Solar Rotation Multiples in Space-Weather Effects

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Abstract

The solar rotation period is the most prominent mid-term periodicity in the temporal behaviour of solar, heliospheric, and geomagnetic parameters. It is also a cause of the repeatedly appearing geomagnetic storms originating from the corotating interaction regions (CIRs). Since geomagnetic CIR-driven storms have a natural periodic character, and geomagnetic storms impact energy infrastructure via geomagnetically induced currents, it is of interest whether this periodic character is also noticeable in the temporal behaviour of electrical-grid failures (EGFs), which, at least to some extent, might be of solar origin.

Keywords Magnetic fields, Interplanetary · Magnetosphere, Geomagnetic Disturbances · Active Regions · Coronal Mass Ejections · Corotating Interaction Regions · Space Weather

1. Introduction

The variability of the Sun, continuously measured from the 18th century, affects the Earth in many ways, depending on solar-activity level. During the solar maximum, transient phenomena such as solar flares and coronal mass ejections (CMEs) are frequent, leading to an increase in the injection, acceleration, and transport of solar energetic particles. It is well known that a strong magnetic storm affects the normal operation of ground located electrical systems (Zois, 2013; Gil et al., 2020) and causes damage to satellites and their equipment (satellite phones, GPS systems, etc.). During solar minimum, the heliospheric magnetic field (HMF) becomes weaker with the regular structure of the Parker spiral. During and near solar minima, corotating interaction regions (CIRs) are observed due to the Sun's rotation, and they are caused by overlapping fast and slow solar-wind structures. Owing to the Sun's rotation, among the broad range of the quasi-periodic changes of different parameters of solar and geomagnetic activity and solar wind as viewed from the arbitrary point of the interplanetary space, periodicities of 25–26 days are observed. Conventionally, the periodicities of solar and geomagnetic activities, solar wind, and other factors characterising the solar-terrestrial connections related to the Sun's rotation are called the 27-day recurrence

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with its higher harmonics (13.5 days, 9 days, etc.) or its multiples (e.g. 54 days, 81 days, etc.).

Much research has been devoted to the solar rotation period visible in the geomagnetic data starting from the studies of Broun (1876), Maunder (1905), and Bartels (1932, 1934).

For instance, for the period 1982–1985 Baker et al. (1990) demonstrated that the geostationary energetic electron fluxes of energies above 0.5 keV (at 6.6 Earth radii) had high auto-correlation peaks at 27 days, as well as at 54 days. In major flares' occurrence during Solar Cycle 19, Bai (1987) reported periodicity of 51 days. Pap, Tobiska, and Bouwer (1990) found a periodicity of 51 days in the data of projected areas of emerging complex sunspot groups. Chowdhury et al. (2015) reported that in the geomagnetic Ap-index temporal variations are apparent near the solar rotational periodicity ≈ 28 , ≈ 31 , and ≈ 32 days with other significant periods around the multiples of solar rotation: ≈ 53 and ≈ 59 days.

In general, solar-driven disturbances are very complex, so this issue is still open for discussion. Solar phenomena have been identified as the cause of major geomagnetic storms, and many studies have been carried out to understand their physical characteristics and effects around the near-Earth space environment (e.g. Vennerstrom et al., 2016; Lefèvre et al., 2016; Pulkkinen et al., 2017; Tsurutani, Lakhina, and Hajra, 2020). It is of particular importance to study geomagnetic storms induced by CMEs (e.g. Balan et al., 2014; Lin et al., 2015; Lawrance et al., 2016; Gopalswamy, 2016) and CIRs (e.g. Molina et al., 2020; Dugassa, Habarulema, and Nigussie, 2020a), separately, because of their distinct character concerning especially the magnetic field B_z and the speed of the convected fields at 1 AU (e.g. Tsurutani, Lakhina, and Hajra, 2020). The latter is especially important for various forecasting purposes (e.g. Sojka, Schunk, and Nicolls, 2014). The distinction between CME-induced and CIR-induced storms has been discussed by Borovsky and Denton (2006), Denton et al. (2006), Dremukhina, Yermolaev, and Lodkina (2020), Dugassa, Habarulema, and Nigussie (2020b), Murphy et al. (2020), Boroyev, Vasiliev, and Baishev (2020), Chakraborty et al. (2020), and Arowolo, Akala, and Oyeyemi (2021). As stated by Borovsky and Denton (2006), CME-driven storms are relatively shorter, have denser plasma sheets, and cause large Dst-index perturbation, and among other effects they can produce dangerous geomagnetically induced currents (GICs), which have impacts on the energy infrastructure (e.g. Torta et al., 2012; Zois, 2013; Schrijver et al., 2014; Bailey et al., 2018; Tozzi et al., 2019; Svanda et al., 2020; Gil et al., 2021a). CIR-driven storms are relatively long in duration, have hotter plasma sheets, and hence produce higher fluxes of relativistic electrons. CME-driven storms are more hazardous to Earth-based systems, and CIR-driven storms are more hazardous to space-based assets, particularly in geosynchronous orbit. CME-driven storms occur randomly in time with a frequency of occurrence that is the highest during solar maximum. In contrast, CIR-driven storms recur with a 27-day periodicity, primarily in the solar cycle's declining phase.

This article is organised in the following way: the second and the third sections introduce data and methods used in our analysis, respectively. In the fourth section we present our results, finishing with the fifth section by summarising our studies.

2. Data

Links between solar activity and geomagnetic variability are well known (Feynman, 1982). In our studies we use three groups of data: i) solar and heliospheric parameters, ii) geomagnetic indices, and iii) the number of electrical-grid failures (EGFs) in South Poland during the period from January 2010 until July 2014.

In the group of solar parameters, we study sunspot number [SSN] as the best solar-activity proxy (Version 2.0, Clette et al., 2016) obtained from the WDC-SILSO, Royal Observatory of Belgium. The second set of data is the solar radio flux [SRF: sfu = $10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}$] as the other most widely used long-term parameter illustrating the solar-activity level (Clette, 2021). As heliospheric parameters, we use solar-wind proton density [SWd: cm^{-3}], temperature [SWT: K], and speed [SWs: km s^{-1}]. The HMF reflects the complexity of the solar coronal magnetic field. Here we consider HMF strength, [B : nT] and components [B_y : nT, B_z : nT]. Also, we take into consideration the heliospheric electric field [E_y : mV m^{-1}] given as (e.g. Tsurutani et al., 2003): $E_y = -V_{\text{SW}} B$, where V_{SW} is the solar-wind velocity at 1 AU.

Among the geomagnetic parameters, we consider global geomagnetic indices: Dst [nT], Ap [nT], and AE [nT], as well as the local K-index from the Polish INTERMAGNET observatory in Belsk. The geomagnetic data set is extended in a unique way by subjecting it to analysis by a local geoelectric-field E-method of computation that is described in Section 3.1. For this purpose we use data of one-minute resolution of the geomagnetic field horizontal components [B_X , B_Y] from the magnetometer in Belsk.

The last data set of electrical-grid failures (EGFs) is built based on the logs from the third-largest electricity producer in Poland, during the period from January 2010 to July 2014. Among the many pieces of information related to the transmission network failure there are possible causes of the failures, the time, the power of undelivered energy, how many end-users suffered from particular failure, etc. Among the reasons there are three categories of failures, which might have been of space-weather origin, i.e. failures related to the ageing of infrastructure components [EGF_{Ag}], failures linked to electronic-device breakdowns and/or switching-off [EGF_{Ed}], and failures having unidentified reasons [EGF_{Un}] (details of failures in Gil et al., 2020). Similar classification was used in the literature (Zois, 2013).

3. Methods

3.1. Geoelectric Field Computation

There are various methods for calculating the geoelectric field [E] (see details in, e.g., Abda et al., 2020, and the references therein). In the frame work of this article, we estimated E from one-minute geomagnetic field data [B] in the frequency domain using a 1D layered conductivity Earth model (Boteler, Pirjola, and Marti, 2019; Boteler and Pirjola, 2019). This model considers the change of conductivity with depth. More precisely, the Earth is represented by N horizontal layers, which are assumed to be homogeneous and infinitely extended in the X (northward) and Y (eastward) directions (Abda et al., 2020). In the Z (downward) direction, each layer is specified by conductivity σ_n and thickness l_n ($n = 1, \dots, N$). Then the layered case of the transfer function K (in the frequency domain f) is expressed by the following recursive formula (Weaver, 1994; Boteler and Pirjola, 2019):

$$K_n = \eta_n \frac{K_{n+1}(1 + e^{-2k_n l_n}) + \eta_n(1 - e^{-2k_n l_n})}{K_{n+1}(1 - e^{-2k_n l_n}) + \eta_n(1 + e^{-2k_n l_n})}, \quad (1)$$

where K_n is the ratio of E to B at the top surface of layer n , while K_{n+1} at the top surface of the underlying layer $n + 1$, $\eta_n = \frac{i2\pi f}{k_n}$, $k_n = \sqrt{i2\pi f \mu_0 \sigma_n}$, i is the imaginary unit, and $\mu_0 = 4\pi 10^{-7} \text{ H m}^{-1}$ (Boteler, Pirjola, and Marti, 2019). The initial value in Equation 1 corresponds to the case when the layer $n = N$ is a uniform half-space and $K_N = \sqrt{\frac{i2\pi f}{\mu_0 \sigma_N}}$. The final value

Figure 1 Time variation of geoelectric field E_X (a), E_Y (b), and $E = \sqrt{E_X^2 + E_Y^2}$ (c), determined for years 2010–2014 using the 1D Earth model number 45 (Ádám, Prácser, and Wesztergom, 2012) and geomagnetic data from the Belsk station.

K_1 ($n = 1$) is the transfer function relating E and B at the Earth's surface (Trichtchenko and Boteler, 2002; Boteler, Pirjola, and Marti, 2019).

Here, to perform analysis of data from the Belsk station (described in Section 2) we applied the Earth model number 45 proposed by Ádám, Prácser, and Wesztergom (2012) and dedicated for Poland. This model consists of four layers with, from the top down, thicknesses and resistivities [l/σ]: 6 km, 5 Ωm ; 105 km, 1000 Ωm ; 300 km, 100 Ωm ; above a half-space of 10 Ωm . It is worth adding that Earth model number 45 has already been used in a number of studies (Viljanen et al., 2013, 2014; Gil et al., 2021a).

In the next step of the analysis, the geomagnetic field $\{B_X, B_Y\}$ was decomposed into its frequency components $\{B_X(f), B_Y(f)\}$ and multiplied by the corresponding transfer-function values, namely $E_X(f) = K(f)B_Y(f)$ and $E_Y(f) = -K(f)B_X(f)$, where $E_X(f)$ and $E_Y(f)$ denote geoelectric-field frequency components. In the final step, we employed the inverse Fourier transform to obtain the value of a geoelectric field in the time domain $[E(t)]$ for both northward $[E_X]$ and eastward $[E_Y]$ components (Boteler, 2012; Boteler and Pirjola, 2019). It is worth adding that to perform the analysis of five years measurements 2010–2014 of geomagnetic field, the numerical calculations were systematically performed in a three-day moving window, while only results for the middle day have been finally used. The temporal variation of geoelectric-field components E_X and E_Y has been computed by applying the above-mentioned procedure, and it is shown in Figure 1.

3.2. Power Spectral Density Analysis

To learn about the characteristics of the spectral content of each studied variable the Lomb–Scargle periodogram can be used (Lomb, 1976; Scargle, 1981). Stationary stochastic processes are a frequently used mathematical model of many natural phenomena. The generally accepted description of the properties of such processes is their power spectral density (PSD). Its non-parametric estimate, called the periodogram, was introduced by

Schuster (1899). Spectral analysis is based on the decomposition of the time series into several sine and cosine functions. Using this analysis, several cycles with various periods and amplitudes, with different contributions to the overall dynamics of the series can be discovered. It allows us to establish the correlation of sine and cosine functions of different frequency with the observed data. If a large correlation is found (a large value of the coefficient of the sine or cosine), it can be concluded that there is a strong periodicity at a given frequency in the data. Particularly intense interest in the periodogram took place after the invention of the fast Fourier transform (FFT: Cooley and Tukey, 1965). Nowadays, numerous modifications and improvements to this method are known and widely used. The goal of all these refinements is to improve the statistical properties (mainly bias and variance reduction) of the periodogram as an estimate of the power spectral density. For non-uniformly sampled data, the Lomb–Scargle periodogram is better suited (Lomb, 1976; Scargle, 1981). The power is defined as

$$P_X(\omega) = \frac{1}{2} \left\{ \frac{[\sum_j X_j \cos \omega(t_j - \tau)]^2}{\sum_j \cos^2 \omega(t_j - \tau)} + \frac{[\sum_j X_j \sin \omega(t_j - \tau)]^2}{\sum_j \sin^2 \omega(t_j - \tau)} \right\}, \quad (2)$$

where X_j are the measurements at the times t_j , ω is the angular frequency, and the time offset τ defined according to the formula

$$\tan(2\omega\tau) = \frac{\sum_j \sin(2\omega t_j)}{\sum_j \cos(2\omega t_j)}. \quad (3)$$

3.3. Bandpass Filter

In order to isolate a rather narrow frequency range we use a bandpass filter method (e.g. Sheno, 2005). For an ideal bandpass filter denoted as $P_b(\omega)$ we would have (Blackledge, 2006):

$$P_b(\omega) = \begin{cases} 1 & \omega_0 - \Omega \leq \omega \leq \omega_0 + \Omega, \\ 0 & \omega \in (-\infty, -\omega_0 - \Omega) \cup (-\omega_0 + \Omega, \omega_0 - \Omega) \cup (\omega_0 + \Omega, +\infty), \\ 1 & -\omega_0 - \Omega \leq \omega \leq -\omega_0 + \Omega, \end{cases} \quad (4)$$

where ω_0 is the normalised band base and Ω its width. In the non-ideal situation, instead of equality, $P_b(\omega)$ tends to unity (see details in, e.g., Christiano and Fitzgerald, 2003).

3.4. Crosswavelet Spectrum and Wavelet Coherence

The commonly used tools in the analysis of mutual connections are various correlation coefficients (e.g. Faber, 2012), as well as regression models (e.g. Lee, 2014). The above-mentioned methods reveal their mutual interdependence in time–frequency space. To study the interconnection between the considered parameters we compute the crosswavelet spectrum (XWT) for EGFs and solar, heliospheric, and geomagnetic parameters listed in Section 2 (denoted in Equation 5 by p) using the corresponding wavelet transforms W_{EGF} and W_p , in the form (Torrence and Compo, 1998)

$$W_{p,\text{EGF}} = W_p W_{\text{EGF}}^*, \quad (5)$$

Figure 2 Lomb periodograms of the daily data of electrical-grid failures (EGFs) linked to the aging of infrastructure elements (Ag, **a**), electronic device operation (Ed, **b**), having unknown reasons (Un, **c**); Dst-index (**d**), K-index from the Polish observatory in Belsk (**e**), AE-index (**f**), SSN (**g**), solar-wind speed (**h**), and local geoelectric field computed based on the geomagnetic field data from Belsk (**i**), in the interval January 2010–July 2014.

where $*$ denotes complex conjugation. The power of the crosswavelet is $|W_{p,EGF}|$ and the phase displays an association between electrical-grid failures and the above-described parameters (Jevrejeva, Moore, and Grinsted, 2003). Our calculation results were obtained using the tools introduced by Jevrejeva, Moore, and Grinsted (2003) and Grinsted, Moore, and Jevrejeva (2004).

The wavelet coherence (*WTC*) is considered. *WTC* (Grinsted, Moore, and Jevrejeva, 2004) is a measure of covariance strength in time–frequency space (Antoniadis and Oppenheim, 1995). The wavelet coherence is described in the following way (Torrence and Webster, 1999):

$$WTC^2 = \frac{|S(W_{p,EGF}/s)|^2}{|S(W_p/s)|^2 |S(W_{EGF}/s)|^2}, \quad (6)$$

where S denotes smoothing and s is the wavelet scale. *WTC* is regarded as a local correlation degree for two continuous wavelet transforms. It is in our case between EGFs in the three considered groups and all the analysed data of solar, heliospheric, and geomagnetic parameters. The *WTC* indicates significant coherence even if the general power is not very high (Grinsted, Moore, and Jevrejeva, 2004).

4. Results and Discussion

All of the data described in Section 2 were subjected to PSD analysis (see Section 3.2). We extracted main periodicities from a few days to over one year. Results of our analysis are presented in Tables 1–2 and Figure 2. Table 1 shows the most significant periods being close to the solar rotation period, double solar rotation (being the most strong multiple of the solar rotation), and one year during the whole time interval studied in this article. Table 2 presents the most substantial periodicities neighbouring solar rotation period for each

Table 1 The most significant periodicities [days] revealed in considered parameters between January 2010 and July 2014.

Parameter	Periodicity [days] $\approx$ solar rotation	Periodicity [days] multiples	Periodicity [days] $\approx$ year
EGF _{Ag}	26	-	389
EGF _{Ed}	23	52	-
EGF _{Un}	32	54	367
Dst-index	29	54	348
K-index	27	54	367
AE-index	29	54	367
B_z of HMF	26	-	-
SSN	27	59	389
SRF	26	-	389
SWs	28	55	367
SWT	28	-	348
SWd	28	-	367
E	27	55	367

Table 2 The most significant periodicities ($\approx$ solar rotation period) between January 2010 and July 2014, for each year separately.

Parameter	Main periodicity [days]				
	2010	2011	2012	2013	2014
EGF _{Ag}	26	30	24	24	25
EGF _{Ed}	32	30	24	27	-
EGF _{Un}	29	33	33	32	28
Dst-index	28	30	30	32	24
K-index	28	30	31	32	28
Ap-index	28	30	30	32	27
AE-index	28	30	31	32	-
B	29	-	-	29	-
B_y of HMF	29	28	25	29	-
B_z of HMF	27	30	26	25	24
SSN	25	25	25	25	27
SRF	25	25	25	25	26
SWs	28	28	27	28	26
SWT	28	26	28	28	27
SWd	28	28	32	28	-
E_y	27	30	30	24	24
E	28	30	31	32	27

studied year separately. Tables 1–2 and Figure 2 show that periodicity at the solar rotation was observed for all of the studied data, during the whole period and/or during each year. Tables 1–2 display that for temporal behaviour of EGF appearance the main periodicity was variable versus time. For failures connected to the aging of infrastructure elements, the main periodicity ranges from 24 days in 2012 and 2013 to 30 days in 2011. For failures that originated from electronic-device switch-off and any kind of unreliability, the main periodicity ranges from 24 days in 2012 to 32 days in 2010. For failures having unknown reason,

Figure 3 Bandpass-filtered daily data of electrical-grid failures (EGFs) linked to the aging of infrastructure elements (Ag, **a**), electronic devices operation (Ed, **b**), having unknown reasons (Un, **c**); Dst-index (**d**), K-index from Polish observatory in Belsk (**e**), AE-index (**f**), SSN (**g**), solar-wind speed SWs (**h**), and local geoelectric field E computed based on the geomagnetic field data from Belsk (**i**), with 27 ± 5 days being the boundaries of this band. On the vertical axes is the bandpass filter.

Figure 4 Bandpass-filtered daily data of electrical-grid failures (EGFs) linked to the aging of infrastructure elements (Ag, **a**), electronic devices operation (Ed, **b**), having unknown reasons (Un, **c**); Dst-index (**d**), K-index from Polish observatory in Belsk (**e**), AE-index (**f**), SSN (**g**), solar-wind speed SWs (**h**), and local geoelectric field E computed based on the geomagnetic field data from Belsk (**i**), with 54 ± 5 days being the boundaries of this band. On the vertical axes is the bandpass filter.

the range of the main periodicity is 28 days in 2014 and 33 days in 2011 and 2012. One can see from Tables 1–2 and Figure 2 that also for the solar, heliospheric, and geomagnetic parameters the main periodicities were not stable during the studied time interval. It varies from 24 days (e.g. for the Dst-index in January 2014–July 2014) to 32 days (e.g. for the Dst-index in 2013).

Figure 5 Wavelet coherence (WTC) of electrical-grid failures (EGFs) having unknown causes and (a) Dst-index and (b) local K-index from Belsk, for the daily data from January 2010 to July 2014. On the x-axis time in days and on the y-axis periods in days.

Figure 6 WTC of EGF_{Un} and (a) solar-wind speed, SWs and (b) local geoelectric field E computed based on the one-minute geomagnetic field data from Belsk.

The methods described in the Sections 3.2, 3.3, and 3.4 were used in the analysis of all of the data described in Section 2, and Figures 4–8 display examples of our results. Figures 3–4 highlight time intervals when periodicity around one (Figure 3) and two (Figure 4) solar rotations in the electrical-grid failures is observed, as well as in solar, heliospheric, and geomagnetic parameters. We use here rather wide filters passing 27 ± 5 and 54 ± 5 days. Periodicity at the solar rotation rate is apparent in all of the parameters. Figure 3a–c shows that in EGFs data this period is especially predominant around the solar maximum epoch, in 2014. Figure 4 reveals that periodicity at twice the solar rotation period is even more noticeable than for a single period in all of the considered parameters. In some time intervals, strengthening of the signal appears both in EGF data and in solar and geomagnetic parameters. It is worth mentioning that time intervals of reinforcement in ≈ 27 -day signal and ≈ 54 -day signal do not totally coincide, i.e. periodicity around 54 days is not necessarily always linked to solar rotation multiples, but other processes might play a role in its formation.

Figures 5–8 represent examples of our results gained using the wavelet spectrum and coherence (Jevrejeva, Moore, and Grinsted, 2003; Grinsted, Moore, and Jevrejeva, 2004). Figures 5–6 expose regions in time–frequency space where EGFs and solar as well as geomagnetic parameters show high common power. Black arrows in the Figures 5–8 designate the relative phase between each two parameters, with right (left) arrow specifying correlation (anti-correlation) and downward (upward) arrow that the first parameter is leading (lagging) the second one in the phase by 90° . One can observe time intervals around the solar rotation and its multiples in all considered parameters, which is in agreement with band-pass filter results (Figures 3–4). However, the phase difference between EGFs and solar as well as geomagnetic parameters is not stable, varying in time. Figures 7–8 depict regions in time–frequency space where EGFs and solar and geomagnetic parameters co-fluctuate. A clear $\approx$

Figure 7 Crosswavelet transform (XWT) of EGFs having unknown causes and (a) Dst-index and (b) K-index, for the daily data from January 2010 to July 2014. On the x -axis time in days and on the y -axis periods in days.

Figure 8 XWT of EGF_{Un} and (a) SWs and (b) E.

one-year periodicity in all of the cases is in agreement with the PSD results (see Table 1) with a rather stable phase difference in the case of SW_s and K-index, which seem to lead EGFs.

Since geomagnetic storms originating from CIRs appear repeatedly at the solar rotation rate, and geomagnetic storms influence the ground energy infrastructure via GICs, a naturally arising question was whether a periodic behaviour appears also in the electrical-grid failures number. Recently, we have shown (Gil et al., 2021a,b) that strong geomagnetic storms are accompanied by an increase in the number of EGFs.

Tsurutani and Hajra (2021) have analysed causes of GICs in the Mäntsälä pipeline greater than 10 A and formulated an important issue: “perhaps the causes are different for different substorm GIC events”. We believe that studies such as that presented above might shed light on this matter.

5. Conclusions

The main findings of this work can be summarised as follows:

- i) The multiples of the solar rotation rate are present in the temporal behaviour of the number of electrical-grid failures in Poland having the following reasons: disruptions connected with electronic devices, aging of the infrastructure components, and having unknown causes.
- ii) Solar rotation and twice the solar rotation recurrences are also visible in the local geoelectric field E computed using the one-minute resolution data of geomagnetic field horizontal components B_x and B_y measured by the Belsk magnetometer.
- iii) Time intervals of strengthening in ≈ 27 -day signal and ≈ 54 -day signal observed in several studied parameters do not totally correspond, i.e. periodicity around 54 days is not

automatically always connected to a solar rotation multiple. It suggests that other processes might play a role in the development of the mentioned periodicity.

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Declarations

Disclosure of Potential Conflicts of Interest The authors declare that they have no conflicts of interest.

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