Code Documentation

Magnetic Turbulence Analysis

DE GELIS Pierre-Marie
M2 Space Sciences and Applications

February 18, 2025

Introduction

This program was developed as part of a Master's project aimed at reproducing the findings of Trevor Bowen's discovery, published in 2024 in *Nature Astronomy*. [look Project Report]

Following the `README.md` file, which provides basic instructions for using the code, the `Analysis_Program` directory comprises three Python files (`.py`):

- **Inputs.py**: This file manages the input parameters and data paths required for the analysis. It ensures that the correct data is loaded and prepared for processing.
- **Processing.py**: This script handles the core data processing tasks, including filtering, noise reduction, and visualization of magnetic field data. It generates various plots to analyze the data effectively.
- **Function_Data_Analysis.py**: This file contains essential functions for magnetic field data analysis, such as calculating rotation matrices, smoothing data, and computing spectrograms. These functions are utilized across the other scripts to perform detailed analyses.

1 Inputs.py

This script is designed for importing and processing magnetic field data for analysis. It includes sections for importing necessary modules, setting data paths, selecting data files, and defining parameters for analysis.

Importing Project Modules

This section imports the necessary modules for the project. It modifies the system path to include the directory containing the project's analysis programs.

Importing Data

This section sets the path to the data directory and allows for the selection of specific data files for analysis. The data files are selected based on their dates, and the script supports multiple dates for comparison.

Data Selection

The script provides options to select data from specific dates:

- Data from 6 September 2022
- Data from 4 April 2024
- Data from 9 August 2021

Each date corresponds to a specific data file, which can be selected by uncommenting the relevant line of code.

Parameters

This section defines the parameters used for data analysis:

- `nperseg`: Number of points for each segment in the analysis.
- `noverlap`: Number of points to overlap between segments, calculated as 80% of `nperseg`.
- `rotation`: Specifies whether to use field-aligned coordinates ('yes') or ('no').

Data-Specific Parameters

Depending on the selected data file, the script sets specific parameters for filtering and time selection:

- `low_filtered_limit` and `high_filtered_limit`: Define the frequency range for filtering.
- `low_limit_cyclo` and `high_limit_cyclo`: Additional filtering limits for specific analyses.
- `low_limit_w` and `high_limit_w`: Further filtering limits for detailed analysis.
- `start_time` and `end_time`: Define the time range for data selection.

These parameters are set individually for each data file to ensure optimal analysis results.

2 Processing.py

This script is designed for processing and visualizing magnetic field data. It includes sections for importing necessary modules, initializing data, processing noise, and creating various visualizations.

Importing Project Modules

This section imports the necessary modules for the project. It modifies the system path to include the directory containing the project's analysis programs.

Data Initialization

This section initializes the data by loading the magnetic field data file and filtering it based on a specified time interval. The data is then prepared for further analysis.

Noise Processing

This section loads and processes noise data. It calculates the 3-sigma noise level by directly multiplying the Power Spectral Density (PSD) by 3.0.

Data Processing and Visualizations

This section contains functions for creating various visualizations of the magnetic field data.

Magnetic Field Evolution

The `create_figure_1` function generates a plot of the magnetic field components and their magnitude over time. It displays the evolution of the magnetic field for the filtered data.

Power Spectral Density

The `create_figure_2` function plots the PSD segments and identifies those exceeding the noise level within a specified frequency range. It displays two log-log plots: one for all PSD segments and another for segments above the noise level.

Spectrograms of PSD and Helicity

The `create_figure_3` function creates a figure with three subplots: PSD spectrogram, helicity spectrogram, and the angle between the magnetic field and the radial direction (θ_{BR}). It visualizes the spectrogram data with frequency filtering.

PSD and Helicity Filtering

The `create_figure_4` function creates a figure with four subplots for PSD and helicity filtering. It applies filters based on helicity and noise levels to segment the data and displays the filtered spectrograms.

Mean Helicity and PSD over Time

The `create_figure_5` function plots the mean helicity and PSD over time within defined frequency bands. It displays the evolution of these values as a function of time.

Function Selection

This section allows for the selection and execution of specific visualization functions. Each function can be uncommented to generate the corresponding plot.

3 Function_Data_Analysis_file

This file contains core functions for magnetic field data analysis. Key functions include:

calculate_rotation_matrix(B0)

Creates a 3x3 rotation matrix to align the coordinate system with the mean magnetic field direction (B0). It uses Gram-Schmidt orthogonalization and returns an orthogonal rotation matrix with components [e1 (B0 direction), e2 (perpendicular), e3 (right-handed system)].

smooth_data(data, window_size)

Applies moving average smoothing with reflected-edge padding. It handles edge cases, returning the original data if the window size is less than or equal to 1, and otherwise returns a smoothed array matching the input length.

calculate_spectrogram_data(...)

Processes spectrogram data with frequency filtering in the range of 0-132Hz. Features include optional PSD compensation, log-transform, and normalization. Returns a dictionary containing filtered frequencies, processed spectrogram data, and time/frequency edges for plotting.

compute_segment_analysis(B_R, B_T, B_N, ...)

Core analysis function using Welch's method. Computes power spectral density (PSD) segments, magnetic helicity spectra, and field-radial angles. It handles coordinate rotation between RTN and field-aligned systems. Returns a tuple containing frequency arrays, PSD/helicity matrices, and timing data.