

Daily geomagnetic variations under variable IMF/solar conditions and their connection with underground conductivity changes in Japan

Emad M. Takla^{*},¹, Akimasa Yoshikawa^{2,3}, Teiji Uozumi⁴, Kirolosse M. Girgis³, A. Abdelkader¹

⁽¹⁾ National Research Institute of Astronomy and Geophysics (NRIAG), 11421 Helwan, Cairo, Egypt

⁽²⁾ Department of Earth and Planetary Sciences, Faculty of Sciences, Kyushu University, Japan

⁽³⁾ International Research Center for Space and Planetary Environmental Science (i-SPES), Kyushu University, Japan

⁽⁴⁾ Laboratory of Lean Satellite Enterprises and In-Orbit Experiment (LaSEINE), Kyushu Institute of Technology (kyutech), Japan

Article history: received October 7, 2023; accepted December, 2, 2023

Abstract

Fluctuations in Solar Wind (SW) and Interplanetary Magnetic Field (IMF) have a relevant effect on the Geomagnetic Field (GF) measurements particularly during extreme space weather events. The current study investigates the variations of horizontal (H), vertical (Z) geomagnetic components under quiet and disturbed IMF and solar conditions as well as the effect of underground conductivity on the stationary geomagnetic measurements in Japan. Results of data analysis show that the response of the GF to IMF and solar parameters fluctuations is variable. The H and Z components were in good agreement with high visual correlation along a latitudinal profile across Japan during quiet times. On the other hand, during the disturbed times related to a Coronal Mass Ejection (CME) launched on 13 May 2005, the GF components varied with the disturbance of IMF and solar parameters. The H components showed highly correlated variations with a significant reduction along the examined profile due to the intensified ionospheric currents, while the Z components recorded in the northern part of Japan showed abnormal daily variations pattern (positive daily variations) with an enhanced amplitude which is opposite to the normal behavior of daily variations recorded in the central and southern parts of Japan (negative daily variations). The observed enhanced and abnormal daily variation of Z components in north Japan, which we consider a remarkable observation here, is possibly linked with underground conductivity anomaly in this region.

Keywords: Daily Geomagnetic Variations (DGVs); Geomagnetic components; Quiet and disturbed times; Interplanetary Magnetic Field (IMF); Coronal Mass Ejection (CME); Underground conductivity

1. Introduction

The Earth's magnetic field, also known as the Geomagnetic Field (GF), varies in time and space. This field can be approximated by a dipolar field located in the center of the Earth. The main part of the total GF is generated internally due to the self-exciting dynamo process in the Earth's core [Merrill et al., 1996; Manda and Purucker, 2005]. In addition to the internal source, the GF has sources in the Earth's crust (crustal field) as well as in the magnetosphere (external field) related to the solar activity. Due to changes in these internal and external sources, the measurable GF on the Earth's surface is not constant, and it undergoes significant variations and oscillations. Over time, observable periodic and random variations of the GF occur in a wide range starting from fractions of seconds to thousands of years. These temporal variations can have long or short-term periods. Changes of internal origin usually have long-term periods while changes due to external sources particularly those associated with solar activity have short-term ones [Courillot and le Mouel, 1988].

The Sun emits charged particles travelling consistently in what is known as solar wind in the Earth's direction. When these particles reach the near-Earth environment, their flow is interrupted by the presence of the GF [Hundhausen, 1972]. The solar wind also carries the magnetic field of the Sun that fills the whole interplanetary space and is known as the Interplanetary Magnetic Field (IMF). The interaction between the IMF, solar wind and the GF occurs mainly in a region called the magnetosphere. The geomagnetic disturbances resulting from this interaction are generally limited to the high-latitude regions unless the vertical component of IMF (B_z) is lastly persistent (several hours or more) in its southward orientation and with considerable magnitudes [Devi et al., 2008]. This interaction mainly depends on the relative orientation of the IMF and GF, especially during extreme solar events [Bothmer and Schwenn, 1998]. Normally, the Earth's magnetosphere does not respond to external sources of variation such as solar wind and IMF, so the magnetospheric currents keep their symmetry. Differently, when conditions are favorable, the magnetosphere responds to external sources of variation and as a result a decrease in the intensity of GF will be observed with different magnitude at different locations and a geomagnetic storm might take place.

One of the most important and significant space weather events is the Coronal Mass Ejection (CME), which can be defined as observable changes in coronal structure of the Sun. CMEs occur with a duration of a few minutes to several hours where outward motion of solar plasma can be detected. During extreme solar events like CME, filament eruptions and massive clouds of solar plasma containing magnetic fields expelled from the Sun are thrown out [Schwenn et al., 2005]. Generally, severe, and huge space weather disturbances in the near-Earth environment are generated by CMEs, which take a few days to propagate from the Sun to the Earth [Kilpua et al., 2019]. On reaching the near-Earth space environment, if CMEs can alter the IMF to have a northward orientation as the GF, then almost no interaction occurs between them. On the other hand, if the CMEs can cause the IMF to have a southward orientation that is opposite to the orientation of the GF, the two fields can effectively interact with each other. In this case, such interaction is known as magnetic reconnection [Dungey, 1961]. During this magnetic reconnection, efficient amounts of energy and huge fluxes of charged particles are transferred from solar wind into magnetosphere. Under the effect of GF, these charged particles circulate around the Earth generating a belt of currents system, known as the ring currents [Daglis et al., 1999]. Another important current system resulting from the solar wind-magnetosphere interaction is the field-aligned currents system. These ionospheric current systems generate magnetic fields, which contribute to the total GF observed on the surface of Earth [Bisi, 2010].

The ionospheric current systems are responsible for the occurrence of regular Daily Geomagnetic Variations (DGVs) with a magnitude of few tens of nano Tesla (nT) that are often known as Solar quiet (Sq) variations. This kind of variation is linked to the solar illumination and so it mainly depends on solar (local) time (LT). Also, it is a quiet variation because it is observable only when solar wind driven turbulences are absent (quiet solar conditions). When solar activity is strong, the resulting geomagnetic disturbances are typically of several hundreds of nTs in magnitude at the ground surface, which can easily hide the normal DGVs. However, DGVs have small amplitude, studies of these variations are very significant for understanding the ionospheric electrodynamics [Richmond, 1979], and for estimating underground electrical conductivity [Campbell et al., 1998, Okeke and Obiora, 2016]. The DGVs include signals not only related to ionospheric currents but also to underground currents induced in the Earth's interior [Yamazaki and Maute, 2017]. The strength of underground-induced currents is roughly one third of the ionospheric ones [Matsushita and Maeda, 1965]. The underground-induced currents are generated in a direction opposite to that of the source ionospheric currents. Therefore, at the ground they act to

Daily geomagnetic variations and underground conductivity changes

reduce the daily variations of vertical geomagnetic component (Z component) and increase the daily variations in horizontal geomagnetic component (H component) as reported by Yamazaki and Maute [2017]. Since a part of the DGV comes from the underground-induced currents, much attention must be paid to investigate anomalous distributions of electrical conductivity within the Earth's crust and mantle through geomagnetic and geoelectric observations and surveys.

Since surface geomagnetic variations are generated by magnetospheric and ionospheric currents as well as underground currents flowing in the conductive Earth layers [Kalegaev et al., 2005], geomagnetic observations are important for monitoring and studying the temporal GF variations and investigating their generation and mechanisms of modifications. These continuous and long-term observations are made in geomagnetic observatories or stations. Thus, such observational measurements make it possible to study the GF variations of both external and internal origins [Takla et al., 2011; 2012]. The geomagnetic networks such as the Geospatial Information Authority of Japan (GSI) and the International Real-time Magnetic Observatory Network (INTERMAGNET) networks have made their data suitable and available for studies on a global scale of the rapid geomagnetic variations caused by external sources.

Studies of GF variations are very important particularly during severe space weather events to understand the couple processes in the interplanetary space, magnetosphere, and ionosphere whose conditions strongly affect space and ground based technological systems and human life in general. Based on geomagnetic observational data, some studies have been conducted in the past to investigate how the variations in IMF during strong solar events can cause variations in the GF like a cause-effect relationship. In the current study, we investigate the ground geomagnetic response to disturbances in the IMF and solar conditions connected with an extreme space weather event that occurred on 13 May 2005 as well as during quiet times. In addition, the influence of the underground conductivity structure on local geomagnetic measurements in Japan was investigated. Such observational measurements make it possible to determine the conductivity difference by studying the response of geomagnetic components to strong solar events.

2. Data sets

Ground-based geomagnetic observatories and stations monitor changes in the GF, and they can be considered as a backbone of the human knowledge about the GF structure and its variations. Currently, modern instruments are used at geomagnetic observatories to record and produce various standardized geomagnetic data products. The fundamental outputs of these instruments are mainly one-minute values of the three (X, Y and Z) GF components. These one-minute data are useful and suitable for studying geomagnetic variations caused by the magnetospheric and ionospheric currents, in particular studying daily variations of the GF and geomagnetic storms.

For examining the impact of a severe space weather event (halo CME occurred on 13 May 2005) on the ground GF measurements as well as the influence of underground conductivity on these measurements, geomagnetic data released by the GSI and INTERMAGNET networks are used in the present study. The GSI data are based on data from fluxgate and proton magnetometers with one-minute sampling rate [Tanabe, 1997]. In addition, the INTERMAGNET that is a worldwide network of digital geomagnetic observatories of ground-based magnetometers uses standard specifications for measuring and recording instruments that also provide one-minute geomagnetic data in near real time [Jankowski and Sucksdorff, 1996].

In the current study, data from five GSI stations and three INTERMAGNET observatories in Japan are used. The GSI stations are the Akaigawa (AKA), Yokohama (YOK), Haramachi (HAR), Totsukawa (TTK) and Muroto (MUR) stations. While the INTERMAGNET observatories are the Memambetsu (MMB), Kakioka (KAK), and Kanoya (KNY) observatories. The INTERMAGNET data are used as reference points in the current study. Details and distribution of the geomagnetic observatories and stations are listed in Table 1 and shown in Fig. 1.

In addition, one minute data of the IMF magnitude (IMF-B) and North-south component of the IMF (IMF-Bz), and the solar parameters such as the Solar Wind (SW) speed, Flow Pressure (FP), and Electric field (Ey) are obtained from the database at the OMNI website (URL: omniweb.gsfc.nasa.gov). Geomagnetic data from both the GSI and INTERMAGNET networks as well as the IMF and solar data have been processed and analyzed using MATLAB scripts prepared for this aim.

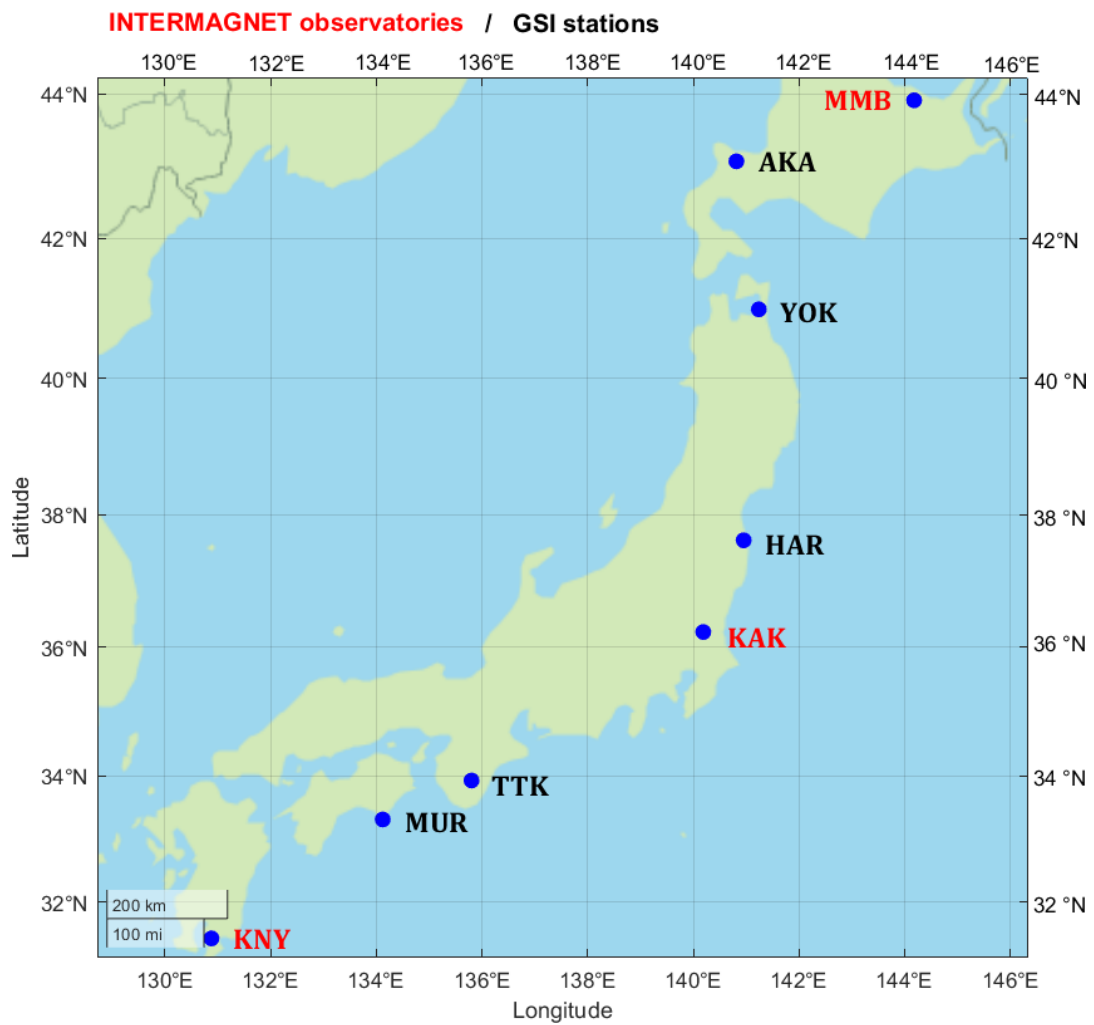


Figure 1. Locations of the GSI geomagnetic stations (in black) and INTERMAGNET observatories (in red) used in the current study.

Station	Code	Network	Geographic		Geomagnetic	
			Latitude	Longitude	Latitude	Longitude
Memambetsu	MMB	INTERMAGNET	43.91	144.18	35.44	148.24
Akaigawa	AKA	GSI	43.07	140.82	34.31	151.09
Yokohama	YOK	GSI	40.99	141.24	32.28	150.43
Haramachi	HAR	GSI	37.62	140.95	28.90	150.25
Kakioka	KAK	INTERMAGNET	36.23	140.19	27.47	150.78
Totsugawa	TTK	GSI	33.93	135.80	24.83	154.52
Muroto	MUR	GSI	33.32	134.12	24.10	155.99
Kanoya	KNY	INTERMAGNET	31.42	130.88	22.00	158.80

Table 1. The GSI and INTERMAGNET stations used in the current study.

3. Data analysis and results

At the beginning, we examined the temporal variation of IMF and solar parameters to choose two time-intervals representing quiet and disturbed times. The first time-interval represents a quiet geomagnetic day as shown in the left-side panels of Fig. 2. These panels show the variations of the IMF-B, IMF-Bz, SW speed, FP, and Ey from top to bottom respectively during 5 October 2005. As revealed from the temporal variations of the examined IMF and solar parameters, no remarkable disturbances are observed during this day (almost a quiet period). On the other hand, a disturbed time-interval is presented in the right-side panels of Fig. 2. This time interval represents a very disturbed day (15 May 2005) due to the occurrence of an intense geomagnetic storm, which was triggered by a severe space weather event. On 13 May 2005 a CME was launched from the Sun. It was an Earth-directed halo CME that erupted following a two-ribbon M8.0 solar flare. The right-side panels of Figure 2 show the in-situ IMF and plasma measurements from the ACE spacecraft just upstream of Earth [Bisi, 2010]. An abrupt increase was observed in the magnitude of the IMF and reached 55 nT then gradually decreased while the Bz component of the IMF reached -50 nT (southward). Also, large fluctuations were observed in the SW speed, FP, and Ey parameters with maximum values of 1000 km/s, 40 nPa, and 40 mV/m respectively. This halo CME caused the strongest magnetic storm in 2005 with a Dst index value reaching -263 nT at its minimum peak [Dasso et al., 2009].

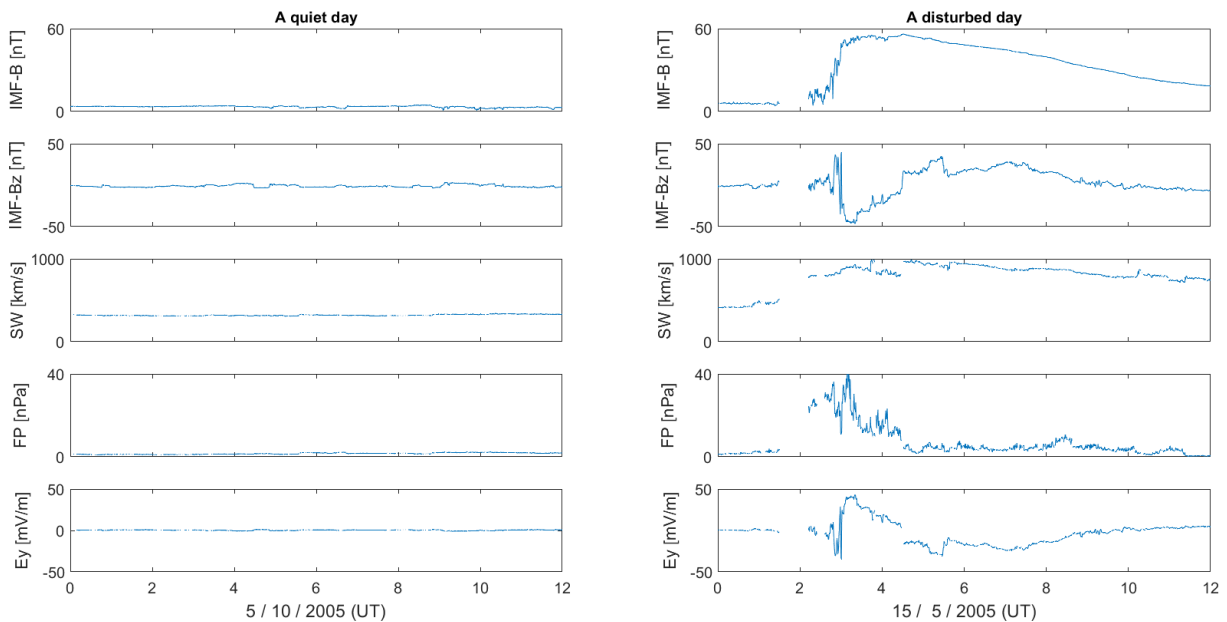


Figure 2. Time series plots of the IMF (B), IMF (Bz), SW speed, FP, and Ey during 5 October 2005 UT (quiet day) and 15 May 2005 UT (disturbed day) in the left- and right-side panels respectively with the same vertical scales. The LT in Japan is UT + 9.

To clarify how these IMF and solar wind fluctuations influenced ground geomagnetic observations during these two time intervals, the recorded geomagnetic data were examined along an array of geomagnetic stations in Japan, as shown in Fig. 1. Generally, the shape and amplitude of quiet day geomagnetic daily variations are subject to day-to-day changes. Since several sources can contribute to the DGVs, most of the day-to-day variability is not yet fully understood [Yamazaki and Maute, 2017]. Therefore, one-minute data of the horizontal north-south component (H component) and the vertical geomagnetic component (Z component) were used to examine the behavior of DGVs during both quiet and disturbed time-intervals. Figure 3 shows temporal geomagnetic variations for the H and Z components recorded along the examined profile on 5 October 2005 (a quiet day). For this quiet day, the IMF and solar wind parameters did not show any significant fluctuations, so the magnetosphere was under quiet conditions. Under these quiet interplanetary conditions, we can observe clear and regular daily (Sq) variations in the geomagnetic components. Geomagnetic observations at all stations show similar patterns of daily variations for

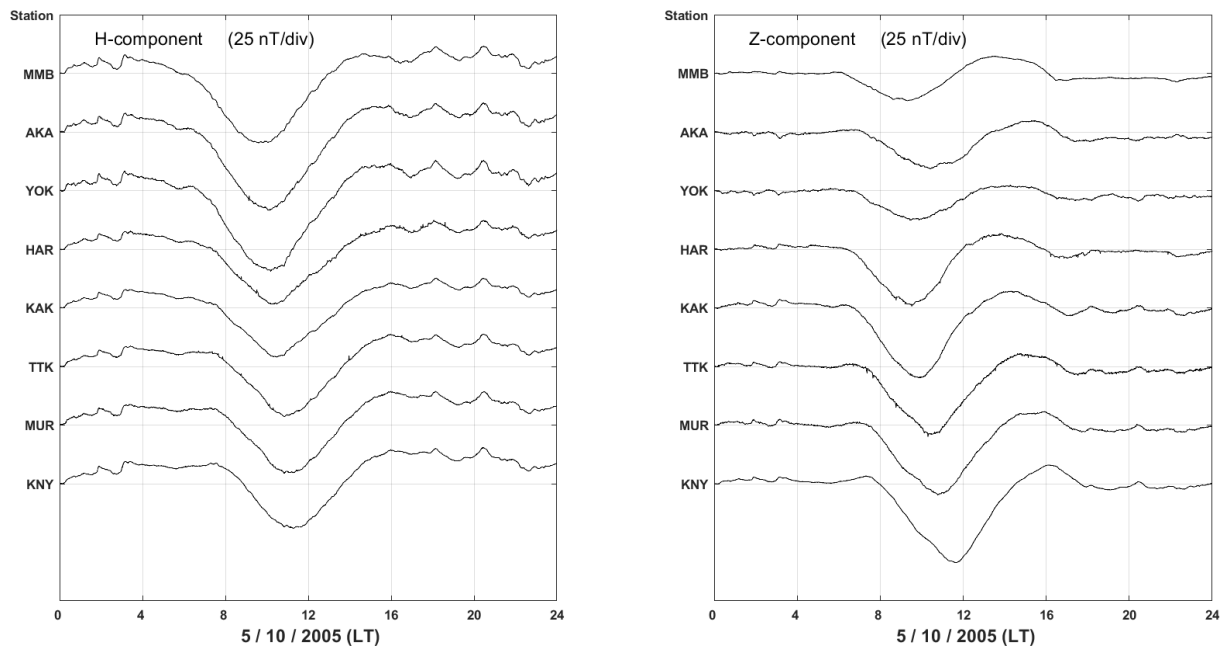


Figure 3. One-minute data of the H components (left side panel) and the Z components (right side panel) data recorded along the examined profile during a quiet day on 5 October 2005 (LT).

both the H and Z components, which are caused by the Earth’s rotation, and they mainly depend on the ionospheric current systems at the side facing the Sun. So far, the variations in H components at different stations are almost identical, while the amplitude of daily variations of Z components shows a notable decrease at stations located in the northern part of Japan (upper three curves in right-side panel of Fig. 3).

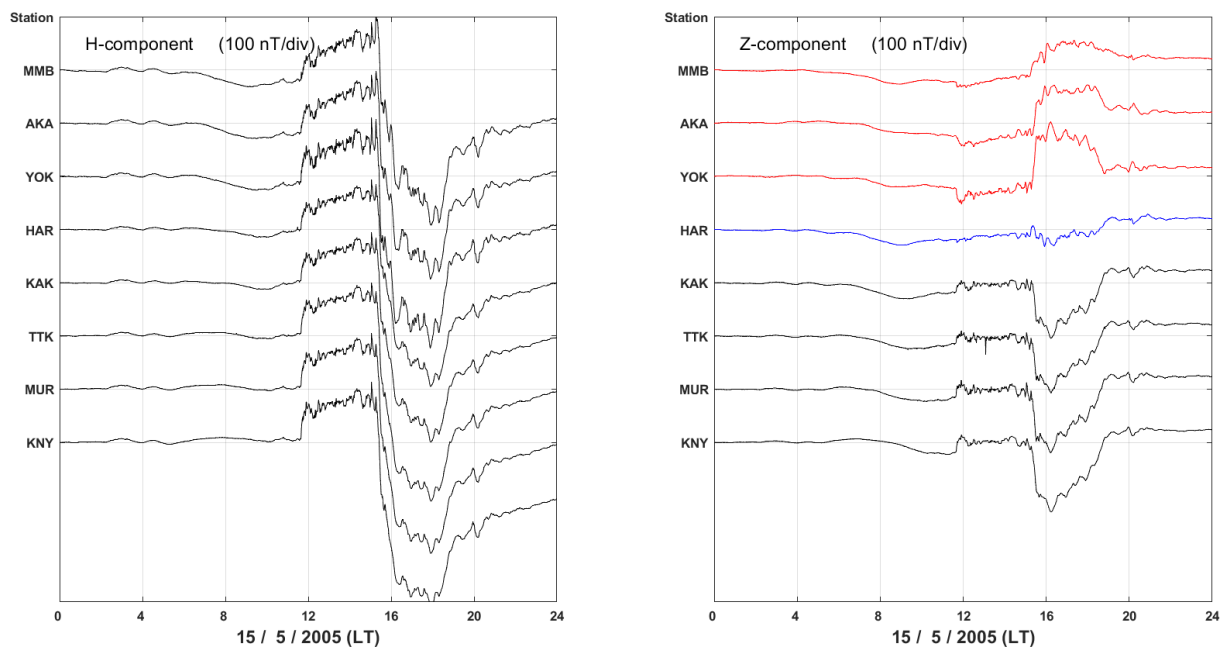


Figure 4. One-minute data of the H components (left side panel) and the Z components (right side panel) data recorded along the examined profile during a disturbed day on 15 May 2005 (LT). The red curves represent abnormal daily variations pattern of the Z components from stations located at the northern part of Japan, the blue curve represents the HAR station (intermediate or transition behavior), while black curves represent other stations in the central and southern parts of Japan.

Daily geomagnetic variations and underground conductivity changes

Generally, geomagnetic activities increase in response to large increases in the magnetospheric and ionospheric current systems, which can be monitored by ground-based magnetometers. Therefore, the geomagnetic measurements during the second time-interval were analyzed to study the impact of severe fluctuations of the IMF and solar parameters on the DGVs. The daily variations of the H components recorded during a disturbed day (15 May 2005) are presented in the left side panel of Fig. 4. By examining the geomagnetic data during the second time-interval, we can observe that, when IMF-Bz turns southward as presented in the right-side panels of Fig 2, strong fluctuations in the H and Z components were observed due to the magnetic reconnection between southward-directed IMF and GF lines. This reconnection is responsible for generating the geomagnetic activity observed along the examined profile. It is evident that there is a high correlation between the H components along the examined profile (H components are still maintaining negative pattern of daily variations). On the other hand, the daily variations of Z components at the northern part of Japan show positive pattern of variations (represented by upper red curves in right-side of Fig. 4) that are seen to be conspicuously opposite to the pattern of variations observed at other stations located in the central and southern parts of Japan which kept showing negative pattern of daily variations (represented by lower black curves in right-side of Fig. 4). The daily variation of Z component at the HAR station seems to be an intermediate stage between the two observed patterns of variations (red and black curves).

For better understanding, we calculated the hourly values for the H and Z components recorded at the YOK (located at the northern part of Japan) and KAK (reference standard observatory) on 5 October 2005 (quiet day) and on 15 May 2005 (disturbed day). The hourly values of H and Z components recorded on 5 October 2005 at the YOK are compared with the corresponding hourly data from the KAK observatory as presented in Fig. 5.

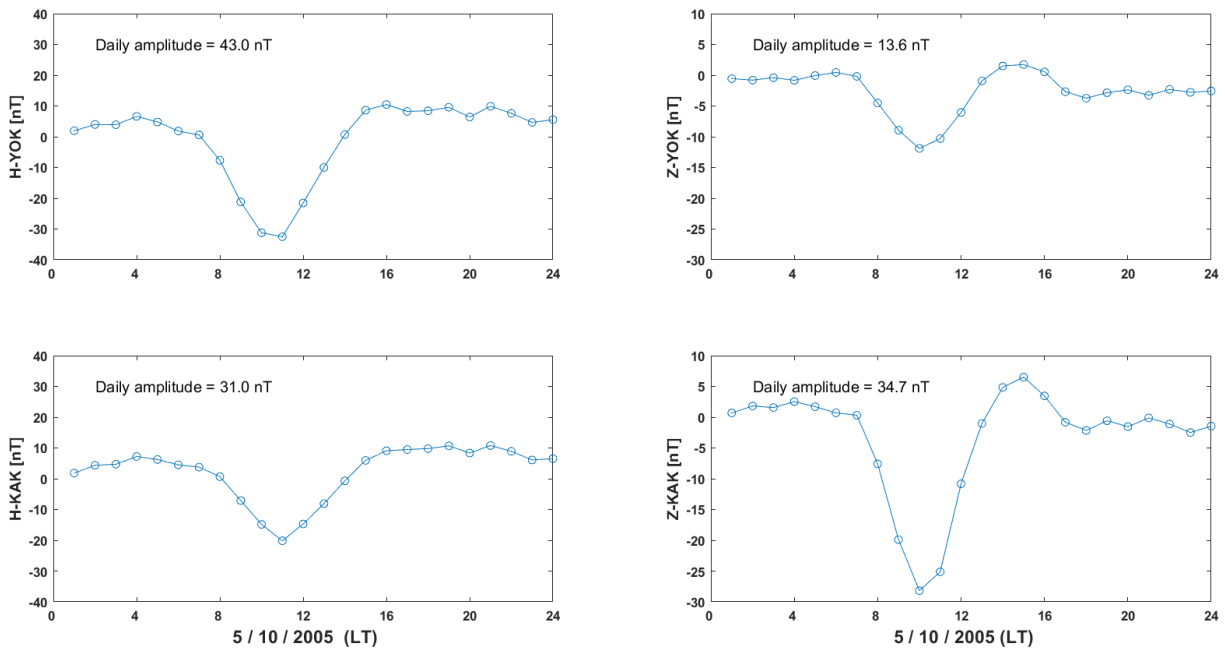


Figure 5. Daily variations of hourly averaged data for the H components (left side panel) and the Z components (right side panel) recorded at the YOK and KAK stations during a quiet day on 5 October 2005 (LT).

Visual inspection indicates a high correlation between each component at both stations. In addition, scatter plots and correlation coefficient (R) of the H and Z component recorded on that day showed a high correlation coefficient ($R = 0.97$ for each component) as shown in Fig. 6.

On the other hand, during the disturbed day (15 May 2005), the hourly values of H components at YOK and KAK kept showing a high visual correlation, while poor anti-correlation was observed between the Z components recorded at the YOK and KAK stations as presented in Fig. 7. Also, visual observation is confirmed from the scatter plots and correlations coefficient (R) represented in Figure 8 where the correlations coefficients were 0.99 and -0.43 for the H and Z components respectively.

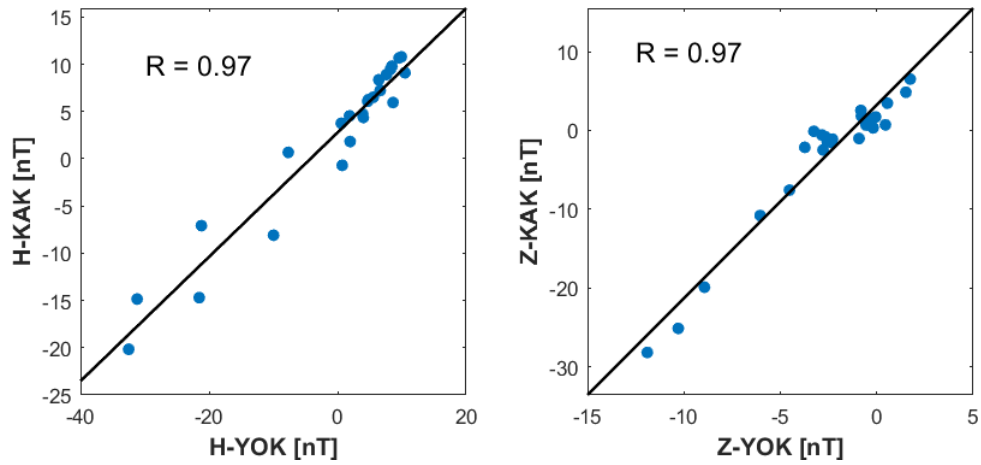


Figure 6. Scatter pots of hourly averaged data for the H components (left side panel) and the Z components (right side panel) recorded at the YOK and KAK stations during a quiet day on 5 October 2005 (LT) with correlation coefficient ($R = 0.97$) for both the H and Z components data.

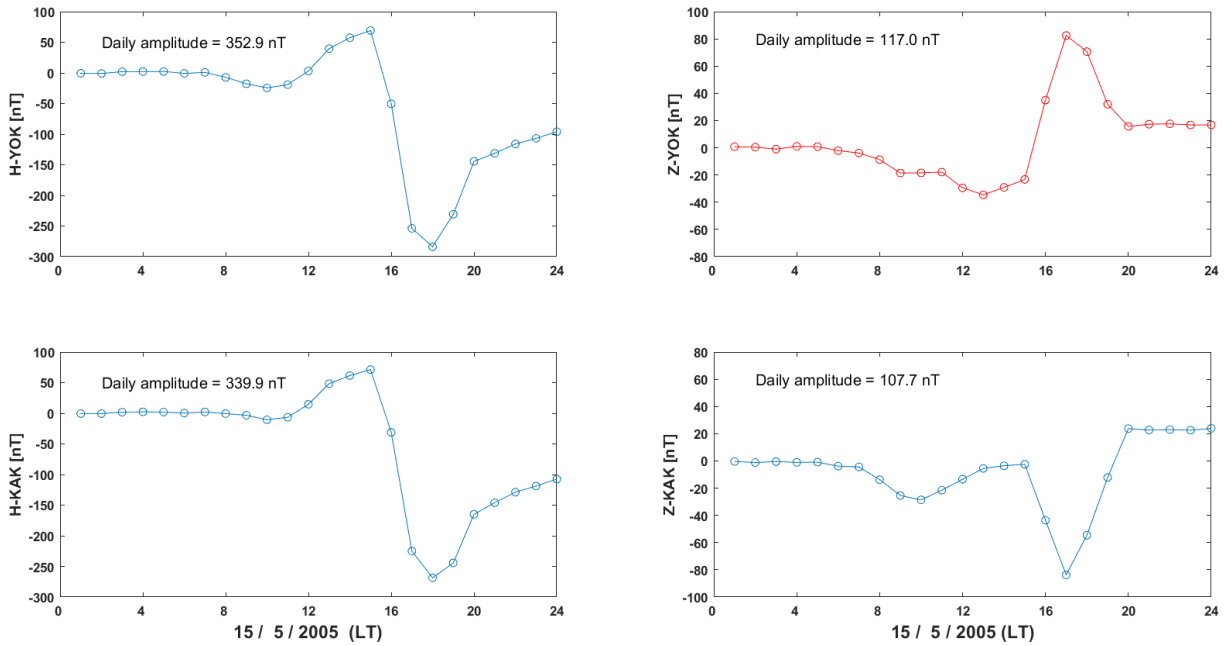


Figure 7. Daily variations of hourly averaged data for the H components (left side panel) and the Z components (right side panel) recorded at the YOK and KAK stations during a disturbed day on 15 May 2005 (LT). Red curve represents the abnormal daily variation of Z component (positive upward) recorded at the YOK station (North of Japan).

Moreover, the daily amplitude ranges of H and Z components are calculated from the maximum minus the minimum values of each geomagnetic component recorded at the YOK and KAK during both the quiet and disturbed days. During the quiet day, the daily amplitude range for H and Z components at the YOK station were 43 nT and 13.6 nT respectively (negative downward), while for the KAK observatory they were 31 nT and 34.7 nT respectively (negative downward). The ratio of daily amplitude range for Z components (YOK/KAK) was ~ 0.4 on the quiet day. On the other hand, during the disturbed day, the daily amplitude range for H and Z components at the YOK station were 352.9 nT (negative downward) and 117 nT (positive upward) respectively, while for the KAK observatory they were 339.9 nT and 107.7 nT respectively (negative downward). The ratio of daily amplitude range for Z components (YOK/KAK) was ~ 1.1 . This means that there is an enhancement (about two and a half times) in

Daily geomagnetic variations and underground conductivity changes

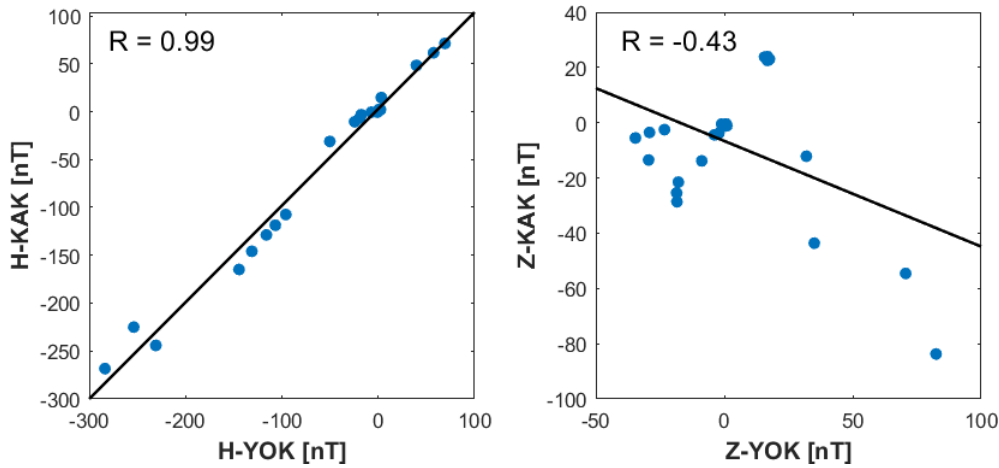


Figure 8. Scatter plots of hourly averaged data for the H components (left side panel) and the Z components (right side panel) recorded at the YOK and KAK stations during a disturbed day on 15 May 2005 (LT) with correlation coefficient ($R = 0.99$) and ($R = -0.43$) respectively.

the amplitude of Z component recorded at the YOK station during the disturbed day compared with the quiet day data and with reference point data (KAK).

4. Discussion

Data from two networks of geomagnetic stations (GSI) and observatories (INTERMAGNET) in Japan are used for the current study. The geomagnetic H and Z components data from eight geomagnetic stations and observatories located on a latitudinal profile extending from the MMB station (North of Japan) to the KNY station (South of Japan). The study mainly investigates the geomagnetic measurements during both quiet and disturbed days as well as the effect of underground conductivity changes on the geomagnetic response to the disturbances of IMF and solar parameters (related to a solar eruptive event of 13 May 2005). The result of data analysis reported here show that the behavior of the geomagnetic response during quiet day differs from that observed during disturbed day. During the quiet day, high visual correlation was observed between all stations along the selected profile for the H and Z components. During the disturbed times, the H components along the examined profile were in agreement with high visual correlation. On contrary, a remarkable observation is noticed in the behavior of Z component where the Z components recorded at the northern stations (YOK, AKA, and MMB) showed a positive daily variation (with an enhancement in their intensities) while the stations located in central and southern parts of Japan kept showing negative daily variation (with a reduction in their intensities). In other words, two different patterns of daily variations were observed (positive and negative daily variations). The Z- component recorded at the HAR station (blue curve in Fig. 4) was nearly like an intermediate (transition) behavior between these two behaviors. It is interesting here to observe the abnormal variations of the Z components at the northern part of Japan.

As was mentioned before, a record of the GF represents a superposition of signals from various internal and external sources. The main contribution is generated internally by the dynamo process in the Earth's core (main field). All other sources (external and crustal sources) only contribute by a fraction of the observed GF (a few percent). The external sources are mainly related to solar activity driving ionospheric and magnetospheric current systems. One of the most important forms of external variations is the DGVs. These daily variations are caused by Sq currents, particularly during quiet IMF and solar conditions [Stening et al., 2005]. These currents exist in the ionosphere region and have 24-hours regular periods (Orlando et al., 1993). During quiet periods, the ionospheric current systems are mostly limited to the polar zone and referred to as polar Sq [Xu, 1989]. In this case, DGVs can be globally observed. The pattern of the daily variation systematically changes with latitude. Generally, the pattern of daily variation in the H component tends to be symmetric about the dip equator, where the GF is completely horizontal. Meanwhile, the daily variation patterns in the Z components reverse at the dip equator (Negative northward and positive southward), for more details, see Yamazaki and Maute [2017].

During disturbed times, the intensity of ionospheric currents is enhanced, and the currents system expands to lower latitudes [Kikuchi et al., 1996; Kikuchi, 2014]. Consequently, the ionospheric currents generate an external magnetic field, which is opposite to the GF. Therefore, when these currents are developed and intensified during eruptive solar events such as CME, a sharp and intense reduction is observed in the horizontal component of the GF. This sharp and intense depression of the H component of GF is known as geomagnetic storm [Gonzalez et al., 1999]. Thus, the horizontal H component generally reflects the impact of outer space on the GF, while the Z component includes the effect of underground activities [Yuan et al., 2018].

Several studies have investigated the behavior of Z component in different regions. According to these studies, the abnormal behavior of the Z component could be due to coastal effects (Srivastava and Sanker Narayan 1970), underground-induced currents [Rajaram et al., 1979; Xu, 2009; Schäfer et al., 2011], or the existence of high electrical conductivity in the crust related to tectonic activities or mineralization effect [Takla et al., 2012; Yuan et al., 2018]. As a result of intensive geomagnetic observations and several geomagnetic surveys, conductivity anomalies were reported in different regions in Japan [Honkura, 1974]. The geomagnetic variation anomalies in Japan could be also related to the undulation of a highly conducting layer in the upper mantle [Kato et al., 1971]. One of the conductivity anomalies was observed in northeastern part of Japan. This anomaly has different characters compared those observed at the central and southern parts of Japan. In addition, intensive observations of heat flow have been carried out in Japan. According to the heat flow distribution in Japan [Watanabe 1972; Uyeda, 1972], rate of heat flow is higher in the northeastern part of Japan compared with the central and southern parts. Moreover, the electrical conductivity structure beneath the Japan is in good agreement with the heat flow distribution [Honkura, 1974].

The high underground conductivity increases the intensity of geomagnetic fluctuations generated by underground currents triggered by external fluctuations and ionospheric currents, acting as an amplifier that affects the geomagnetic measurements. When the external field increases, the effect of the amplifier from the high underground conductivity is more evident [Zhao et al., 2022]. Thus, the underground conductivity can be the main source of the observed abnormal behavior of Z component at the northern part of Japan,

Finally, we think that the observed reduction of H components relates to the ring currents generated due to the disturbance conditions in the IMF and solar parameters. In addition, the amplitude enhancement and positive daily variations of the Z components during the disturbed times observed in the northern part of Japan indicate that the cause (source) of such behavior in this region is likely due to changes in the underground conductivity in the northern part of Japan compared with the central and southern parts of Japan, where negative daily variations are observed as normal behavior of daily variations at these latitudes. Therefore, the anomalous behavior of the Z component daily variations may come from effect of the horizontal heterogeneous distribution of the ground electrical conductivity in Japan. These results could lead to investigation on the strong relationship between underground electric conductivity and the anomalous variations in the GF measurements (mainly in Z component).

5. Summary and conclusion

In the present investigation, we have studied the effect of IMF/solar fluctuations linked with a halo CME launched from the Sun on 13 May 2005 on the GF measurements. Data from an array of magnetometers belonging to the GSI and INTERMAGNET networks in Japan are used in the current study. Geomagnetic data recorded during solar quiet and disturbed days are analyzed to examine the DGVs of H and Z components in Japan under different IMF and solar conditions. In addition, the impact of the underground conductivity on the geomagnetic measurements is investigated. The main remarks drawn from the current study are listed below:

- The H and Z components recorded in different points of Japan are in good agreement and correlation during quiet solar conditions.
- During a severe solar event (halo CME) launched on 13 May 2005, changes in the IMF and solar parameters significantly affected the variability of the geomagnetic components along the examined profile. The H components showed highly correlated variations along the examined profile with significant reduction. On the other hand, abnormal behavior in the Z component daily variations (Positive daily variations) is observed in the Northern part of Japan (MMB, AKA, and YOK stations) compared with measurements recorded in the central and southern part of Japan (Negative daily variations).

Daily geomagnetic variations and underground conductivity changes

- An enhancement (about 2.5 times higher) in the amplitude of Z components was observed at stations located in the northern part of Japan compared with reference observatory data (KAK observatory).

In conclusion, under disturbed conditions with a southward orientation of IMF, a magnetic reconnection takes place, and the ionospheric currents system is intensified causing variations in the GF. Therefore, the observed decrease in H component can be linked with the ring currents generated due to disturbance in IMF and solar conditions, while the abnormal pattern of the Z component daily variation in north Japan can be linked with a high underground electrical conductivity anomaly in this region.

Acknowledgments. The authors wish to thank the GSI and INTERMAGNET groups for their ceaseless continuous support of the observation and providing the geomagnetic data. Moreover, the authors thank the OMNIweb team for providing the data needed for this research work.

References

- Bisi, M.M., A.R. Breen and B.V. Jackson, et al. (2010). From the Sun to the Earth: The 13 May 2005 Coronal Mass Ejection. *Sol Phys* 265, 49-127. <https://doi.org/10.1007/s11207-010-9602-8>.
- Bothmer, V. and R. Schwenn (1998). The structure and origin of magnetic clouds in the solar wind. *Ann. Geophys.*, 16, 1-24, <https://doi.org/10.1007/s00585-997-0001-x>.
- Campbell, W.H., C.E. Barton, F.H. Chamalaun and W. Welsh (1998). Quiet-day ionospheric currents and their application to upper mantle conductivity in Australia. *Earth Planet. Space*, 50, 347-360, <https://doi.org/10.1186/BF03352121>.
- Courtilot, V. and J.L. Le Mouel (1988). Time Variations of the Earth's Magnetic Field: From Daily to Secular. *Ann. Rev. Earth Planet. Sci.*, 16, 389-476. <http://dx.doi.org/10.1146/annurev.ea.16.050188.002133>.
- Daglis, I.A., R.M. Thorne, W. Baumjohann and S. Orsini (1999). The terrestrial ring current: Origin, formation, and decay. *Rev. Geophys.*, 37, 407. <https://doi.org/10.1029/1999RG900009>.
- Dasso, S., C.H. Mandrini and B. Schmieder, et al. (2009). Linking two consecutive nonmerging magnetic clouds with their solar sources. *J. Geophys. Res. (Space Phys.)*, 114(A13), 2109. doi:10.1029/2008JA013102.
- Devi, B., S. Dubey, S. Saini, et al. (2008). Geomagnetic field variation during winter storm at localized southern and northern high latitude. *J. Astrophys. Astron.*, 29, 275-280. <https://doi.org/10.1007/s12036-008-0036-8>.
- Dungey, J.W. (1961). Interplanetary Magnetic Field and the Auroral Zones, *Phys. Rev. Lett.* 6, 47, <https://doi.org/10.1103/PhysRevLett.6.47>.
- Gonzalez, W.D., B.T. Tsurutani and A.L.C. De Gonzalez (1999). Interplanetary origin of geomagnetic storms. *Space Sci. Rev.*, 88 (3), 529-562. <https://doi.org/10.1023/A:1005160129098>.
- Honkura, Y. (1974). Electrical conductivity anomalies beneath the Japan arc. *J. Geomag. Geoelec.*, 26, 147-171, <https://doi.org/10.5636/jgg.26.147>.
- Hundhausen, A.J. (1972). *Coronal Expansion and Solar Wind*. Phys. Chem. Space, 5, 94-121. Springer. New York.
- Jankowski, J. and C. Sucksdorff (1996). *Guide for magnetic measurements and observatory practice*. Warsaw: IAGA, p.238.
- Kalegaev, V.V., N.Y. Ganushkina, T.I. Pulkkinen, M.V. Kubyskhina, H.J. Singer and C.T. Russell (2005). Relation between the ring current and the tail current during magnetic storms. *Ann. Geophys.*, 23, 523-533, <https://doi.org/10.5194/angeo-23-523-2005>.
- Kato Y., M. Daguchi, M. Seto and T. Aruga (1971). Northeastern Japan anomaly of the upper mantle, *Sci. Rep. Tohoku Univ., Ser.*, 5, 21, 19-35.
- Kikuchi, T. (2014). Transmission line model for the near-instantaneous transmission of the ionospheric electric field and currents to the equator. *J. Geophys. Res. Space Phys.*, 119, 1131-1156. <https://doi.org/10.1002/2013JA019515>.
- Kikuchi, T., H. Lühr, T. Kitamura, O. Saka and K. Schlegel (1996). Direct penetration of the polar electric field to the equator during a DP2 event as detected by the auroral and equatorial magnetometer chains and the EISCAT radar. *J. Geophys. Res.*, 101(A8), 17, 161-17, 173. <https://doi.org/10.1029/96JA01299>.
- Kilpua, E.K.J., N. Lugaz, M.L. Mays and M. Temmer (2019). Forecasting the structure and orientation of earthbound coronal mass ejections. *Space Weather*, 17, 498-526. <https://doi.org/10.1029/2018SW001944>.

- Mandea, M. and M. Purucker (2005). Observing: Modeling, and Interpreting Magnetic Fields of the Solid Earth. *Surv. Geophys.*, 26, 415-459.
- Matsushita, S. and H. Maeda (1965). On the geomagnetic lunar daily variation field. *J. Geophys. Res.*, 70(11), 2559-2578. doi:10.1029/JZ070i011p02559.
- Merrill, R.T., M.W. McElhinny and P.L. McFadden (1996). The magnetic field of the Earth. Academic Press, San Diego, pp. 531.
- Okeke, F.N. and D.N. Obiora (2016). Application of solar quiet day (Sq) current in determining mantle electrical-depth conductivity structure—a review. *J. Afr. Earth Sci.*, 114, 54-62, <https://doi.org/10.1016/j.jafrearsci.2015.11.015>.
- Orlando, M., G. Moreno, M. Parisi and M. Storini (1993). Semiannual variation of the geomagnetic activity and solar wind parameters, *Geophys. Res. Lett.*, 20(20), 2271-2274, <https://doi.org/10.1029/93GL02245>.
- Rajaram, M., B.P. Singh, N. Nityananda and A.K. Agrawal (1979). Effect of the presence of a conducting channel between India and Sri Lanka Island on the features of the equatorial electrojet. *Geophys. J. Int.*, 56, Issue 1, 127-138, <https://doi.org/10.1111/j.1365-246X.1979.tb04772.x>.
- Richmond, A.D. (1979). Ionospheric wind dynamo theory: a review. *J. Geomagn. Geoelectr.*, 31, <https://doi.org/10.5636/jgg.31.287>.
- Schäfer, A., L. Houpt, H. Brasse and N. Hoffmann (2011). The North German Conductivity Anomaly revisited. *Geophys. J. Int.*, 187, Issue 1, October 2011, Pages 85-98, <https://doi.org/10.1111/j.1365-246X.2011.05145.x>.
- Schwenn, R., A. Dal Lago, E. Huttunen and W.D. Gonzalez (2005). The association of coronal mass ejections with their effects near the Earth. *Ann. Geophys.*, 23, 1033-1059, <https://doi.org/10.5194/angeo-23-1033-2005>.
- Srivastava, B.J. and P.V. Sankernarayan (1970). Anomalous geomagnetic variations in the peninsular India-ocean effect and upper mantle conductivity structure. *Bull. Natl. Geophys. Res. Inst.*, 8, 125-134.
- Stening, R., T. Reztsova and L.H. Minh (2005). Day-to-day changes in the latitudes of the foci of the Sq current system and their relation to equatorial electrojet strength, *J. Geophys. Res.*, 110, <https://doi.org/10.1029/2005JA011219>.
- Takla, E.M., K. Yumoto, J. Ishitsuka, D. Rosales, S. Dutra, T. Uozumi and S. Abe (2012). Geomagnetic variations possibly associated with the Pisco earthquake on 15 August 2007, Peru. *Tectonophysics*, 524-525, 29-36, doi:10.1016/j.tecto.2011.12.008.
- Takla, E.M., K. Yumoto, P.R. Sutcliffe, V.M. Nikiforov and R. Marshall (2011). Possible association between anomalous geomagnetic variations and the Molise Earthquakes at Central Italy during 2002. *Phys. Earth Planet. In.*, 185, 29-35, doi:10.1016/j.pepi.2010.12.003.
- Tanabe, T. (1997). The continuous observation equipment of geomagnetism installed in the whole country. *J. Geospatial Inf. Authority Japan*, 87, 4-12.
- Uyeda, S. (1972). Heat flow, Chap. V in “The Crust and Upper Mantle of the Japanese Area, Part 1”, edited by S. Miyamura and S. Uyeda, *Earthq. Res. Inst., Univ. Tokyo*, pp. 97-105.
- Watanabe, T. (1972). Heat flow through the ocean floor, Chap. I in “Marine Physics”, edited by M. Hoshino, Tokai Univ. Press, Tokyo, pp. 2-107.
- Xu, W.Y. (2009). *Physics of Electromagnetic Phenomena of the Earth*, Hefei: Press of University of Science and Technology of China.
- Yamazaki, Y. and A. Maute (2017). Sq and EEJ—A Review on the Daily Variation of the Geomagnetic Field Caused by Ionospheric Dynamo Currents. *Space Sci Rev.* 206: 299-405. DOI 10.1007/s11214-016-0282-z.
- Yuan, G.P., H.Y. Li, G.X. Zhang and Y. Pan (2018). Daily Variation Ratio of Geomagnetic Z Component and its Relationship with Magnetic Storms and Earthquakes. *Earthquake*, 38, 139-146, <https://doi.org/10.3969/j.issn.1000-3274.2018.01.013>.
- Zhao, X., Y. He, Q. Li and X. Liu (2022). Analysis of the geomagnetic component Z daily variation amplitude based on the Geomagnetic Network of China during solar quiet days. *Chin. J. Geophys.* (in Chinese), 65(10): 3728-3742, doi: 10.6038/cjg2022P0628.

***CORRESPONDING AUTHOR: Emad M. TAKLA,**

National Research Institute of Astronomy and Geophysics (NRIAG), 11421 Helwan, Cairo, Egypt
e-mail: emad.takla@nriag.sci.eg