SOLARIS: An application for the visualization of magnetic reconnections

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***Abstract*—In this paper, we present the development of an interactive web application designed to allow the general public to explore and analyze multiple variables related to the interplanetary magnetic field and its components. The application was developed as part of a NASA challenge and is accompanied by code in JUPYTER NOTEBOOK with PYTHON that incorporates wavelet transforms for more detailed analysis. In this article, we describe the methodology used in the development of the web application, as well as the results obtained through its implementation.**

***Index Terms*—Web application, Magnetic reconnection, Data analysis, Wavelet Transforms.**

I. INTRODUCTION

The interplanetary magnetic field is a fundamental piece of space physics, playing a critical role in the interaction between the solar wind and the planets of the solar system, particularly for the life in our Earth planet. Understanding the characteristics and dynamics of this field is essential to advance our knowledge of space physics and predict solar events that may affect Earth and other space missions.

Magnetic reconnection [1], [2] in the context of the Sun refers to the process in which magnetic field lines in the solar atmosphere, especially in the solar corona, change their configuration. This occurs when initially separated magnetic field lines approach and join together. When these lines reconnect, they release a large amount of energy in the form of solar flares and coronal mass ejections (CMEs).

In the Sun, magnetic reconnection is a significant cause of explosive solar events. During reconnection, the stored magnetic energy is converted into thermal and kinetic energy, resulting in solar flares that can affect communications on Earth and satellite navigation systems, among other things. It can also lead to coronal mass ejections, which are massive ejections of solar material into space, and when these CMEs impact Earth, they can disrupt conditions in the Earth's magnetosphere and cause geomagnetic storms.

Understanding and studying magnetic reconnection is of critical importance for various aspects of life on Earth, technology, and communications. Here are some key reasons:

1) Earth's Protection from Solar Storms: Magnetic reconnection on the Sun can lead to massive solar eruptions and coronal mass ejections that, when they reach Earth, can severely disrupt our magnetosphere and satellite communications. Understanding this process is essential for developing early warning systems and risk mitigation strategies.
2) Space Technology and Satellites: Satellites and spacecraft in Earth's orbit are constantly exposed to solar wind radiation and charged particles. Magnetic reconnection can negatively impact their operation and lifespan. Studying it is crucial for designing resilient space technology and reliable navigation systems.
3) Scientific Research: Magnetic reconnection is a fundamental process in plasma physics and astrophysics. Studying it helps us better understand the behavior of plasmas in the universe, from the Sun to the far reaches of interplanetary space.
4) Earth Applications: In addition to its relevance in space, magnetic reconnection also occurs in Earth's magnetosphere. Understanding it is vital for protecting power grids, navigation systems, and communications during extreme geomagnetic events.
5) Technological Advancements: Research into magnetic reconnection can have applications beyond solar storm protection. It can inspire advances in energy generation and control, as well as in nuclear fusion, potentially revolutionizing how we obtain energy in the future.

The phenomenon of magnetic reconnection is essential for Earth's safety, technological development, understanding the universe, and advancing cutting-edge technologies. Its ongoing study plays a crucial role in safeguarding our society and driving progress in science and technology.

NASA issued a challenge to develop an interactive web application that would allow anyone to explore and analyze data related to the interplanetary magnetic field. The goal was to provide an educational and research tool accessible to the general public.

II. DATA

The primary source of information is NASA's OMNIWEB site (https://omniweb.gsfc.nasa.gov) and the direct access to the high resolution (5 min) data is located into the web direction https://omniweb.gsfc.nasa.gov/form/omni_min.html, which stands as a pillar of reliability and authority in the field of solar astrophysics. Over a period spanning from 2018 to 2023, high-resolution data have been collected, with a sampling frequency of 5 minutes. This monumental dataset comprises approximately 468 thousand records and encompasses a wide range of crucial measurements, including the magnitude of the magnetic field in its B_x, B_y and B_z components, as well as data relating to flow speed (S), flow temperature (T) and proton density (D). This abundant reservoir of information allows a thorough analysis of the variations in the interplanetary magnetic field and its correlation with the magnetic reconnections on the Sun, providing an unparalleled perspective for understanding solar phenomena and their consequences in space physics.

Figure 1 shows the behavior of the emerging dynamics of the interplanetary magnetic field in magnitude and its components in the period January 2020.

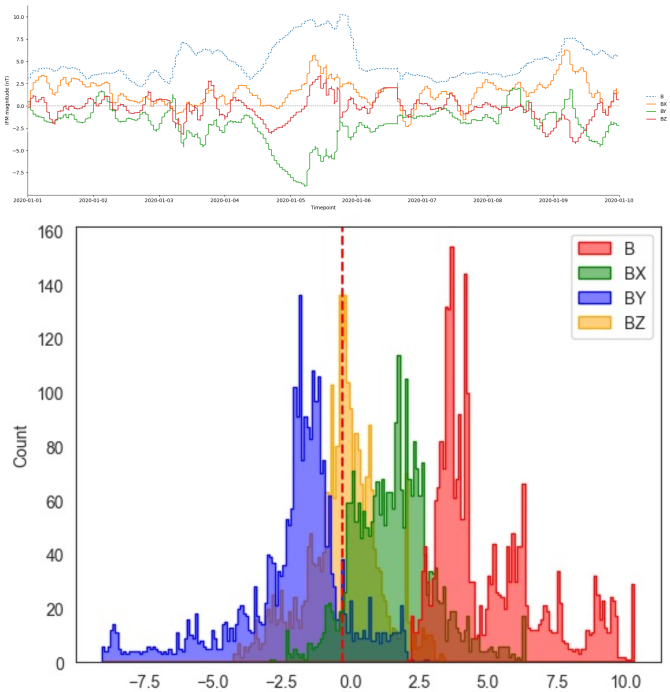

Fig. 1. Top: Interplanetary Magnetic Field (magnitude and components) for period between 2020-01-01 to 2020-01-10. Bottom: Probability Distribution Function for Interplanetary Magnetic Field (magnitude and components) in same perdiod.

In the same way, figure 2 shows the behavior of the emerging dynamics of the flow temperature, proton density and flow speed variables in magnitude in the same sampling period.

III. Methodology

The methodology used has been developed with the purpose of creating a state-of-the-art tool that allows the scientific community and the general public to explore and understand the complex interactions of the interplanetary magnetic field. The project is divided into two essential components: the design of an interactive web application and the implementation of advanced techniques, such as the wavelet transform, for interplanetary magnetic data analysis. Through this combination,

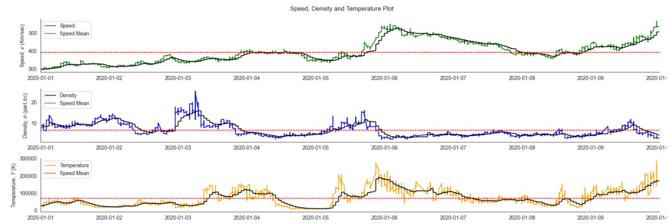

Fig. 2. Flow temperature (in Kelvin degrees), proton density (in n/cc) and flow speed (in km/sec) variables for period between 2020-01-01 to 2020-01-10.

we seek to provide an accessible and effective educational and research experience for all those interested in the study of these cosmic phenomena.

A. The web application

The web application has been developed using NEXT.JS, which is a framework built on React. The primary goal of this application is to provide a user-friendly interface for the general public, effectively serving as an observatory.

Users have the option to select specific date ranges or individual days to focus on specific data for better visualization. Within the application, we can find components related to the interplanetary magnetic field, as measured by various NASA missions, satellites, and international collaborations. Alongside the magnetic field data, the application also displays magnetic field components, solar wind speed (represented as S in km/sec), proton density (represented as D in n/cc), and flux temperature (represented as T in degrees Kelvin).

Once the data is plotted, calculations are performed to identify instances where the interplanetary magnetic field time series exhibits an opposite direction to Earth's magnetic field, which naturally points toward the geographic north pole. These calculations provide statistical information to determine when an event might be considered a magnetic reconnection scenario (See Fig. 3). Additionally, specific thresholds are applied to further refine the data. Specifically, three thresholds are used: T greater than the mean temperature (T_{mean}), S greater than the mean wind speed (S_{mean}), and D greater than the mean proton density (D_{mean}). These averages are computed exclusively for the selected time interval as defined by the user.

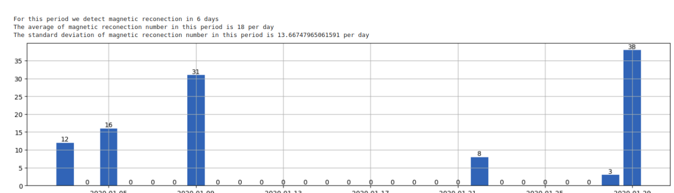

Fig. 3. Estimated number of magnetic reconections in the interval 2020-01-01 to 2020-01-30 from application.

The application allows users to select a variety of variables related to the interplanetary magnetic field, including magnetic field strength, solar wind speed, and plasma density. The data used in the application were obtained from reliable sources and are updated regularly.

The application's intuitive user interface allows users to visualize data in the form of interactive graphs and three-dimensional maps. In addition, users can apply wavelet transforms to the data to analyze frequency and multiscale features, providing a deeper understanding of magnetic field dynamics.

B. Implementation of Wavelet Transforms

Additionally a PYTHON code in the JUPYTER NOTEBOOK has been developed in order to use more powerful mathematical tools, modeling and signal analysis in this case of the z component of the IMF.

The Wavelet Transform [3], [4] is a signal processing technique that provides both time and frequency domain resolution simultaneously, making it especially useful for analyzing non-stationary signals. In contrast, the Fourier Transform [5] provides frequency information but lacks temporal resolution, while the Short-Time Fourier Transform (STFT) improves temporal resolution but has limitations in frequency resolution.

Like the Fourier transform, the continuous wavelet transform (CWT) uses inner products to measure the similarity between a signal and an analyzing function. In the Fourier transform, the analyzing functions are complex exponentials, e^{iwt}. The resulting transform is a function of a single variable, w. In the short-time Fourier transform, the analyzing functions are windowed complex exponentials, $w(t)e^{iwt}$, and the result is a function of two variables. The STFT coefficients, $F(w,\tau)$, represent the match between the signal and a sinusoid with angular frequency w in an interval of a specified length centered at τ.

The mathematical model of the wavelet transform for a function F (generally a signal series), which depends on the scale of the parameter and τ, is represented as follows

$$F(\tau, s) = \frac{1}{\sqrt{|s|_{-\infty}}} \int_{-\infty}^{+\infty} f(t)\psi^{*}\left(\frac{t-\tau}{s}\right) dt, \qquad (1)$$

where where * denotes the complex conjugate, the parameter s is called a scale parameter (analogous to frequency) and $\psi(t)$ is a continuous function in both the time domain and the frequency domain called the mother wavelet and the overline represents operation of complex conjugate. Not only do the values of scale and position affect the CWT coefficients, but the choice of wavelet also affects the values of the coefficients.

The most commonly used CWT wavelet is the Morlet wavelet. The Morlet wavelet is simply a Gaussian-windowed complex sinusoid $\psi(t) = \frac{1}{\sqrt{2\pi}} e^{-iw_0 t} e^{-t^2/2}$.

To enhance the analysis capabilities of the application, we implemented wavelet transforms in the associated JUPYTER NOTEBOOK code. This allows users to decompose magnetic signals into different scales and frequencies, which facilitates the detection of hidden patterns and trends in the data. The integration of this advanced technique into the application extends its usefulness for both educational and research purposes.

Figure 4 shows the result of the CWT application for the January 2020 sampling period. The CWT coefficients are plotted, showing the time-frequency representation of the data. Transient features or oscillations associated with magnetic reconnection events may manifest as distinct patterns in this plot.

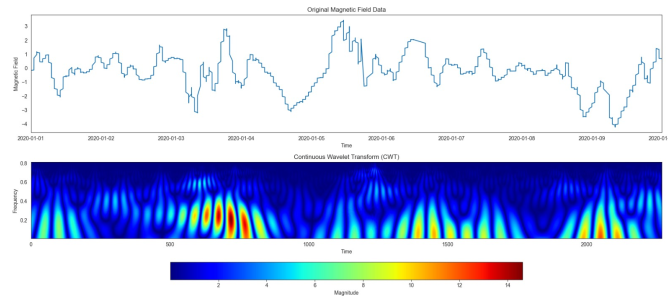

Fig. 4. CWT coefficients plotted showing the time-frequency representation of the data for period between 2020-01-01 to 2020-01-10.

To identify magnetic reconnection events, the figure shows unusual patterns, abrupt changes or features that stand out on the plot in terms of the magnitude of the transform. Some of these changes are obvious to the naked eye but some others are invisible to visual inspection, however the transform is able to show them in the frequency spectrum, making it possible to detect events that are out of the norm.

IV. CONCLUSIONS

In this paper, we have presented the successful development of an interactive web application for the study of the interplanetary magnetic field and its components. The application offers researchers and the general public a valuable tool to explore and analyze magnetic field related data in real time. The incorporation of wavelet transforms in data analysis further expands the possibilities for research and discovery in the field of space physics. This project demonstrates the potential for collaboration between the scientific community and NASA to further the understanding and interest in space exploration.

We hope that this research and the resulting application will contribute to the continued advancement of our understanding of the interplanetary magnetic field and its importance in space physics.

V. AVAILABLE RESOURCES

All available resources that have been used for the results in the solution of this challenge have been placed in open repositories and freely accessible to anyone in the world.

- The web application "SOLARIS" that has been designed is available at the web address: https://6522f7df47086d6550413d99–solariswebapp.netlify.app/.
- The code written in PYTHON in JUPYTER NOTEBOOK has been placed at: https://github.com/TheSkyLabTeam/Solaris/tree/main.
- Additionally, a version that can be deployed online with the possibility of real-time execution making use of our

data (obtained from NASA) can be found at the web address: XXX.

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