STUDY OF THE STRONGEST GEOMAGNETIC EVENTS IN THE 25th SOLAR CYCLE

ASIMOPOLOS Natalia-Silvia, ASIMOPOLOS Laurențiu, ASIMOPOLOS Adrian-Aristide, DINU Luminița, BALEA Bogdan

Abstract. The 25th Solar Cycle began in December 2019 and is heading towards its maximum. Every 11 years or so, the Sun goes through periods of low (minimum) or high (maximum) solar activity, which is associated with the amount of sunspots on its surface. These dark regions, some of which can exceed the size of the Earth, are caused by solar flares that generate strong magnetic fields. Based on the recordings from the INTERMAGNET observatories and the planetary geomagnetic indices from January 2023-April 2024, we performed the analysis of geomagnetic storms and selected the first three strongest events. Following the Fourier, wavelet and wavelet coherence analyses of geomagnetic data taken at one minute, for 20 observatories and comparing them with the physical parameters of solar activity, available on specialized websites, we exemplified in the paper the most relevant characteristics of geomagnetic storms in 2023 and early 2024.

Keywords: Geomagnetic storm, Geomagnetic indices, Solar activity, Wavelet coherence, Multi-spectral analyses.

Rezumat. Studiu privind cele mai puternice evenimente geomagnetice din cel de-al 25-lea ciclu solar. Ciclul Solar al 25-lea a început în decembrie 2019 și se îndreaptă spre maximul lui. La fiecare aproximativ 11 ani, Soarele trece prin perioade de activitate solară scăzută (de minim) sau ridicată (de maxim), care este asociată cu cantitatea de pete solare de pe suprafața sa. Aceste regiuni întunecate, dintre care unele pot depăși dimensiunea Pământului sunt determinate de erupțiile solare ce generează câmpuri magnetice puternice. Pe baza înregistrărilor din observatoarele INTERMAGNET și a indicilor geomagnetici planetari din perioada ianuarie 2023-aprilie 2024, am efectuat analiza furtunilor geomagnetice și am selectat primele trei evenimente cele mai puternice. În urma analizelor Fourier, wavelet și coerența wavelet ale datelor geomagnetice prelevate la un minut, pentru 20 de observatoare, comparându-le cu parametrii fizici ai activității solare, disponibili pe site-urile de specialitate, am exemplificat în lucrare, cele mai relevante caracteristici ale furtunilor geomagnetice din anul 2023 și începutul anului 2024.

Cuvinte cheie: Furtuna geomagnetică, Indici geomagnetici, Activitate Solară, Coerență wavelet, Analize multi-spectrale.

INTRODUCTION

Detailed information about the analysis and predictions about solar cycle 25, which is in the ascendant towards a maximum that should occur in 2025 and it started with the solar minimum in December 2019, can be found on the specialized websites from the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA). Dark spots on the Sun indicate where solar flares or coronal mass ejections (CMEs) occur and the sudden release of a massive cloud of hydrogen ions, electrons and protons is ejected from the Sun's surface. 48-72 hours pass from the appearance of sunspots until the impact with the Earth's Magnetosphere. The severity of geomagnetic storms is estimated by the disturbance storm time (Dst) index as it measures the rise and recovery of the ring current in the Earth's magnetosphere. The lower values indicate that more energy is stored in the Earth's magnetosphere and implicitly increase the geomagnetic storm's degree. The scientific works related to these geomagnetic phenomena with multidisciplinary approaches, which were the basis of this work, are: ASIMOPOLOS N. S. (2018), ASIMOPOLOS L. et al. (2012), BENOIT (2012), CAMPBELL (2003). The mathematical and software approaches can be found in the reference works: BOX et al. (2016), BISGAARD & KULAHCI (2011) as well as the link https://www.mathworks.com. Also, available data https://science.nasa.gov/science-news/science-at-nasa/, https://www.spaceweatherlive.com/en/solar-activity/solar-cycle.html, https://www.intermagnet.org/ , http://www.noaa.gov.

25th SOLAR CYCLE PROGRESSION

The Sunspot Number Prediction Panel of SWPC Space Weather Operations (SWO), Daily Observations, predicted Cycle 25 to reach a maximum of 115 occurring in July, 2025 (Figs. 1-3). The error bars on this prediction mean the panel expects the cycle maximum could be between 105-125 with the peak occurring between November 2024 and March 2026.

Kp is calculated from the *K* values or the geomagnetic recordings of the 13 geomagnetic observatories. It is designed to measure solar particle radiation by its magnetic effects and today it is considered a proxy for the energy input from the solar wind to Earth.

From the *Kp* index are derived the geomagnetic indices *ap, Ap, Cp, C9* and the classification of international *Q-days* (quiet days in the sense of days with low geomagnetic activity) and *D-days* (disturbed days in the sense of days with high geomagnetic activity). The *K*-index quantifies disturbances in the horizontal component of Earth's magnetic field with an integer in the range 0–9 with 1 being calm and 5 or more indicating a geomagnetic storm. It is derived from the maximum fluctuations of horizontal components observed on a magnetometer during a three-hour interval. The official planetary *Kp*-index is derived by calculating a weighted average of *K*-indices from a network of 13 geomagnetic observatories at mid-latitude locations.

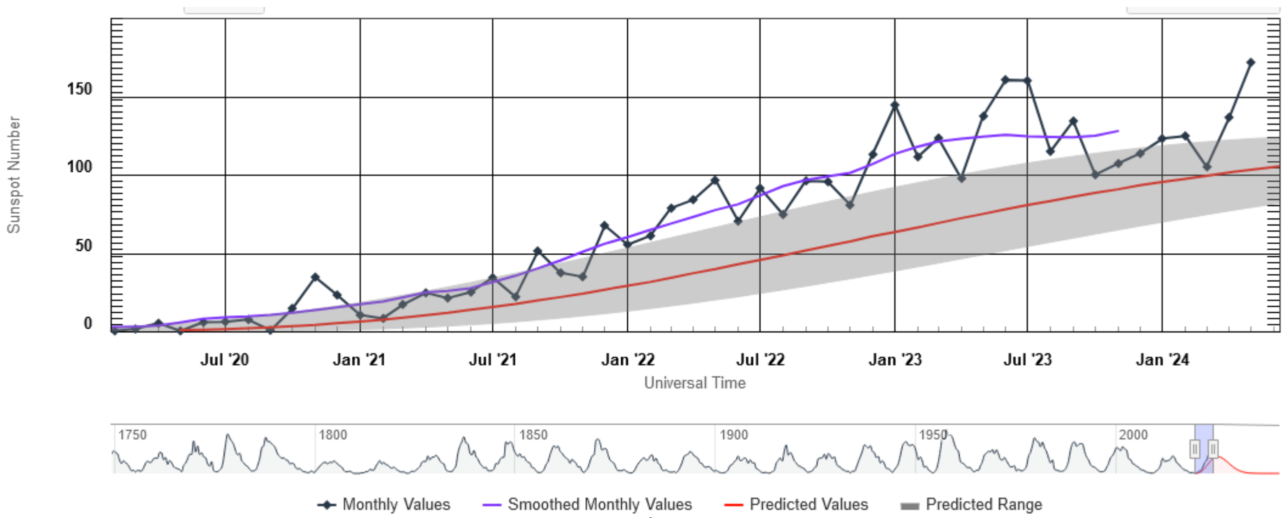

Figure 1. Sanspot Number Prediction of 25th Solar Cycle (https://www.swpc.noaa.gov).

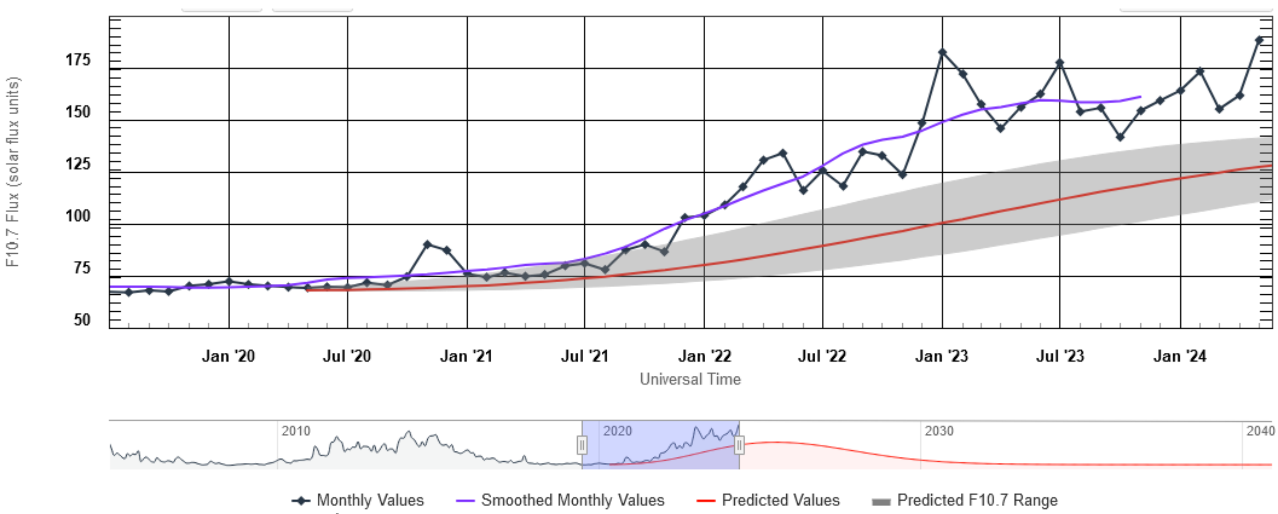

Figure 2. 25th Solar Cycle 10.7 cm Radio Flux Progression (https://www.swpc.noaa.gov).

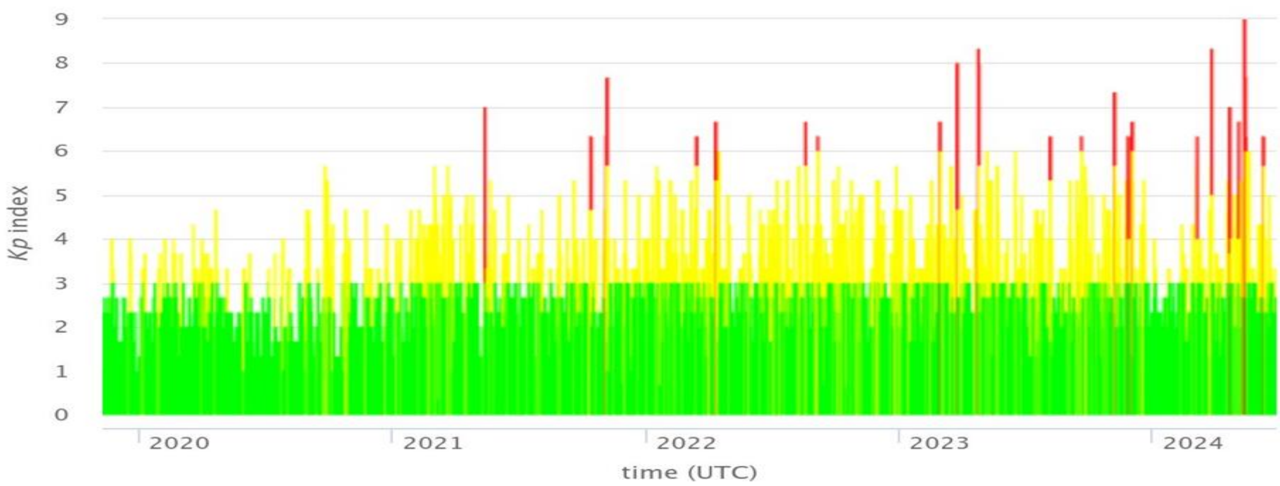

Figure 3. Kp indices in 25th Solar Cycle (https://kp.gfz-potsdam.de).

ANALYSIS ON THE STRONGEST GEOMAGNETIC EVENTS IN THE CURRENT SOLAR CYCLE

We have selected the most important geomagnetic storms from the period January 2023 – April 2024 (table 1), when the *Kp* index was 8, which corresponds to strong storms. We analysed the data monitored at the Surlari Observatory, through spectral and wavelet methods, corroborated with data from 25 other INTERMAGNET observatories and astrophysical/geophysical data from the most developed space weather websites.

Table 1. The most important storms geomagnetic (https://www.sidc.be/).

Event date	Dst min	Kp final
23-24 April 2023	-213	8+
5 November 2023	-172	7+
23-24 March 2023	-163	8o
26-27 February 2023	-132	7-
24 March 2024	-128	8+
19 April 2024	-122	7o
3 March 2024	-112	6+
1 December 2023	-108	7-

In Fig. 4 are geomagnetic series (X, Y, Z, F) from Surlari Observatory, March 22-26, 2023.

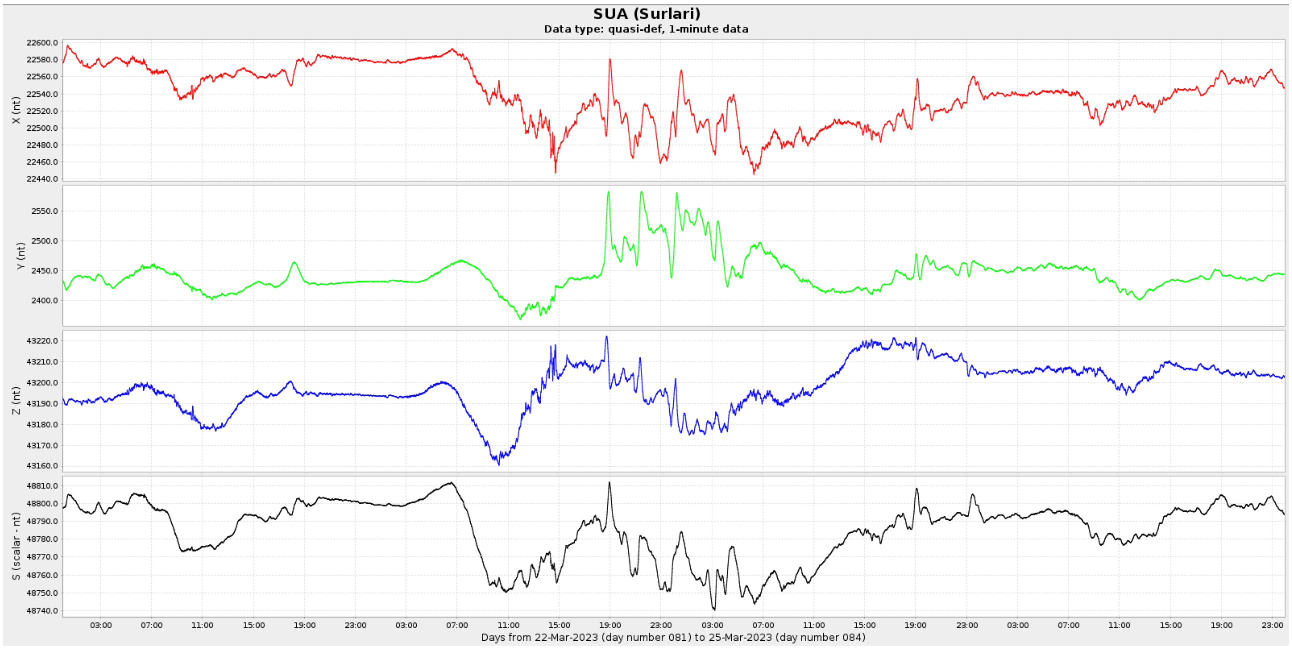

Figure 4. Geomagnetic Storm of March 24, 2023; Surlari Observatory, period March 22-26, 2023.

On the afternoon of April 23, 2023, at 2:12 PM EDT, a moderate solar flare (M1.7) erupted from the sun, ejecting a billion tons of superheated magnetized gas from the sun known as plasma. This ejection, known as a Coronal Mass Ejection (CME), travelled nearly two million miles per hour and reached the Earth in two days. NOAA's Space Weather Prediction Centre has issued a minor geomagnetic storm (G1) for April 23, 2023 and a moderate geomagnetic storm (G2) for April 24, 2023, with only a 5% and 30% chance of the storm becoming severe – extreme conditions in the two days. A strong and extreme geomagnetic storm warning was issued by the Space Weather Prediction Centre (SWPC) at 15:26 EDT on April 23, 2023. The geomagnetic storm arrived earlier and was stronger than expected. Fig. 5 contains the analysis performed for the data from the Surlari Observatory and Fig. 6 is the wavelet coherence between North and East of geomagnetic field.

For the geomagnetic storms of March and November, 2024, we present the magnetograms from Surlari (Figs. 7 and 8) and the wavelet analysis (Fig. 9). In Figs. 10 and 11 we present the wavelet coherence between Surlari, Tatuoca and Honolulu observatories. We chose a period of 4 days for the analysis March 22-26, 2024; the used values have a sampling rate of 1 minute. The wavelet coherence defined by the function *wcoherence(x,y)* in Matlab is a measure of the correlation between two real 1D vector signals of the same length x and y in the time-frequency plane (https://www.mathworks.com).

Wavelet coherence is applicable to the analysis of non-stationary signals and uses the analytical Morlet wavelet, being able to detect events such as geomagnetic field anomalies, change points and transients. The arrows in the *"wcoherence"* plot indicate the phase relationship between the two signals at each time and frequency point (or period). The phase angle of the cross spectrum is the same as the phase difference between the signals. The direction of the arrows in regions of high coherence can help to understand the phase relationship. For example, if the arrows point to the right, it indicates that the two signals are in phase (0 delay), and if they point to the left, it indicates an anti-phase relationship (1/2 cycle delay). A 1/4 cycle offset in a signal at a given frequency is indicated by a vertically pointing arrow. Therefore, an arrow pointing in the northeast direction (between 0 and 1/4 cycle offset direction) corresponds to a delay of 1/8 cycle (half of 1/4) and similarly an arrow pointing in the northwest (between 1/4 and 1/2 cycle offset direction) corresponds to a 3/8 cycle delay (adding half of 1/4 to 1/4). Delays move counterclockwise.

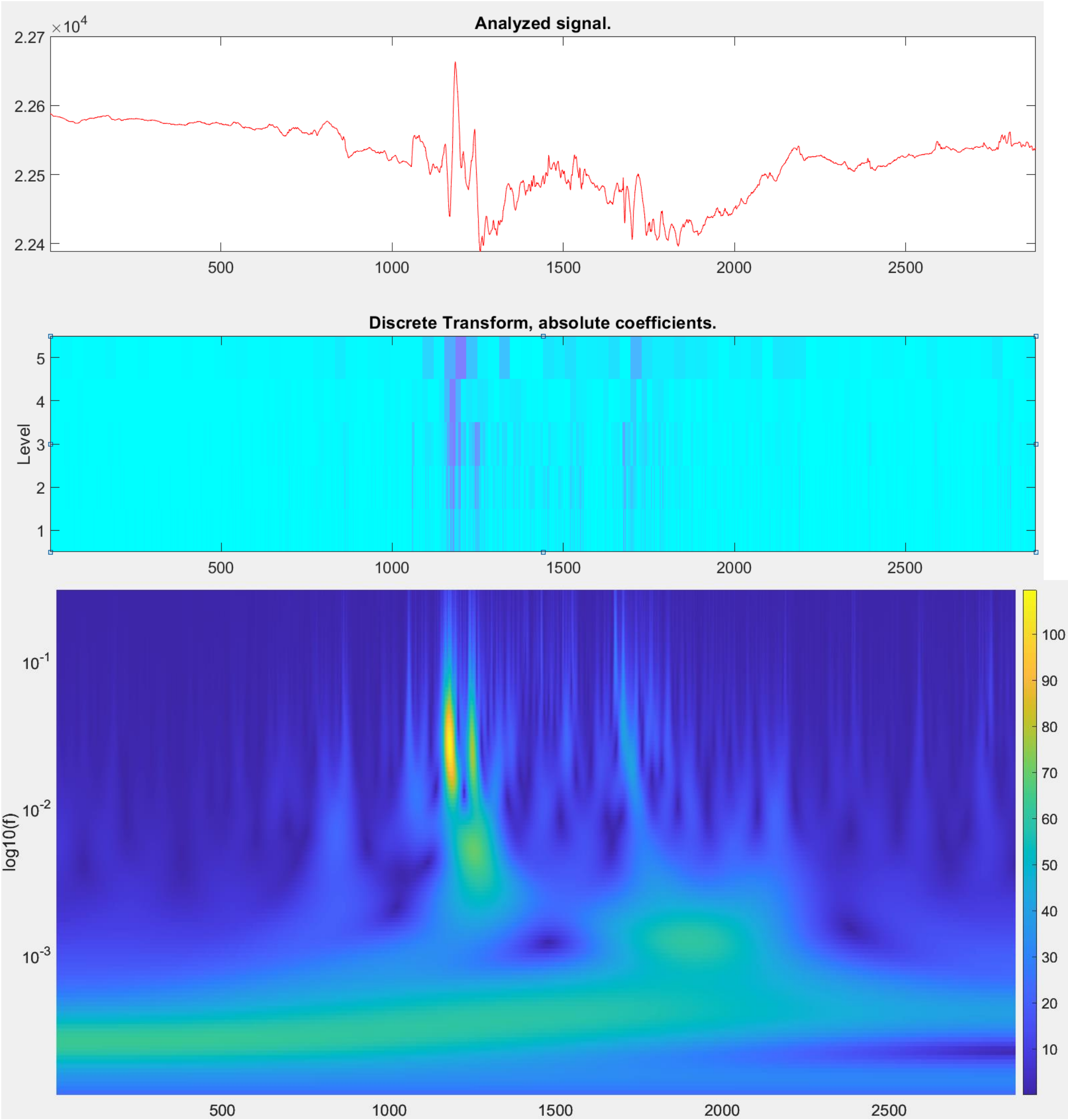

Figure 5. Geomagnetic Storm of April 23-24, 2023. Multispectral wavelet analysis for the North (Hx) geomagnetic component, Surlari observatory; This figure comprises 3 images, in top-down order: the geomagnetic signal recorded on the North direction, spectral analysis of North geomagnetic field and wavelet analyses for the level 5th with the db5 function in MATLAB.

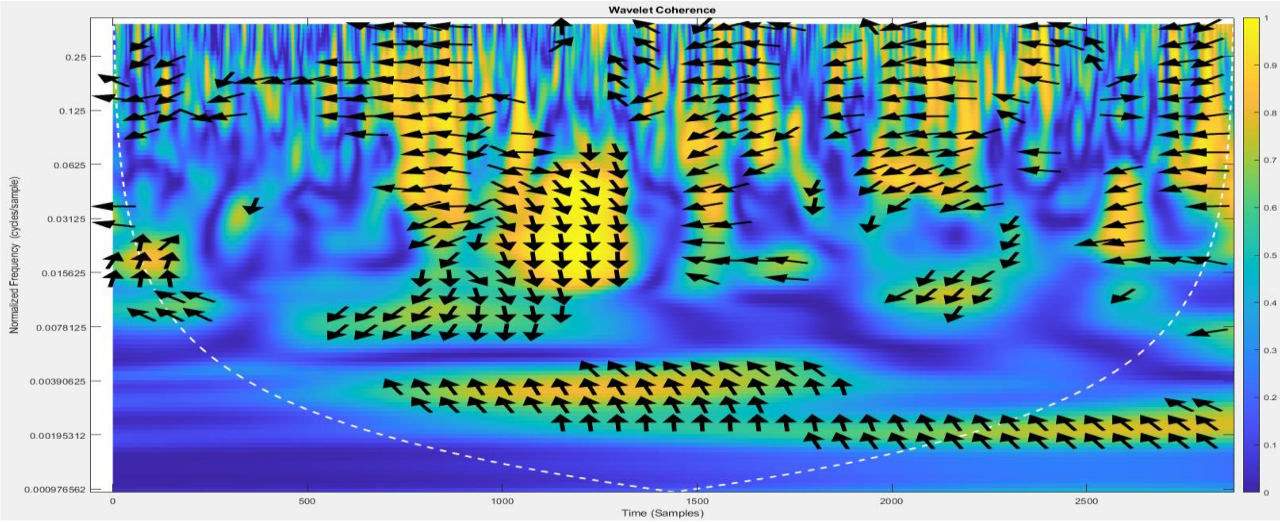

Figure 6. Wavelet coherence between horizontals components Hx and Hy,
from the Surlari observatory April 23-24, 2023.

Fig. 7 shows the magnetogram from the Surlari observatory for the geomagnetic storm of November 5, 2023.

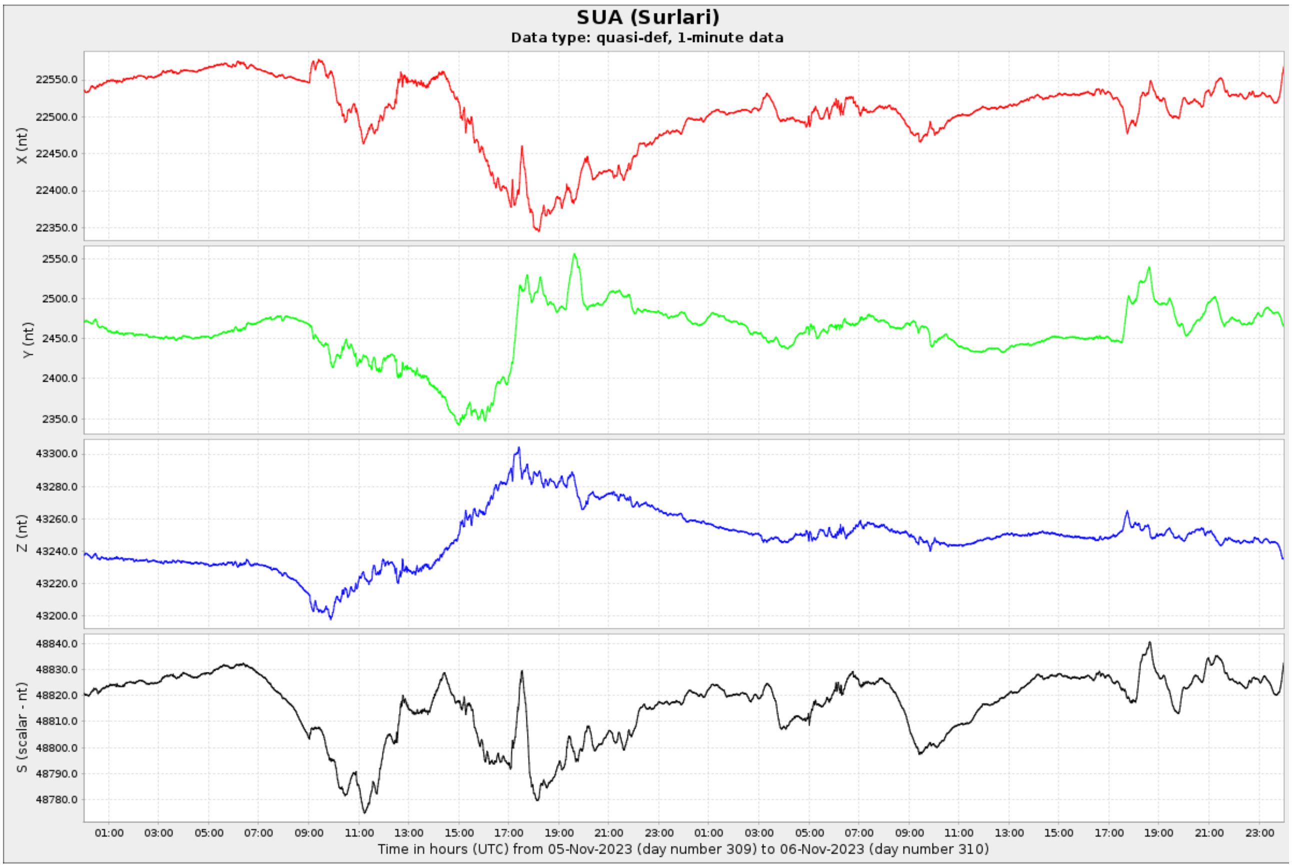

Figure 7. Magnetogram from the Surlari observatory for the geomagnetic storm of November 5, 2023.

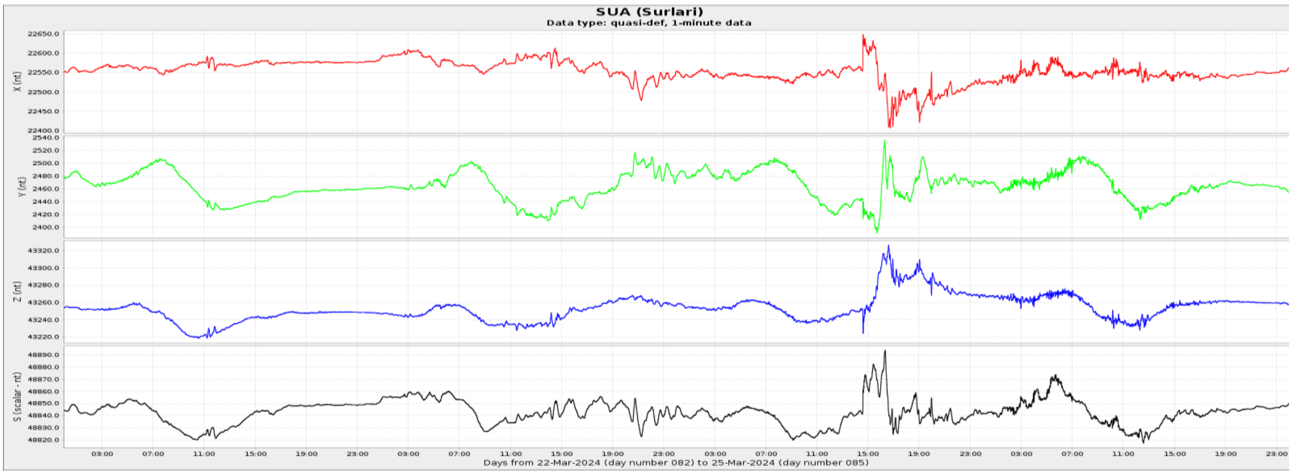

Figure 8. Magnetogram from the Surlari for the geomagnetic storm of March 24, 2024; period March 22-26

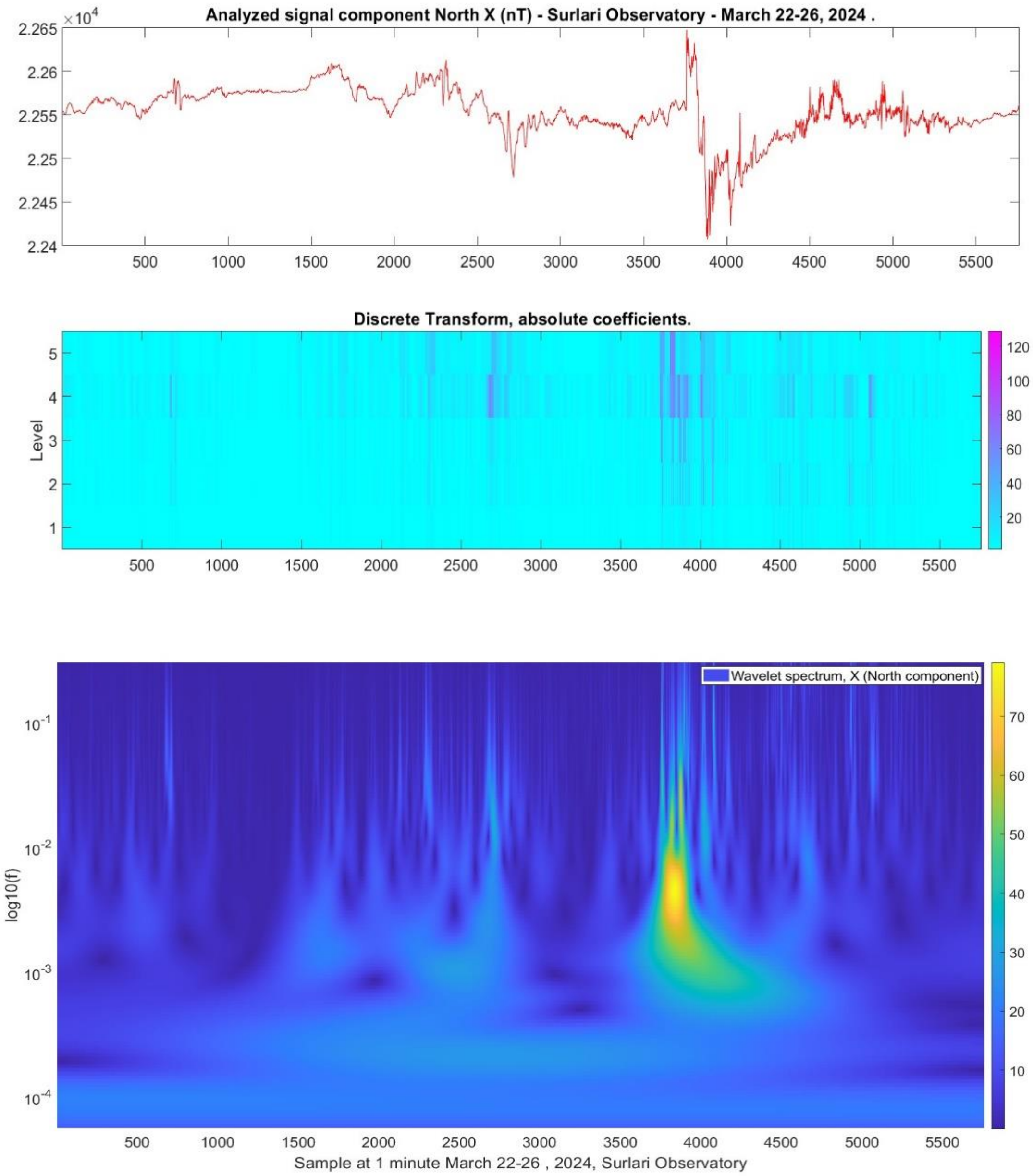

Figure 9. Multispectral wavelet analysis for the North geomagnetic component (Hx) from Surlari (USA); in top-down order: the geomagnetic signal recorded on the North direction, spectral analysis of North geomagnetic field and wavelet analyses for the level 5th with the db5 function in MATLAB.

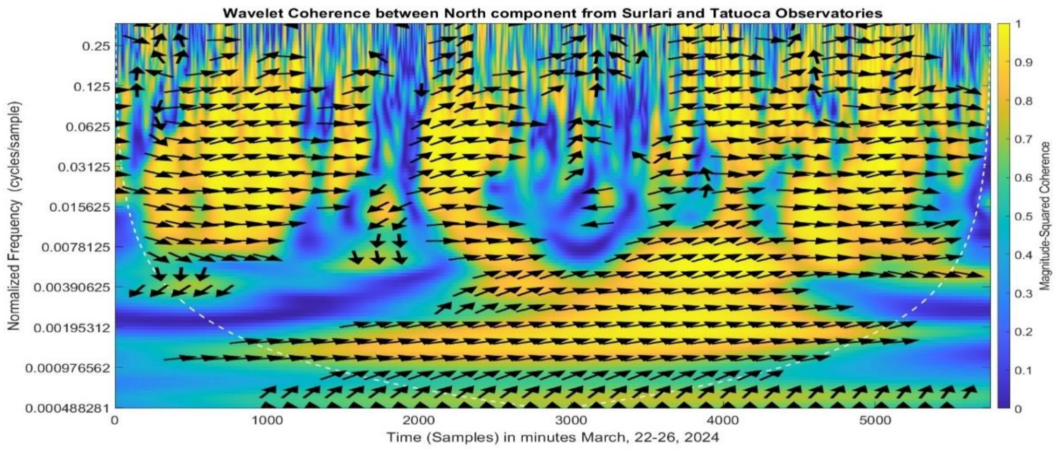

Figure 10. Wavelet coherence between the Surlari and Tatuoca Observatories, North direction (X).

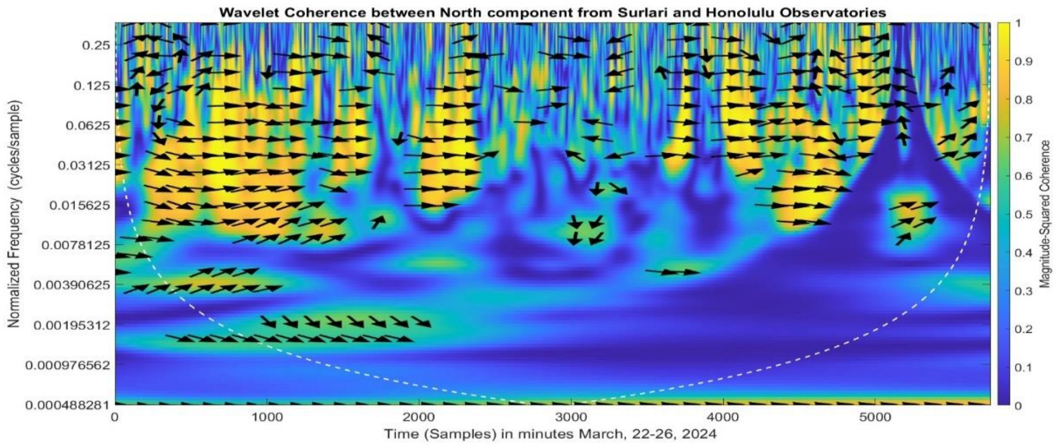

Figure 11. Wavelet coherence between Surlari and Honolulu Observatories, North direction (X).

CONCLUSIONS

From the performed analyses, all the observatories in INTERMAGNET recorded simultaneous pulses during the geomagnetic storms, indicating a synchronous relationship between them. We used statistical, spectral and wavelet methods, which highlighted the strongest geomagnetic storms. The Fourier transform cannot show which of the harmonic components is present at a time in the geomagnetic data series. Wavelet analysis gives us three-dimensional information (time, frequency, amplitude) or a two-dimensional shape, when the amplitude is encoded by colour intensity levels. A first step in the wavelet analysis is Short Time Fourier Transform, applied successively with different narrow windows, for the best accuracy of time location. Increasing the window improves the resolution in frequency, but decreases the resolution in time. In wavelet analysis we can choose the many different mother functions and we can make the comparations between there.

The wavelet transform is one of the ways of representing the signals in the multi-resolution analysis where the analysed geomagnetic signal is described by a sequence of approximations that contain more and more information. Each level of approximation contains on one hand all the information available at the previous level plus an additional detail component. When geomagnetic data are processed by standard deconvolution algorithms, such as predictive deconvolutions, the data contain phase errors. These errors in wavelet phase arise because the time series do not meet the strict requirements upon which deconvolution algorithms depend. Model based wavelet processing is a technique for correcting such phase errors. Based on forecast analysis we can get an estimate, but we get the maximum precision, only after the CME has occurred and we can visualize it through telescopes in the form of dark spots on the solar disk. From that moment, a geomagnetic storm is possible in an interval of two or three days. We can expect more extreme space weather events powerful geomagnetic storms as the sun builds towards a peak in its 11-year solar activity cycle, expected to occur in 2025.

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REFERENCES

ASIMOPOLOS N. S. & ASIMOPOLOS L. 2018. *Study on the high-intensity geomagnetic storm from march 2015, based on terrestrial and satellite data*. Micro and Nano Tehnologies & Space Tehnologies & Planetary Science. SGEM. **18**: 593-600,

ASIMOPOLOS L., SĂNDULESCU A. M., ASIMOPOLOS N. S., NICULICI E. 2012. *Analysis of data from Surlari National Geomagnetic Observatory*. Edit. Ars Docendi. București. 96 pp.

BENOIT S. L. 2012. *INTERMAGNET Technical reference manual - Version 4.6*. Murchison House West Mains Road Edinburgh. 100 pp.

BISGAARD S. & KULAHCI M. 2011. *Time series analysis and forecasting by example*. John Wiley & Sons. Hoboken. New Jersey. 382 pp

BOX G. E. P., JENKINS G. M., REINSEL G. C., LJUNG G. M. 2016. *Time series analysis - Forecasting and Control, Fifth Edition*. John Wiley & Sons. Hoboken. New Jersey. 709 pp.

CAMPBELL W. H. 2003. *Introduction to Geomagnetic Fields*. Cambridge University Press. 350 pp.

***. https://science.nasa.gov/science-news/science-at-nasa/ (accessed January 05, 2024).

***. https://www.spaceweatherlive.com/en/solar-activity/solar-cycle.html (accessed January 07, 2024).

***. https://www.intermagnet.org/ (accessed January 10, 2024).

***. http://www.noaa.gov (accessed January 15, 2024).

***. https://www.mathworks.com (accessed January 18, 2024).

***. https://www.sidc.be/ (accessed January 20, 2024).

Asimopolos Natalia-Silvia
Geological Institute of Romania
1st Caransebeș Street, 012271 - Bucharest, Romania.
E-mail: natalia.asimopolos@igr.ro, asi_nata@yahoo.com

Asimopolos Laurențiu
Geological Institute of Romania
1st Caransebeș Street, 012271 - Bucharest, Romania.
E-mail: laurentiu.asimopolos@igr.ro, asimopolos@gmail.com

Asimopolos Adrian-Aristide
National University for Science and Technology POLITEHNICA of Bucharest,
Faculty of Transports, 313 Splaiul Independentei, 060042 - Bucharest, Romania.
E-mail: adrian.asimopolos@gmail.com

Dinu Luminița
Geological Institute of Romania
1st Caransebeș Street, 012271 - Bucharest, Romania.
E-mail: luminita_iancu84@yahoo.com

Balea Bogdan-Valeriu
Geological Institute of Romania
1st Caransebeș Street, 012271 - Bucharest, Romania.
E-mail: baleavaleriu@gmail.com

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