International Research Experience Program (JIREP)

Project name:

Geomagnetic Regional Response during Geomagnetic Storm Periods

Carlos Isaac Castellanos-Velazco

PhD student

Instituto de Geofísica Unidad Michoacán,
Universinad Nacional Autónoma de México

Summary

The investigation of geomagnetic responses at a regional level is crucial for a deeper comprehension of the dynamics underlying various adverse effects linked to space weather. This project aims to explore and comprehend the regional geomagnetic response's variability during geomagnetic storm (GMS) occurrences. Previous research successfully identified the geomagnetic response correlated with ionospheric currents during transitional geomagnetic storms in a medium-low latitude region. The current endeavor seeks to replicate this experiment in an equatorial latitude region, where ionospheric and magnetospheric influences may exhibit significant variations. This study is proposed to utilize magnetic data sourced from the magnetometer network established by the Instituto de Geofísica del Perú (IGP).

1. Introduction

1.1. Motivation

Geomagnetic storms (GMS) are important space weather phenomena. They are temporal weakening of the Earth's magnetic field (EMF) due to the entry of particles and energy from the solar wind into the magnetospheric environment. This process causes an intensification of the magnetospheric currents and specifically, an increase of the ring current. The intensification of such current results in the induction of a magnetic field that opposes the EMF, weakening it in the process.

The occurrence of GMS can have detrimental effects on the reliability of communication and navigation systems, and in extreme cases, even disrupt power supply systems. These disruptions often result in significant economic losses. Therefore, continuous study of GMS and their associated consequences is crucial to mitigate their impact on various systems. The monitoring of geomagnetic activity (GMA) is facilitated through the use of geomagnetic indices. These indices serve as quantitative measures of the impact of GMA on a planetary scale, calculated from processed geomagnetic measurements.

While GMS are global phenomena, regional variations can occur due to Earth's heterogeneity, asymmetries in magnetospheric and ionospheric current systems, and their interactions within specific sectors. Consequently, factors such as geomagnetic latitude, local time, and season of the year can influence the characteristics of GMS at regional levels.

Given that regional response disparities stem from specific physical mechanisms, the question arises: what are these mechanisms, and which ones have the greatest impact on particular regions? Can we pinpoint the effects associated with these mechanisms?

1.2. Sources of the magnetic field

In space weather studies, magnetic field contributions are typically categorized into two main sources: regular magnetic field and disturbed magnetic field. The regular magnetic field exhibits cyclic variations attributed to processes within the ionosphere, like the Solar Quiet (SQ) current. This current arises from variations in solar radiation reaching the ionosphere, leading to partial ionization and atmospheric heating (Margaret G. Kivelson, 1995; Baumjohann and Treumann, 1999). Magnetic fluctuations linked to the SQ current typically range from 10 to 100 nT throughout the day (Jankowski and Sucksdorff, 1996; Gjerloev, 2012). The intensity of these fluctuations is influenced by factors such as geomagnetic latitude, season, local time, and solar activity levels (Jankowski and Sucksdorff, 1996; Gombosi, 1998; Knecht and B.M, 1985).

Within the regular magnetic field, tidal effects caused by the gravitational forces of the Sun and the Moon are also considered, leading to magnetic variations in the ionosphere (Bartels, 2013). These variations are significantly influenced by the translational cycle of the Moon (gravitational effect) and the rotation of the Sun (changes in radiation incidence on atmosphere), resulting in seasonal magnetic variations. This seasonal variation contributes to the "day-to-day variation", characterized by changes in both behavior and magnitude of the diurnal variation from one day to the next one. The day-to-day variation typically exhibits small amplitudes, around ~ 10 nT, although its intensity is also influenced by factors such as the season of the year, geomagnetic latitude, the lunar cycle, and solar rotation.

In terms of the disturbed magnetic field, it is primarily attributed to GMSs and the induced magnetic fields associated with them. According to Le Huy and Amory-Mazaudier (2005), magnetic disturbances related to geomagnetic storms can be subclassified into magnetospheric contributions and ionospheric contributions.

On one hand, the magnetospheric contribution stems from the intensified activity of magnetospheric currents during GMS events. On the other hand, the ionospheric contribution arises from the presence of two ionospheric currents. Notably, for mid and low latitudes, the disturbed polar current 2 ($DP2$) (Nishida, 1968) and disturbed dynamo ($Ddyn$) (Blanc and Richmond, 1980) currents are prominent. These currents are known for their impact on the ionosphere and their influence at mid and low latitudes during GMS. Moreover, they induce quasi-periodic fluctuations, with well-defined frequencies (periods), in the EMF on a regional scale, which are observable using magnetometers.

1.3. Objectives

The aim of this study is to characterize geomagnetic response differences based on variations in latitude and local time, with a specific focus on equatorial regions. The region of interest is Peru, which hosts a network of magnetometers. This area presents the ionospheric mechanism such as the equatorial electrojet (EEJ), not typically observed in mid-low latitudes. Through selected case studies, our objective is to identify and isolate regional geomagnetic variations, along with the magnetic signatures associated with the underlying physical mechanisms. A comprehensive understanding of these processes contributes to a deeper insight into the effects of space weather and their diverse impacts on different regions.

1.4. Hypothesis

The geomagnetic responses associated with a GMS are due to ionospheric activity, as well as the variations of the magnetospheric currents in local time. In order to have a better understanding of regional space weather, it is necessary to take into account the development of these systems from the perspective of a specific region. In addition, the local responses of regions with different geomagnetic latitudes will be compared. It will be assumed that this comparison will allow us to identify differences and similarities between regional responses and geomagnetic latitude. For this purpose, we consider geomagnetic indices to identify and characterize the GMS. On one hand, planetary indices allow characterizing geomagnetic activity at the planetary level. Meanwhile, regional indices combine planetary and regional response. For the regional case, it is necessary to have access to EMF measurements within the study region. This practice makes it possible to have a better understanding of some of the ionospheric and magnetospheric processes in such regions.

1.5. prior research

In Martinez-Breton et al. (2016) they investigated variations in geomagnetic response over local time, revealing discrepancies in the planetary geomagnetic response compared to observations over central Mexico. The significance of examining magnetic-ionospheric contributions in relation to local time, particularly in Mexico, was emphasized. Subsequently, Corona-Romero et al. (2018) conducted a more detailed analysis of local geomagnetic response, introducing the local geomagnetic indices $DeltaH_{mex}$ and K_{mex} for the first time in Mexico. This work highlighted differences between these regional indices and their planetary counterparts, suggesting that local variations may primarily stem from ionospheric processes. Additionally, studies conducted in Sergeeva et al. (2019); Sergeeva et al. (2020) explored ionospheric behavior during GMS periods.

In Castellanos-Velazco (2022), it was shown that geomagnetic disturbances occured during six GMSs in central Mexico. The regional EMF response was shown to be linked to the presence of ionospheric currents disturbed dynamo ($Ddyn$) and disturbed polar no. 2 ($DP2$). Using the methodology proposed by Younas et al. (2020), magnetic fluctuations associated with these ionospheric currents were isolated. Additionally, total electron content (TEC) analysis confirmed the consistency of the magnetic response with ionospheric behavior during storm periods. Expanding upon this work, Castellanos-Velazco et al. (2024) extended the study to 20 GMSs and implemented improvements in magnetic data processing for enhanced result accuracy. Their findings underscore the importance of conducting similar investigations in diverse regions to provide context for their results.

Three additional GMS occurring in 2023 have been incorporated into the analysis, marking the initial intense events of solar cycle 25, which is currently unfolding. To explore local geomagnetic responses in other regions, the INTERMAGNET (International Real-Time Magnetic Observatory Network) public platform was utilized (INTERMAGNET, 2021). However, it's important to acknowledge that the study's scope is constrained by the availability of geomagnetic records in each region. Consequently, there are events and regions that remain unstudied due to data unavailability.

2. Methodology

2.1. Study Cases

For this project, we propose utilizing the 23 GMSs (Table 1) previously analyzed. These GMSs were selected based on specific criteria derived from the peaks of the local geomagnetic indices ΔH_{local} and K_{local} in Mexico. Specifically, events were chosen where $\Delta H \leq -120$ nT and $K_{local} \geq 7$. By selecting events with available magnetometer data in Peru, our objective is to compare regional response differences effectively.

These events also encompass recent intense GMSs that transpired in the latter half of 2023 and thus far in 2024. Additionally, it is important to note that, based on preliminary assessments, the number of case studies may be narrowed down for subsequent stages of the project. This will allow us to concentrate our efforts on events with a more pronounced regional response compared to others in the project.

2.2. Data processing

For regional TGM studies, we use data from magnetometers situated in the region of interest. These records provide valuable insights into variations of electric currents in both, the ionosphere and magnetosphere (Bartels, 2013). However, it's important to note that the output data includes magnetic contributions from processes beyond GMS events (Amory-Mazaudier et al., 2017; Younas et al., 2020). Therefore, an initial processing step is necessary to isolate and identify the magnetic information specifically associated with GMSs.

2.3. Baseline derivation

In the EMF, there are cyclical variations with periods of less than one year, known as *regular variations* (Knecht and B.M, 1985). Among these, the most significant are the day-to-day variation (H_0) and the diurnal variation (H_{SQ}) (Gjerloev, 2012; van de Kamp, 2013). Once these regular variations are identified, their magnetic contribution is eliminated from the output data, as outlined in the following expression:

$$H = H_{raw} - (H_0 - H_{SQ}), \tag{1}$$

Tabla 1: Case studies: Event number, GMS Starting date, Minimum (Maximum) value reached during events for $\mathrm{Dst}(\mathrm{K_P})$ and $\Delta\mathrm{H_{local}}(\mathrm{K_{local}})$

Event #	Beginning of Main phase	^{a}Dst minimum [nT]	$^{b}\Delta$H minimum [nT]	$^{a}\mathrm{K_p}$ maximum	$^{b}\mathrm{K_{local}}$ maximum
1	2003/05/29	-144	-190	8+	9
2	2003/10/14	-85	-126	7+	7-
3	2003/11/20	-422	-441	9-	9
4	2004/07/22	-170	-167	9-	8+
5	2004/08/30	-129	-154	7	7-
6	2004/11/08	-374	-398	9-	9
7	2005/05/15	-247	-206	8+	7
8	2005/06/12	-106	-120	7+	6+
9	2005/08/24	-184	-138	9-	9-
10	2005/08/31	-122	-125	7	6+
11	2006/08/19	-79	-131	6	7-
12	2006/12/14	-162	-247	8+	9
13	2015/03/15	-222	-282	8	8-
14	2015/10/07	-124	-143	7+	7+
15	2015/12/20	-155	-189	7-	7
16	2016/03/06	-98	-120	6	7
17	2016/10/13	-104	-128	6+	6+
18	2017/05/27	-125	145	7	8
19	2017/09/07	-124	-170	8+	8+
20	2018/09/25	-175	-176	7+	7-
21	2023/02/26	-144	-190	8+	9
22	2023/03/23	-85	-126	7+	7-
23	2023/04/23	-422	-441	9-	9

Comments for the Table.
[a] Dst and Kp were obtained from the International Service of Geomagnetic Indices (ISGI).
[b] Regional geomagnetic $\Delta\mathrm{H_{local}}$ and $\mathrm{K_{local}}$ were computed by the Space Weather National Laboratory, using resgisters from the magnetic observatory from Teoloyucan, Mexico (events 1-20) and the magnetic station in Coeneo Michoacan, Mexico (events 21 - 23).

here, H_{raw} represents the raw magnetometer output data. The identification of regular variations relies on statistical principles, wherein the search for the most "common" values, associated with calm periods, is conducted. Additionally, this process discerns instances of data variation, attributed to periods of disturbance. For further elaboration on this topic, refer to sections 4.1 and 4.2 in the Appendix.

2.4. Ionospheric current identification

The process of identifying magnetic signatures follows the same approach as that outlined in Le Huy and Amory-Mazaudier (2005); Amory-Mazaudier et al. (2017); Younas et al. (2020). In this process, the measurements from a specific magnetometer results from the combination of several magnetic field sources, as described below:

$$H = H_P + H_{reg} \tag{2}$$

here, H_P represents the magnetic field perturbations in the region under study, and $H_{reg} =$

$H_0 + H_{SQ}$ represents the regular variations. Additionally, the magnetic field perturbations can be expressed as:

$$H_P = H_{mag} + H_{iono} \tag{3}$$

In Equation 3, the first term on the right-hand side represents the magnetospheric contribution, while the second term represents the ionospheric contribution. It's common in the literature to approximate H_{mag} as $GI_P \cdot cos(\lambda)$, where GI_P is the planetary geomagnetic index, typically Dst or its higher resolution equivalent $SYM-H$, and λ is the geomagnetic latitude of the region of interest. $H_{iono} = H_{Ddyn} + H_{DP2}$, denotes the magnetic fluctuations associated with the $Ddyn$ and $DP2$ ionospheric currents. Given that the $Ddyn$ and $DP2$ currents generate quasi-periodic fluctuations with characteristic periods distinct from each other, their effects can be isolated using frequency filters.

$$H_{Ddyn} + H_{DP2} = H - (GI_P \cdot cos(\lambda) + H_0 + H_{SQ}). \tag{4}$$

Building upon Equation (4), Younas et al. (2020) proposes utilizing frequency filters to isolate the magnetic signatures of $Ddyn$ and $DP2$. Previous research (Nishida, 1968; Blanc and Richmond, 1980) indicates that the periods during which $Ddyn$ and $DP2$ induce fluctuations in the regional magnetic field are approximately around 24 hours and less than or equal to 4 hours, respectively. Consequently, it is imperative to configure a band-pass filter for H_{Ddyn} and a high-pass filter for H_{DP2}.

While the cutoff frequency for the high-pass filter is well-defined ($f \geq 6.94 \times 10^{-5}$ Hz or $T \leq 4$ hours) as indicated by Nishida (1968), determining the cutoff frequencies for the band-pass filter is more intricate. These frequencies can significantly vary for each GMS. To tackle this challenge, Castellanos-Velazco et al. (2024) employed power spectral density (PSD) on the outcome of Equation 4 for each GMS. Utilizing PSD allows for the detection of power peaks at specific frequencies, aligning with the frequency ranges of H_{Ddyn} fluctuations. Once these power peaks are identified, the cutoff frequencies are adjusted accordingly. Subsequently, the filtering process is executed to isolate the magnetic fluctuations of H_{Ddyn} and H_{DP2}.

The limitations associated with the method described above include

1. The power spectrum method only enables the study of intensities in the frequency domain, lacking the ability to analyze the specific time periods during which these intensity peaks occur (Younas et al., 2021)

2. It aims to approximate all magnetospheric activity using a geomagnetic index, thereby disregarding the effects of the ring current.

3. It approximates the ring current as a longitudinally symmetrical current, whereas in reality, it comprises both symmetrical and asymmetrical components.

To address these problems, the following additional procedure is proposed:

2.5. Frequency and Time Analysis: Wavelets

As mentioned in the conclusions of Castellanos-Velazco et al. (2024), a good way to improve the understanding of the regional geomagnetic response in storm periods is time and frequency domain analysis. Time and frequency domain analysis was conducted in a similar manner in a previous study (Younas et al., 2021). Preliminary wavelet studies of the events listed in Table 1 have already been conducted using Teoloyucan and Coeneo data, building on the approach outlined in Younas et al. (2021).

This complementary analysis tool has certain advantages, since it makes it possible to detect the moment in time when certain fluctuations occur at a certain frequency. This aspect is not readily observable in PSD (it may be an effect limited to a short period, or a persistent effect). Wavelets, on the other hand, allow for the precise localization in time of specific frequency fluctuations, providing valuable insight into their temporal occurrence.

The wavelet transform is utilized for analyzing time series featuring non-stationary power across various frequencies (Torrence and Compo, 1998). It is essential to consider the wavelet form or function. In this work, we employ the *Morlet* wavelet due to its effectiveness. Similar to the PSD, the wavelet power enables visualization of energy peaks corresponding to significant frequencies. However, it also provides temporal information, offering a comprehensive analysis of the data Paschmann and Daly (1998); Torrence and Compo (1998).

2.6. Individual identification of magnetospheric sources

According to Newell and Gjerloev (2012), a noteworthy contributor to the regional geomagnetic response is the partial ring current, active during the main phase of GMSs. However, it's essential to acknowledge that magneto-pause and magneto-tail currents may also impact the Dst and $SYM-H$ indices, potentially influencing regional space weather dynamics. This influence is particularly significant when considering factors such as the local time of GMS occurrence.

Modeling techniques offer a mean to approximate the magnetic contributions stemming from magneto-pause, magneto-tail, and partial ring currents (Kalegaev et al., 2008). The model proposed by Alekseev (1978) is implemented in Alexeev et al. (1996); Kalegaev et al. (2008). In this model, the magnetic field associated with each potential magnetospheric source is determined based on interplanetary medium conditions and geomagnetic responses. Thus, from the first term on the right-hand side of Equation 3:

$$H_{mag} = H_{mp}(\psi, R_1) + H_t(\psi, R_1, R_2, \Phi_{pc}) + H_r(\psi, h_r) + H_{pr}(\psi, I_{pr}, \theta_{pr}) + H_{mr}(\psi, R_1, h_r) \quad (5)$$

In this equation, H_{mp} represents the magnetic field induced by the magneto-pause and shielding the magnetic field, while H_r stands for the magnetic field associated with the ring symmetrical current. Additionally, H_t denotes the magneto-tail field, H_{pr} represents the field associated with the partial ring current, and H_{mr} signifies the magnetic field of the magneto-pause that shields the current field.

Additionally, the model requires input parameters. These are the tilt angle psi of the rotation axis, R_1 which is the distance to the magneto-pause subsolar point, R_2 is the distance from the Earth to the edge of the magneto-tail current sheet, Phi_{pc} is the magnetic flux in the tail lobes, h_r is the field of the ring current at the center of the Earth, I_{pr} is the maximum intensity of region 1 of the field-aligned current, θ_{pr} is the latitude of the equatorial electrojet in the westward direction, and I_{pr} is the total current of the partial ring.

It's important to highlight that certain parameters are established through complementary models, leveraging data from the interplanetary medium. For accessing such data, platforms like https://omniweb.gsfc.nasa.gov/ offer valuable resources including solar wind speed, solar wind density, interplanetary magnetic field, and more.

3. Concluding Remarks

Previous studies have examined the central region of Mexico, laying the groundwork for the project proposed herein. Initial outcomes from wavelet analysis demonstrate coherence with power spectra results. Generally, power peaks fall within the 24-10 hour range, consistent with prior research. However, these peaks also coincide with the main phase of each storm, contrary to the expected behavior of the Ddyn current, which typically exhibits effects with a delay of several hours. Consequently, further investigations are necessary to resolve these discrepancies. Additionally, not all case studies exhibit a notable magnetic contribution from ionospheric currents Ddyn and DP2. Therefore, it is imperative to expand the analysis to ascertain the conditions under which the effects of $Ddyn$ and $DP2$ manifest.

For this project, removing the effects linked to the asymmetric ring current is anticipated to yield distinct results. As this current is confined to the local sector where the study region is situated during GMS events (Newell and Gjerloev, 2012), its influence is significantly reduced. Recognizing the magnetic contribution of the partial ring current and distinguishing it from the effects of $Ddyn$ and $DP2$ is crucial for understanding regional space weather dynamics.

4. Appendix

4.1. day to day variation

To determine the day-to-day variation or H_0, the initial step wraps identifying a daily representative value that can serve as a common benchmark for each day (Gjerloev, 2012). For this study, the median of each day was initially chosen as the daily representative value. Once calculated, these values are interpolated, resulting in a time series with a temporal resolution of 1 minute. This interpolated time series constitutes the baseline H_0. Establishing a threshold is crucial to enable the algorithm to automatically identify daily values associated with storm periods for removal. Consequently, any value surpassing the threshold will be classified as a disturbed day:

$$Umbral = H_{med} + \frac{\sigma \cdot 1.3490}{n} \tag{6}$$

Equation 6 references a normal distribution of the data for each event. Despite perturbation conditions skewing distributions towards negative values, they maintain a normal distribution shape. H_{med} represents the median (typical value) in each time window, while $\sigma \cdot 1.3490$ denotes the interquartile range for normal distributions. Additionally, n serves as a factor experimentally determined to adjust the threshold. This method enables a more accurate derivation of the baseline H_0 during storm periods. For days featuring the storm recovery phase, a semi-manual approach is employed, where operators manually discard daily values coinciding with this phase. While suitable for specific event studies, this manual intervention proves impractical for real-time observations and is thus not recommended for such scenarios.

4.2. Diurnal variation

To derive the diurnal variation (H_{SQ}), quiet days must first be identified. These are days marked by lower geomagnetic activity, with the contribution primarily stemming from the ionospheric current of the sun quiet. Subsequently, a baseline is established from this average, denoted as H_{SQ}, which is then subtracted from the original time series, along with H_0.

In this study, we adhered to the criterion proposed by van de Kamp (2013), which focuses on identifying the maximum daily fluctuation. Using a time window with sufficient days and a resolution of 1 minute, the data is resampled to hourly intervals. Hourly interquartile ranges are then calculated to describe the hourly variation. Subsequently, the maximum variation for each day, represented as $MAX(\sigma)/MAX(IQR)$, is determined. The days with the lowest values within the time window are designated as the local quietest days, denoted as $MAX(\textbf{\textit{LQD}})$. For this investigation, two such LQD are utilized: one day prior to the event and the second day following the event, effectively framing the storm period. The closer temporally the LQD are to each other, the more accurate the baseline will be, although the separation threshold between the DQLs can extend up to 66 days. Subsequently, a smoothing function, as outlined in Gjerloev (2012), is applied to the resulting time series, which we designate as H_{SQ}.

4.3. Peak Detection: Whitaker-Hayes Algorithm

One challenge in preprocessing magnetic field data is dealing with extreme values, as they can significantly impact subsequent analyses. Hence, it's crucial to develop an algorithm capable of detecting and eliminating these outliers from the time series before preprocessing. To address this, we implement the Whitaker-Hayes algorithm. Notably, this algorithm is computationally efficient, making it feasible for most computational systems to execute Whitaker and Hayes (2018).

The algorithm operates by assessing the distance of a given value from the center of the data distribution, utilizing measures of variation such as standard deviation or interquartile range. It employs the Modified Z-score (MZS), which utilizes the Median Absolute Deviation (MAD). To address peaks (Whitaker and Hayes, 2018; Coca, 2019), a first-order derivative on the continuous data, denoted as $\nabla H(i) = H(i) - H(i-1)$, is computed to determine the MZS. The algorithm is expressed as follows:

$$|z(i)| = \left| 0.6745 \cdot \frac{\nabla H(i) - M}{MAD} \right| \tag{7}$$

The criterion proposed by the American Society for Quality Control is 3.5 and above, although, according to Coca (2019), the threshold will depend on the specific time series. The final step involves replacing extreme values with null values, and if needed, interpolation with neighboring values can be applied.

References

Alekseev, I.I., 1978. Regular magnetic field in the magnetosphere of the earth. Geomagnetism and Aeronomy 18, 656–665.

Alexeev, I.I., Belenkaya, E.S., Kalegaev, V.V., Feldstein, Y.I., Grafe, A., 1996. Magnetic storms and magnetotail currents. Journal of Geophysical Research: Space Physics 101, 7737–7747. URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/95JA03509, doi:https://doi.org/10.1029/95JA03509, arXiv:https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/95JA03509.

Amory-Mazaudier, C., Bolaji, O.S., Doumbia, V., 2017. On the historical origins of the CEJ, DP2, and Ddyn current systems and their roles in the predictions of ionospheric responses to geomagnetic storms at equatorial latitudes. Journal of Geophysical Research (Space Physics) 122, 7827–7833. doi:10.1002/2017JA024132.

Bartels, J., 2013. Iii - the geomagnetic measures for the time-variations of solar corpuscular radiation, described for use in correlation studies in other geophysical fields, in: International Council of Scientific Unions Comité Spécial de l'Année Géophysique Internationale (CSAGI) (Ed.), Geomagnetism. Pergamon. volume 4 of *Annals of The International Geophysical Year*, pp. 227–236. URL: https://www.sciencedirect.com/science/article/pii/B9781483213040500075, doi:https://doi.org/10.1016/B978-1-4832-1304-0.50007-5.

Baumjohann, W., Treumann, R.A., 1999. Basic Space Plasma Physics. Imperial College Press, 57 Shelton Street Covent Garden London WC2H 9HE.

Blanc, M., Richmond, A.D., 1980. The ionospheric disturbance dynamo. Journal of Geophysical Research 85, 1669–1686. doi:10.1029/JA085iA04p01669.

Castellanos-Velazco, 2022. Manifestaciones regionales de tormentas geomagneticas ocurridas durante los ciclos solares 23 y 24 .

Castellanos-Velazco, C., Corona-Romero, P., González-Esparza, J., Sergeeva, M., Caccavari-Garza, A., Gatica-Acevedo, V., 2024. Low latitude geomagnetic response associated with intense geomagnetic storms: Regional space weather in mexico. Journal of Atmospheric and Solar-Terrestrial Physics , 106237URL: https://www.sciencedirect.com/science/article/pii/S1364682624000658, doi:https://doi.org/10.1016/j.jastp.2024.106237.

Coca, N., 2019. Removing Spikes from Raman Spectra with Anomaly Detection: Whitaker-Hayes algorithm in Python. URL: https://towardsdatascience.com/removing-spikes-from-raman-spectra-8a9fdda0ac22. accessed = 2023-11-10.

Corona-Romero, P., Sanchez-Garcia, E., Sergeeva, M., Gonzalez-Esparza, A., Cifuentes-Nava, G., Hernandez-Quintero, J.E., Caccavari, A., Aguilar-Rodriguez, E., Mejia-Ambriz, J., De la Luz, V., Gonzalez, L., 2018. Kmex: the mexican geomagnetic k index, pp. 96–100. doi:10.29327/2pangeo.a29.

Gjerloev, J.W., 2012. The SuperMAG data processing technique. Journal of Geophysical Research (Space Physics) 117, A09213. doi:10.1029/2012JA017683.

Gombosi, T.I., 1998. Physics of the Space Environment. Cambridge Atmospheric and Space Science Series, Cambridge University Press. doi:10.1017/CBO9780511529474.

INTERMAGNET, 2021. International real-time magnetic observatory network. URL: https://www.intermagnet.org/index-eng.php.

Jankowski, J., Sucksdorff, C., 1996. Iaga guide for magnetic measurements and observatory practice. URL: https://api.semanticscholar.org/CorpusID:107045138.

Kalegaev, V.V., Bakhmina, K.Y., Alexeev, I.I., Belenkaya, E.S., Feldstein, Y.I., Ganushkina, N.V., 2008. Ring current asymmetry during a magnetic storm. Geomagnetism and Aeronomy 48, 747–758. doi:10.1134/S0016793208060078.

Knecht, D., B.M, .S., 1985. HANDBOOK OF GEOPHYSICS AND THE SPACE ENVIROMENT, chapter 4, THE GEOMAGNETIC FIELD. ed by A. S. Jursa, Boston: Air Force Geophysics Laborator.

Le Huy, M., Amory-Mazaudier, C., 2005. Magnetic signature of the ionospheric disturbance dynamo at equatorial latitudes: "D_{dyn}". Journal of Geophysical Research (Space Physics) 110, A10301. doi:10.1029/2004JA010578.

Margaret G. Kivelson, C.T.R., 1995. Introduction to Space Physycs. Press Syndicate of the University of Cambridge.

Martinez-Breton, L.J., Ortega, B.M., Hernandez-Quintero, J.E., 2016. Relationship between the minima of the horizontal magnetic component measured in Mexico and the Dst and $SYM-H$ indices for geomagnetic storms with Dst $\pm -100nT$ during the descending phase of solar cycle 23. Geofisica Internacional 55, 155–164.

Newell, P.T., Gjerloev, J.W., 2012. SuperMAG-based partial ring current indices. Journal of Geophysical Research (Space Physics) 117, A05215. doi:10.1029/2012JA017586.

Nishida, A., 1968. Geomagnetic D_p 2 fluctuations and associated magnetospheric phenomena. Journal of Geophysical Research 73, 1795–1803. doi:10.1029/JA073i005p01795.

Paschmann, G., Daly, P.W., 1998. Analysis Methods for Multi-Spacecraft Data. ISSI Scientific Reports Series SR-001, ESA/ISSI, Vol. 1. ISBN 1608-280X, 1998. ISSI Scientific Reports Series 1.

Sergeeva, M., Kalishin, A., Maltseva, O., Blagoveshchensky, D., Gonzalez-Esparza, A., Corona-Romero, P., Gatica Acevedo, V., 2020. Possibility of signal reflection from the northern crest of eia: case study , 1–4doi:10.23919/EuCAP48036.2020.9135786.

Sergeeva, M.A., Gonzalez-Esparza, J.A., Blagoveshchensky, D.V., Maltseva, O.A., Chernov, A.G., Corona-Romero, P., De la Luz, V., Mejia-Ambriz, J.C., Gonzalez, L.X., Romero-Hernandez, E., Rodriguez-Martinez, M., Aguilar-Rodriguez, E., Andrade, E., Villanueva, P., Gatica-Acevedo, V.J., 2019. First observations of oblique ionospheric sounding chirp signal in Mexico. Results in Physics 12, 1002–1003. doi:10.1016/j.rinp.2018.12.077.

Torrence, C., Compo, G.P., 1998. A Practical Guide to Wavelet Analysis. Bulletin of the American Meteorological Society 79, 61–78. doi:10.1175/1520-0477(1998)079<0061:APGTWA>2.0.CO;2.

van de Kamp, M., 2013. Harmonic quiet-day curves as magnetometer baselines for ionospheric current analyses. Geoscientific Instrumentation, Methods and Data Systems 2, 289–304. doi:10.5194/gi-2-289-2013.

Whitaker, D.A., Hayes, K., 2018. A simple algorithm for despiking raman spectra. Chemometrics and Intelligent Laboratory Systems 179, 82–84. URL: https://www.sciencedirect.com/science/article/pii/S0169743918301758, doi:https://doi.org/10.1016/j.chemolab.2018.06.009.

Younas, W., Amory-Mazaudier, C., Khan, M., Fleury, R., 2020. Ionospheric and Magnetic Signatures of a Space Weather Event on 25-29 August 2018: CME and HSSWs. Journal of Geophysical Research (Space Physics) 125, e27981. doi:10.1029/2020JA027981.

Younas, W., Amory-Mazaudier, C., Khan, M., Le Huy, M., 2021. Magnetic Signatures of Ionospheric Disturbance Dynamo for CME and HSSWs Generated Storms. Space Weather 19, e02825. doi:10.1029/2021SW002825.