THE NUMERICAL ANALYSIS APPLIED IN THE EVALUATION OF GEOMAGNETIC ACTIVITY

ASIMOPOLOS Natalia-Silvia, ASIMOPOLOS Adrian-Aristide, ASIMOPOLOS Laurențiu

Abstract. An important direction within the core project of the Geological Institute of Romania entitled "Geomagnetism, a modern tool in space weather forecasting and rapid response to associated natural hazards for the protection of critical infrastructures and national air traffic security" is the study of geomagnetic storms and the methodology for complex analysis of these phenomena. We used the Fourier and Wavelet spectral methodology for the study of the strong storm of January 1, 2025. The data used come from http://www.intermagnet.org, and the software package used is from https://www.mathworks.com. A very good correlation is noted between the geomagnetic observatories records, the wavelet analyses performed and the wavelet coherences.

Keywords: Geomagnetic activity, Spectral analysis, Wavelet, Geomagnetic storm.

Rezumat. Analiza numerică aplicată în evaluarea activității geomagnetice. O direcție importantă în cadrul proiectului central al Institutului Geologic din România, intitulat „Geomagnetismul, instrument modern în prognoza meteo spațială și răspuns rapid la hazardele naturale asociate pentru protecția infrastructurilor critice și securitatea traficului aerian național", este studiul furtunilor geomagnetice și metodologia de analiză complexă a acestor fenomene. Am utilizat metodologia spectrală Fourier și Wavelet pentru studiul furtunii puternice din 1 ianuarie 2025. Datele utilizate provin de la http://www.intermagnet.org, iar pachetul software utilizat este de la https://www.mathworks.com. Se observă o corelație foarte bună între înregistrările observatoarelor geomagnetice, analizele wavelet efectuate și coerențele wavelet.

Cuvinte cheie: Activitate geomagnetică, Analiză spectrală, Wavelet, Furtună geomagnetică.

INTRODUCTION

Solar cycle 25, which is in the maximum activity in 2025, it started with the solar minimum in December 2019. On January 1, 2025, there was the strongest geomagnetic storm this year. Can be found details on the specialized websites such us [http://www.noaa.gov] or [https://kp.gfz.de/en/figures/kp-daily-plots]. Coronal mass ejections (CMEs) and dark spots on the Sun indicate where are the sudden release of a massive cloud of hydrogen ions, electrons and protons.

The numerical analysis applied in the evaluation of geomagnetic activity used in the current work is Fourier, wavelet and multispectral spectral analysis.

The scientific works related to this topic with multidisciplinary approaches, which were the basis of this work, are: ASIMOPOLOS & ASIMOPOLOS (2018), BENOIT (2012) and GEBBINS & HERRERO-BERVERA (2007). The mathematical and software approaches can be found in the reference works: CHATFIELD (1989), DAUBECHIES (1990), TORRENCE & COMPO (1998), as well as the link https://www. mathworks.com.

METHODOLOGIES

Fourier analysis is the process of decomposing a function into oscillatory components while the operation of rebuilding the function from these pieces is known as Fourier synthesis. Determining what component frequencies are present in geomagnetic time series would involve computing the Fourier transform of a sampled signal. One could then re-synthesize the same signal by including the frequency components as revealed in the Fourier analysis.

The decomposition process itself is called a Fourier transformation. Its output, the Fourier transform, is often given a more specific name, which depends on the domain and other properties of the function being transformed. Moreover, the original concept of Fourier analysis has been extended over time to apply to more and more abstract and general situations, and the general field is often known as harmonic analysis. Each transform used for analysis has a corresponding inverse transform that can be used for synthesis. To use Fourier analysis, data must be equally spaced. Usually, it is the monitoring rate used in the INTERMAGNET geomagnetic observatories [http://www.intermagnet.org], 0.5 seconds. Different approaches have been developed for analysing unequally spaced data, notably the least-squares spectral analysis methods that use least squares fit of sinusoids to data samples.

Fourier analysis has a major disadvantage compared to multiresolution analysis, because by converting to the frequency domain, time information will be lost. Many signals contain numerous non-stationary or transient portions. These parts are often the most important of the signal, but Fourier analysis cannot detect them.

If the time window is chosen correctly then the actual virtual sequence coincides with infinite duration signal, otherwise the virtual signal is distorted compared the real signal. Using a time window for signal processing is equivalent to the filtering problem, but the goal is to mitigate potential discontinuities at the end of finite segment of the data evolution over time. In order to achieve the best possible accuracy, the spectral window used (Fourier transform of the time window) must satisfy the following basic requirements: main lobe of the window should be very narrow; main lobe contains most of the window energy; the energy of the secondary lobes must be evenly distributed between them.

Generally, these three requirements cannot be met by any window because the first two requirements are contradictory. From this point of view, we can say that there is no optimal window, each providing a compromise between the three requirements.

Short-Term Fourier Transform (STFT) transforms the signal into two-dimensional function of time and scale. This adaptation is considered as the bridge between global analysis techniques and recent theory of wavelet functions. STFT is a compromise between how to view the signal in time domain and frequency domain, showing when and how often is a event in a signal. Accuracy of this analysis is limited in relation with window size.

Wavelet Transform (WT) was developed from STFT and represents an analysis technique with variable size of sliding window. This allows the use of long-time intervals to obtain a good accurate of low frequency but less accuracy in time. If we want to increase the accuracy of time, we use short time intervals keeping only the information about high-frequency. Simple and efficient algorithms exist for both wavelet packet decomposition and optimal decomposition selection. This toolbox uses an adaptive filtering algorithm, based on work by Coifman and Wickerhauser, with direct applications in optimal signal coding and data compression.

Such algorithms allow the Wavelet Packet from Matlab [https://www.mathworks.com] to include “Best Level” and “Best Tree” features that optimize the decomposition both globally and with respect to each node.

As a mathematical tool, wavelets can be used to extract information from many kinds of data, including geomagnetic signals. Several families of wavelets (” Haar”, “Daubechies”, “Ricker”, “Coiflets”, “Symlets”, “Morlet”, “Mexican Hat”, “Meyer”, “Pisson”, “Mathieu”) that have proven to be especially useful are included in this toolbox.

EXAMPLES AND RESULTS

To exemplify the applicability of the numerical methods presented in the evaluation of geomagnetic activity, we chose the largest geomagnetic storm of this year, which occurred on January 1, 2025.

To exemplify the applicability of the numerical methods presented in the assessment of geomagnetic activity, we chose the largest geomagnetic storm of this year, which occurred on January 1, 2025. We analyzed data from several observatories, of which we exemplify three observatories: Surlari (USA), Romania, Lycksele (LYC), Sweden and Scott Base (SBA), for which we sampled data for each geomagnetic component and analyzed them using the wavelet technique. The magnetograms for the three analyzed observatories are presented in figure 1, where the correlation of the peaks on each component at the two observatories is observed. The data source is from the website https://www.intermagnet.org, for the observatories Surlari (Romania) – Latitude 44.680 , Longitude 26.250, Elevation 84m, Sampling 0.5 seconds, Instruments: X, Y, Z FGE(DTU), F: GSM90(GEM Systems), LYCKSELE (SWEDEN) - Latitude 64.600, Longitude 18.700, Elevation 0m, Instruments: X, Y, Z FGE(DTU), F: GSM90(GEM Systems) and SCOTT BASE (NEW ZEALAND) - Latitude -77.829, Longitude 166.671, Elevation 132m.

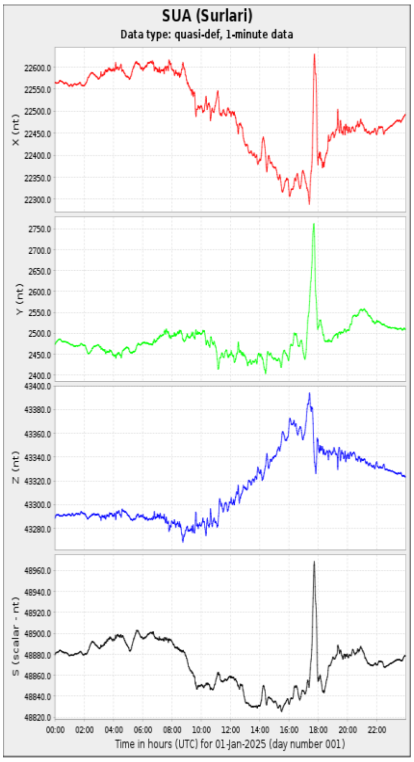

Figure 1a. Magnetogram at the Surlari Observatory.

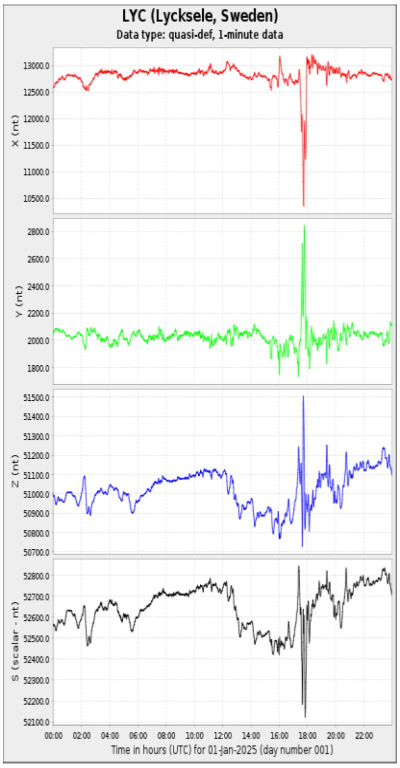

Figure 1b. Magnetogram at the Lycksele Observatory.

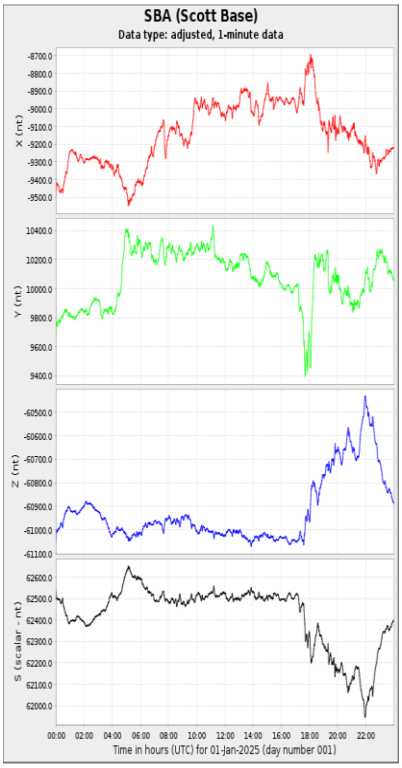

Figure 1c. Magnetogram at the Scott Base Observatory.

Figs. 2, 3 and 4 show the wavelet analyzes for the Surlari, Lycksele and Scott Base observatories. These three figures contain four images each: top left is the X component (North), top right is the Y component (East), bottom left is the Z component (Vertical), bottom right is the F component on January 1, 2025.

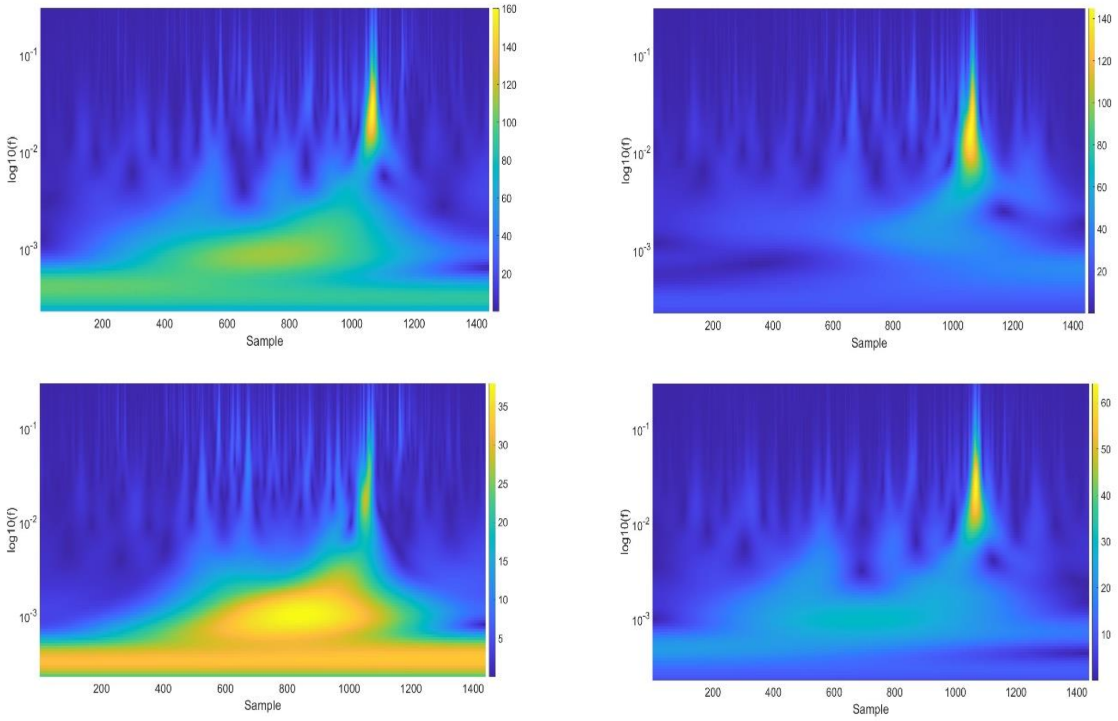

Figure 2. Wavelet analyses of Geomagnetic field at Surlari Observatory (SUA),
X (North field), Y (East field), Z (Vertical field), F (Total field).

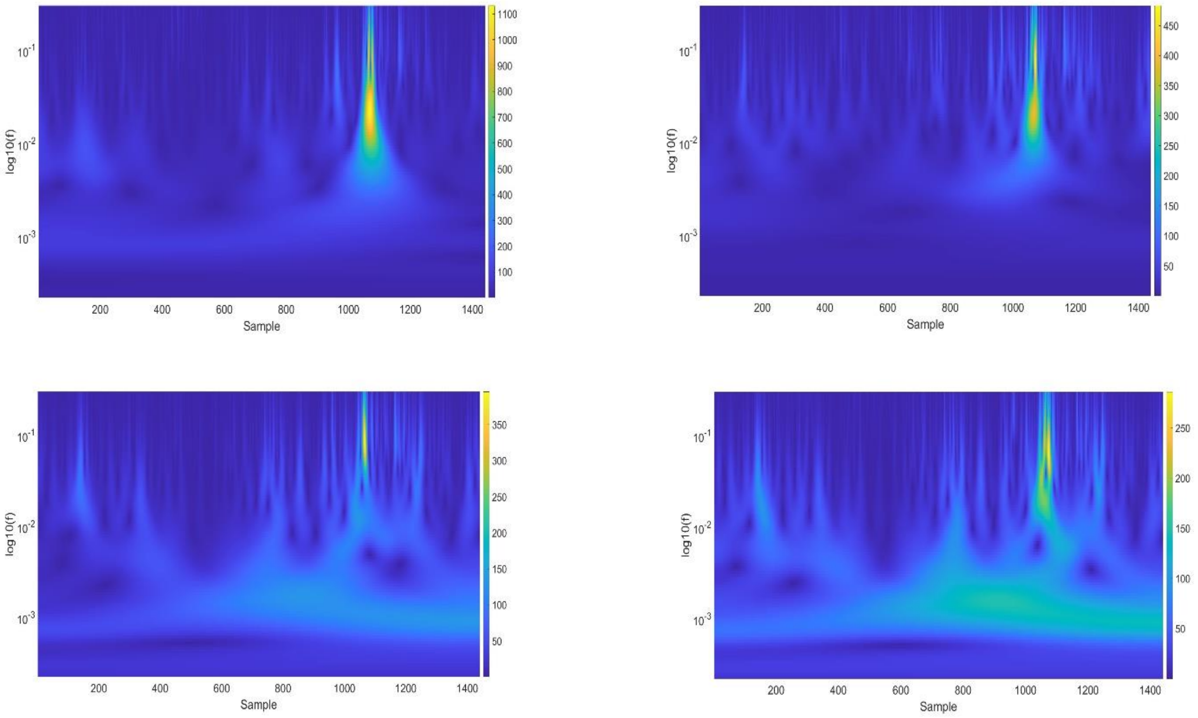

Figure 3. Wavelet analyses of Geomagnetic field at Lycksele Observatory (SUA),
X (North field), Y (East field), Z (Vertical field), F (Total field).

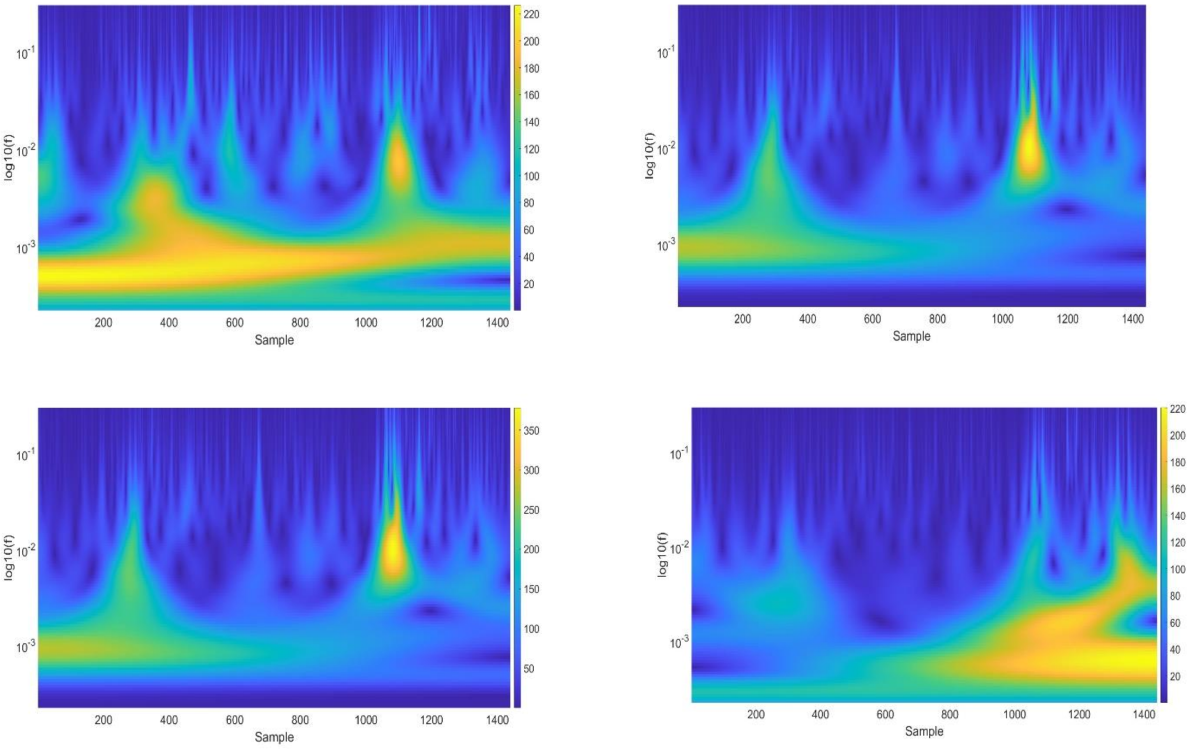

Figure 4. Wavelet analyses of Geomagnetic field at Scott Base Observatory (SBA),
X (North field), Y (East field), Z (Vertical field), F (Total field).

In all the previous figures, a very good correlation is noted, component by component, between the three observatories. In addition, the correlation with the three-hour indices (geomagnetic storm level 8) in figure 5 is also noted.

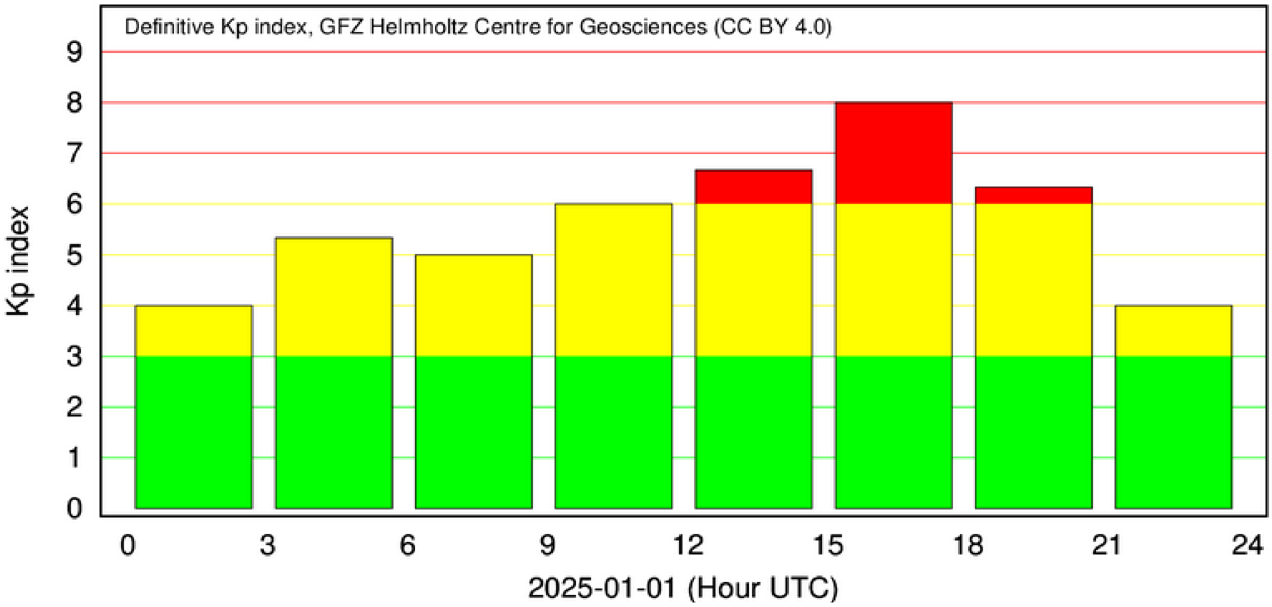

Figure 5. Kp index from January 1, 2025 [https://kp.gfz.de/en/figures/kp-daily-plots].

In the following 5 figures (Figs. 6-10), the wavelet coherence between the X, Y, Z and F components of the analyzed observatories is exemplified.

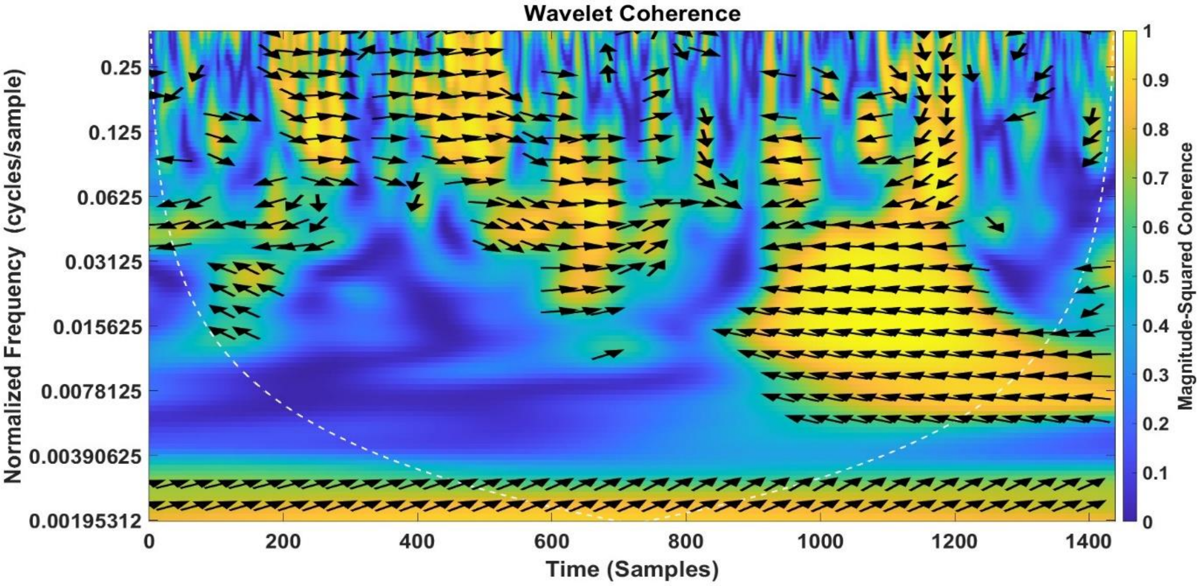

Figure 6. Wavelet coherence between X (North) components from SUA and LYC Observatories.

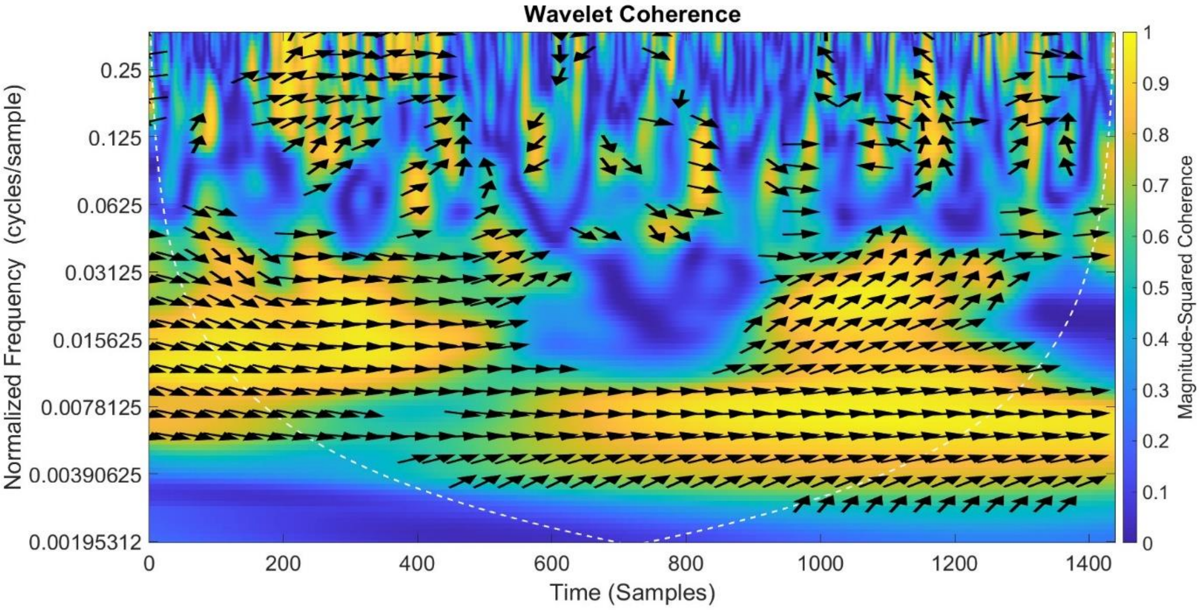

Figure 7. Wavelet coherence between Y (East) components from SUA and LYC Observatories.

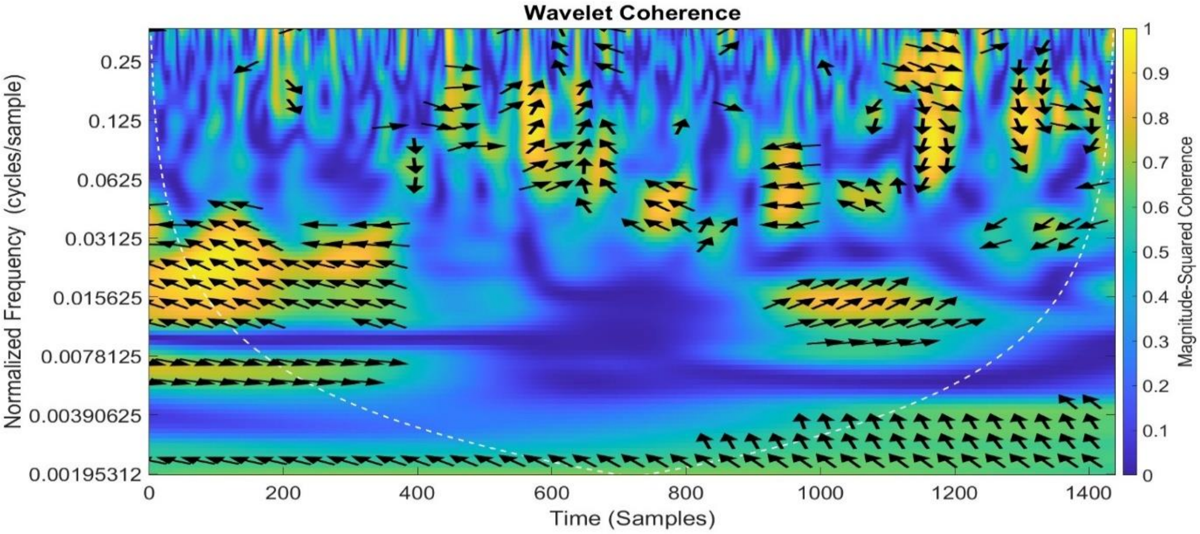

Figure 8. Wavelet coherence between Z (Vertical) components from SUA and LYC Observatories.

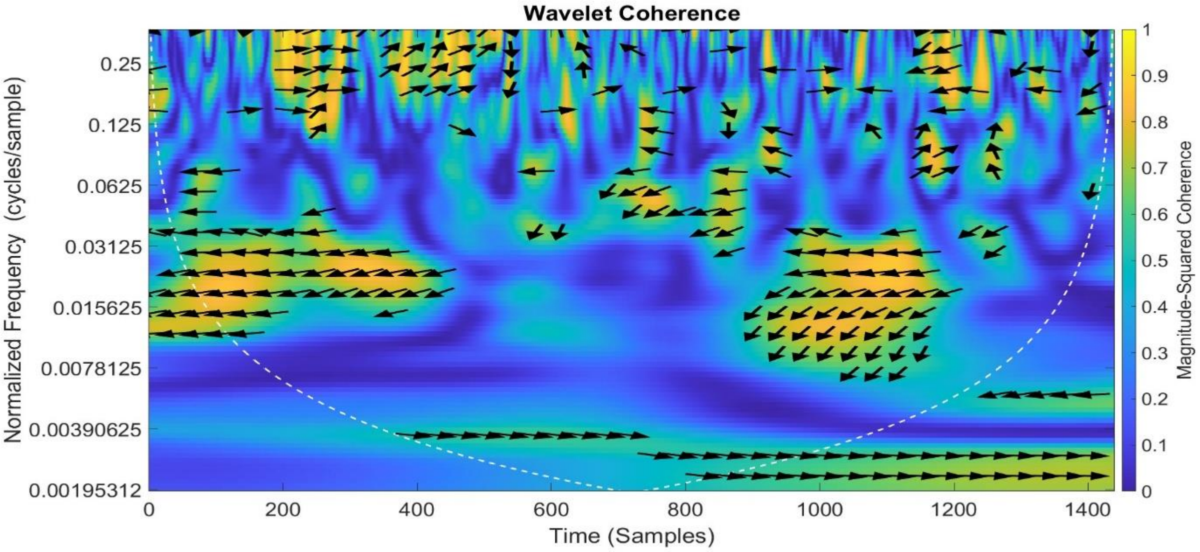

Figure 9. Wavelet coherence between F (Total geomagnetic field) from SUA and LYC Observatories.

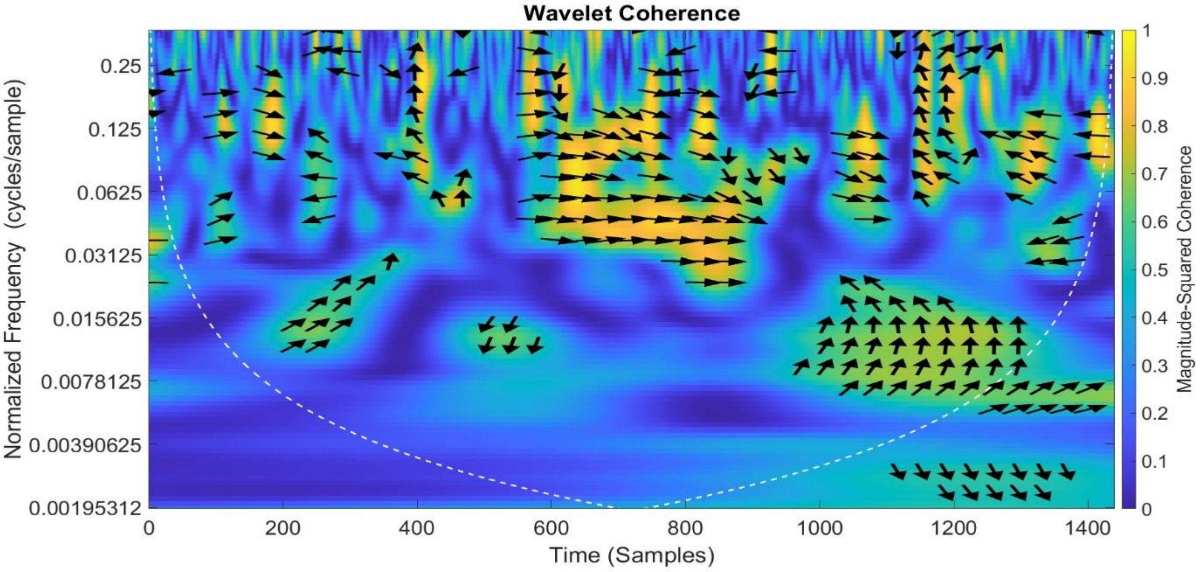

Figure 10. Wavelet coherence between X (North) components from SUA and SBA Observatories.

CONCLUSIONS

The wavelet technique allowed us to analyze the local components of the magnetic field through variable frequency windows and different functions, based on geomagnetic data from three observatories (Surlari in Romania, Lycksele in Sweden and Scott Base in New Zeeland) during the geomagnetic storm of January 1, 2025. Windows with longer time intervals allowed us to extract low-frequency information, average window times led us to extract medium-frequency information, and very narrow windows highlight high frequencies or details of the analyzed signals (in Figs. 2-5). The model of the disturbed geomagnetic field is composed of periodic oscillations plus non-periodic oscillations given by the impact of the solar wind on the terrestrial magnetosphere. 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 transitions. The arrows in the coherence plot indicate the phase relationship between the two signals at each time point and frequency (or period). The phase angle of the cross-spectrum is the same as the phase difference between the signals (in Figs. 6-10). The direction of the arrows in regions of high coherence can help to understand the phase relationship. From the data analyzed from the three geomagnetic observatories for the three triaxial components and the total field, very good wave correlation and coherence were observed during the 2025 storm.

ACKNOWLEDGEMENT

This paper was supported by Installation and Special Objective of National Interest (IOSIN) – Surlari National Geomagnetic Geomagnetic Observatory and Core Program PN23390401/2023-2026. Also, we thank the national institutes that support them and INTERMAGNET for promoting high standards of magnetic observatory practice.

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*. Issue 6.1, SGEM 2018. **18**: 593-600.

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

CHATFIELD C. 1989. *The Analysis of Time Series: An Introduction*. 4th Edition. Chapman and Hall. 241 pp.

DAUBECHIES I. 1990. The wavelet transforms time-frequency localization and signal analysis. *IEEE Trans. Inform. Theory*. **36**: 961-1004.

GEBBINS D. & HERRERO-BERVERA E. 2007. *Encyclopedia of Geomagnetism and Paleomagnetism*. Springer. Berlin. 311-360.

TORRENCE C. & COMPO G. P. A Practical Guide to Wavelet Analysis. *Bulletin of the American Meteorological Society*. **79**(1): 61-78.

***. http://www.intermagnet.org (Accessed January 12, 2025)

***. http://www.noaa.gov (Accessed January 13, 2025)

***. https://kp.gfz.de/en/figures/kp-daily-plots (Accessed January 13, 2025)

***. https://www.mathworks.com (Accessed January 12, 2025)

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

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

Received March 11, 2025
Accepted: August 24, 2025