the variation of the geomagnetic variations (dB/dt) at HUA, KOU, MBO and TAM correspondent to its local time of the event. The red dotted line is the initial stage of the storm.

4.2 Correlation Analysis

Fig. 5 represents the correlation coefficients between the geomagnetic variations observed at eight low-latitude stations. Notably, TAM shows a strong positive correlation with MBO (0.8988), indicating a high degree of similarity in geomagnetic variations between these two stations. This suggests that these locations experience similar geomagnetic influences, likely due to their geographical proximity and similar space weather conditions. Following, ABG and GUA (0.7691) which have a strong correlation, implies that these stations share similar geomagnetic variation patterns. Additionally, ABG and MUT (0.743) also shows a strong correlation, suggesting that the geomagnetic variations at these stations are closely related. Two more pair stations have a high positive correlation are MUT - GUA, TAM - ABG, and AAE - ABG with correlation of 0.6909, 0.65 and 0.622 respectively. This suggests that the geomagnetic variations at these stations are significantly related, indicating a regional geomagnetic connection.

HUA and MBO is notably has moderate correlation at 0.5973, following KOU and MUT at 0.05947 then HUA and KOU at 0.5736. MBO and GUA (0.5567) also have a moderate correlation, indicating that geomagnetic variations at these locations are somewhat related. These moderate values suggest some degree of shared geomagnetic influences, though not as strong as those observed between TAM and MBO.

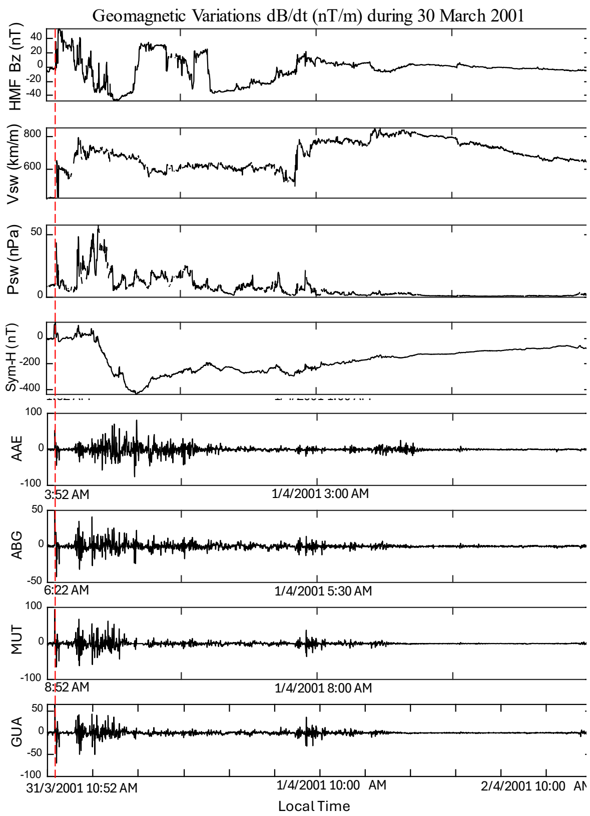

Fig. 4 The geomagnetic storm event on 31st March 2001, consists of the heliospheric magnetic field (HMF) Bz component, solar wind, solar wind dynamic pressure, Sym-H index, and followed by the variation of the geomagnetic variations (dB/dt) at AAE, ABG, MUT and GUA correspondent to its local time of the event. The red dotted line is the initial stage of the storm.

Conversely, the correlation between KOU and MUT is notably low (0.05947) followed by KOU and GUA (0.1713), indicating almost no linear relationship between the geomagnetic variations at these stations. The low correlation suggests a weak linear relationship. Critically, the correlation matrix provides a valuable tool for identifying which stations can serve as proxies for others in the event of data gaps. For example, due to the high correlation between Tamanrasset and Mbour, data

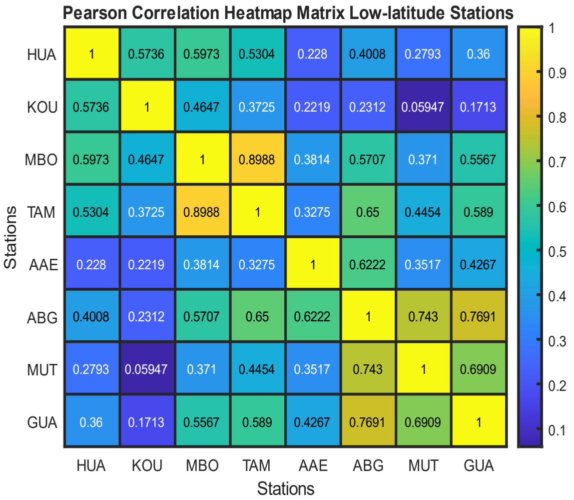

Fig. 5. Pearson Correlation heatmap matrix of geomagnetic variations between low-latitude stations on March 31, 2001.

from one station could reliably fill gaps in the other. Similarly, Alibag's data could substitute for gaps in Guam's data due to their high correlation. In conclusion, the Pearson Correlation Matrix elucidates the interconnected nature of geomagnetic variations across these low-latitude stations. We will look further into the data with strong correlation > 0.6 in the following section.

4.3 Time Series Analysis

In the context of time series analysis, this work conducted a cross-correlation test for two stations that showed high correlation in the Pearson's Correlation analysis. Fig. 6 exhibit the cross-correlation coefficient between the dB/dt values at various low latitude stations. Cross-correlation study of the dB/dt across low-latitude stations during the geomagnetic storm on 31st March 2001 helps in understanding the phase synchronism of geomagnetic fluctuations.

The results of the study reveal that all the station pairs included in the study exhibit high cross-correlation coefficients at lag zero, but the major pairs are TAM and ABG, TAM and MBO, MUT and GUA, ABG and MUT, ABG and GUA, while a moderate correlation exists between AAE and ABG.

These two strong simultaneous correlations imply that the changes in the magnetic field at these stations are very much in phase during the storm perhaps due to the geographical location of these stations and their closeness in terms of latitude. Large values near lag zero in several of the plots indicate that the rate of change of dB at one station is rapidly followed by the rates at others, and thus, geomagnetic conditions persist over short lags. These findings suggest that data from highly correlated stations are effectively used for the data gap filling, thereby improving the quality of geomagnetic observations in the low latitude areas. Moreover, the correlation of these disturbances from one station to another makes it possible to use this relationship to enhance the space weather forecast and modeling.

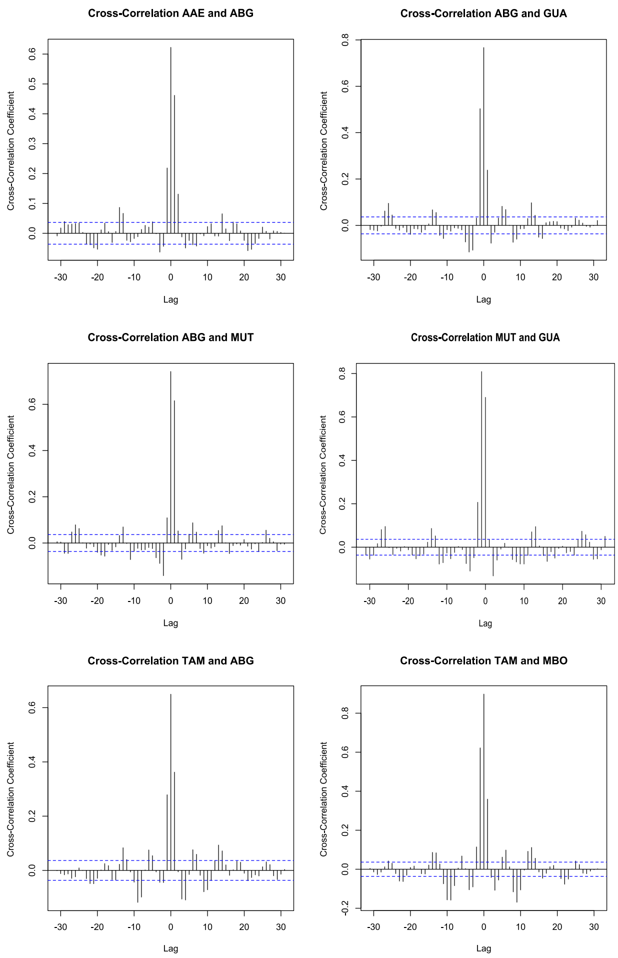

Fig. 6 Cross correlation between dB/dt across different low-latitude stations during the geomagnetic storm on 31st March 2001.

The scatter plots presented in These results further show that, there are various geomagnetic variations that exist at these low-latitude stations and these variations are related in some forms. The correlation coefficients for MBO and TAM were high, thus, these locations could be substituted if the data is unavailable because they are similar in geomagnetic terms. As much as the above coefficients of determination values of other station pairs (ABG-GUA, MUT-GUA, ABG-MUT) show that both these stations also have similar geomagnetic characteristics thought though not to the same extent as the above stations.

Thus, the assessment indicates that some low-latitude magnetic observatories have a close correlation with the changes in dB/dt, which could indicate data interchange between the stations in the case of data loss. It is most valuable for enhancing the stability and longevity of geomagnetic monitoring and research in the low latitude areas where accurate and constant data points are very significant for dealing with effects of geomagnetic storms.

Fig. 7 illustrates the data distribution between geomagnetic field variations dB/dt at different low-latitude locations. Specifically, the top left plot shows a strong positive correlation (r = 0.8979) between Mbour

(MBO) and Tamanrasset (TAM), indicating a high degree of similarity in their geomagnetic activities.

Similarly, the top right plot depicts a moderate positive correlation (r = 0.76696) between Alibag (ABG) and Guam (GUA), suggesting a significant, albeit weaker, relationship compared to the MBO-TAM pair. The bottom left plot shows the correlation between Muntinlupa (MUT) and Guam (GUA) with a Pearson coefficient of 0.69031, which is lower but still demonstrates a substantial correlation. Lastly, the bottom right plot between Alibag (ABG) and Muntinlupa (MUT) has a Pearson coefficient of 0.74184, reflecting a moderately strong positive correlation.

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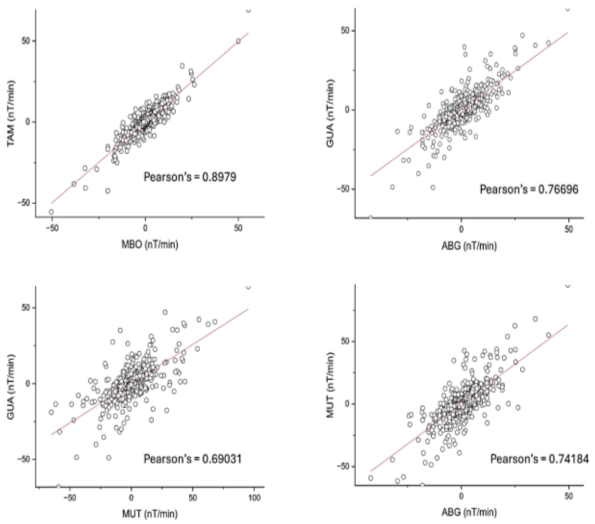

Fig. 7 Scatter plots depict data distribution with Pearson correlation coefficients between geomagnetic field variations dB/dt at different low-latitude locations. (Top left) Tamanrasset (TAM) vs. Mbour (MBO), (Top right) Guam (GUA) vs. Alibag (ABG), (Bottom left) Guam (GUA) vs. Muntinlupa (MUT), (Bottom right) Muntinlupa (MUT) vs. Alibag (ABG).

5. CONCLUSION

This work was focused on the analysis of cross-correlation between geomagnetic time series from eight low-latitude stations in order to determine the possibility of data substitution in the cases of long-term missing data. Several station pairs showed notable relations such as TAM and MBO, ABG and GUA, ABG and MUT having a similarity to a large extent in the change in geomagnetism. This proves to show that these stations are affected by the same geomagnetic activities and can be used interchangeably in case one station has a data gap.

The Pearson Correlation Matrix was useful in understanding the interdependence of geomagnetic variations at low-latitude stations. By extending the cross-correlation analysis, it also pointed out that during geomagnetic storms, these variations are synchronous, and it is possible to use data from highly correlated stations for gap filling to obtain continuous geomagnetic records.

Thus, revealing the sets of stations with high correlations, this study provides the methodological base to improve the reliability of geomagnetic observations in low latitude areas. This approach also solves the problem of data scarcity and enhances researchers' knowledge of ionospheric and magnetospheric processes, which contributes to creating better geomagnetic models and improving space weather prognosis. The findings of this study highlight the necessity of preserving and employing detailed geomagnetic data to both improve research and lessen geomagnetic disruptions' effects on technological applications.

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