Arrival Window of Halo CME (Coronal Mass Ejection) And Its Prediction Using Aditya L1 SWISS Data Assessments

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Abstract

India's Aditya-L1 mission features the SWIS instrument that allows a continuous recording of the solar wind ion flux, energy, and directional properties. For this purpose, it uses two Top-Hat Analysers covering 0.1–20 keV with full 360° angular coverage. The magnetic mass analyser in THA-1 separates H^+ from He^{2+}, thus allowing the accurate monitoring of helium abundance changes that frequently occur during the passing of halo CMEs and the structures connected to them. Such measurements provide a timeline for the arrival of the CME through the detection of early signatures like ion composition changes, speed, and High-Speed particle levels. By observing the time-dependent changes of the solar wind parameters measured by SWIS, the research intends to enhance the short-term forecasting of halo CME arrival at L1 and deepen the understanding of their impact. The multi-directional and adjustable configuration of the instrument enables it to keep a continuous record of the disturbances in the Heliosphere layer and be able to anticipate space weather.

Keywords - Halo Coronal Mass Ejection, CME Arrival Prediction, Solar Wind Ion Spectrometer (SWIS), Solar Wind Composition, Solar Wind Velocity, Lagrange Point L1

Introduction

The solar wind constitutes ionized plasma of the Sun's billion-degree corona is carried away from the Sun into the interplanetary medium by the solar wind, the particle flux is driven by the million-degree corona. This flow conserves the overall conditions of the heliosphere, in the slow and fast streams of about 300–500 km s^{-1} and 500–750 km s^{-1}, respectively, during quiet times, and each comes from a different solar region. While the solar wind establishes the average state of the heliosphere, explosive releases of energy in the form of transient events, such as CMEs, produce sudden and large-amplitude variations. Among these, halo CMEs, the ones whose expansion seems to wrap the solar disk, are relatively important since Earth-directed halo CMEs can compress the magnetosphere and cause moderate to intense geomagnetic storms. These, in turn, influence satellite operations, navigation networks, radio communication, and power-grid stability, making an early and accurate prediction of halo CME arrivals a priority in space-weather forecasting.

Fractional plasma solar wind observations are necessary to locate the interplanetary space planet disturbances that are the result of CME-induced shocks. Compositionally, the solar wind is primarily made up of protons (H^+), alpha particles (He^{2+}), and trace heavy ions. The solar wind is a changing one as the shock, sheath, and magnetic ejecta encounter the passage of the CME. Its composition, speed, density, and temperature characterize these changes. Parametric changes such as sudden changes in velocity, heightened density, temperature decreasing, or He^{2+}/H^+ abundance ratio altering, are all the first indicators of CME movement. Continuous measurements from spacecraft located at the Sun–Earth L1 point, such as ACE, Wind, DSCOVR, and SOHO, on the one hand, and close to the Sun from missions like Parker Solar Probe and Solar Orbiter on the other, have helped considerably in understanding the evolution of CMEs. Nevertheless, the problem of uncertainties in their arrival time predictions is still so big that it is often more than a couple of hours away because a real prediction depends on a very complicated interaction of a CME with the background solar wind, for which high-cadence, species-resolved ion measurements are only seldomly available.

Aditya-L1 is India's ambitious project that is adding an entirely new dimension to the capabilities of the present solar physics missions. The mission was launched in September 2023 and has been operating in a halo orbit around the L1 point since January 2024. The mission is equipped with a variety of instruments for imaging as well as in situ observations of the Sun.

Among the experiments carried out on the Indian Aditya-L1 mission, the solar wind particle experiment (ASPEX) is the most prominent and important, and it affords the continuous observation of solar-wind ions through two distinct subsystems: the solar wind ion spectrometer (SWIS) and the supra-thermal and energetic particle spectrometer (STEPS). SWIS with two Top-Hat electrostatic analysers covering a full 360° angle can carry out measurements of ion fluxes, directional anisotropies, and electron-resolved energy distributions in the energy range of 0.1–20 keV. By its inherent ability, SWIS can separate proton and alpha particles and as a result, detailed tracking of helium abundance can be achieved—this can be used as a key tool for the identifications of the CME and solar-wind source regions. The fact that SWIS is highly precise and can monitor several directions simultaneously at short intervals means that it becomes possible to notice those really faint, early-stage plasma signatures from which the subsequent arrival of the halo CME can be inferred

Since the performance of reliable solar-wind diagnostics is a prerequisite for the prediction of geomagnetic disturbances, the information produced by SWIS may have a considerable impact on the development of models predicting arrival times and therefore on the improvement of those models. It is by examining solar wind variable data that SWIS is storing that we can discover the phenomenon of the solar wind precursors to the CME propagation and, therefore, better estimate the time window of CME arrival at L1. This research is targeted at discovering and proving that potential.

Key objective

The main goal of this study is to figure out when the effect of a Halo Coronal Mass Ejection (CME) will arrive at the Earth by monitoring changes in the solar wind plasma that is made by the Solar Wind Ion Spectrometer (SWIS) onboard the Aditya-L1 spacecraft.

1. To methodically employ the Solar Wind Ion Spectrometer (SWIS) Level-2 data products from the ASPEX payload onboard the Aditya-L1 mission in the detection and analysis of transient solar wind disturbances, with the identification of halo Coronal Mass Ejection (CME) events being the main emphasis is to utilize the ion measurements at the highest resolution as provided by SWIS which will help in understanding variability in solar wind and picking out the signatures associated with large-scale eruptive solar phenomena.

2. To deeply analyse the SWIS plasma parameters like particle flux, ion number density, bulk flow velocity, and thermal/kinetic temperature to help in defining the distinct behavioural patterns that come with the passage of the CME. The aim is to distinguish the CME-driven perturbations from those in the ambient solar wind streams by looking at the variations, discontinuities, and anomalous enhancements in these parameters.

3. To create a detailed scheme of work for handling the time-series measurements of SWIS data that would lead to determining reliable quantitative thresholds for the identification of halo CME events. This involves the creation of statistical techniques, anomaly-detection algorithms, and change-point analysis methods that are capable of pinpointing sudden and sustained deviations in solar wind parameters.

4. To come up with a complete approach for dealing with the time series data from SWIS in order to find trustworthy quantitative criteria for recognizing halo CME events. This work consists of devising statistical methods, anomaly-detection algorithms, and change-point analysis techniques that can pinpoint abrupt and continuing departures from the norm in solar wind parameters.

5. To confirm the occurrence of the CME events by linking the SWIS-derived signatures to the independently identified events in international space weather catalogues like those of SOHO, STEREO, and NOAA Space Weather Prediction Centre. This cross verification will not only lead to the detection methodology's robustness but also help in detecting thresholds calibration through ground-truth events.

6. The main aim of the International Space Weather Forecast Program is to develop a real-time solar wind monitoring system that can be eventually used for the Aditya-L1 data by creating a preliminary operational pipeline.

This goal reveals the translational impact of the work by being in line with both national and global initiatives that are directed at improving early-warning systems for geomagnetic storms and other space-weather disturbances.

Expected Outcomes

This Study is Expected to generate data which is scientifically reliable and useful for practical outcomes for detection characterization of halo CME events using SWIS time-series data.

I. **Identification of threshold(s) or derived parameter(s) from SWIS data time-series that are indicative of halo CME events.**

   The aim of this work is to establish the physically meaningful threshold and derived parameters from the SWIS time-series data that could indicate halo CME-driven disturbances at the L1 point. This work utilizes plasma parameters, which are proton density, bulk velocity, ion temperature, and particle flux. It carries out a comparative analysis between quiet solar wind intervals and intervals associated with confirmed halo CME events. Measuring in quantitative terms how these parameters deviate from their normal background levels during the passage of CMEs through sudden spikes, sustained enhancement, or through distinct profile patterns would help in establishing ranges for the numerical thresholds beyond which the likelihood of a halo CME becomes high.

II. **Improved understanding of transient solar wind signatures at L1 location.**

   This work contributes to an improved understanding of transient solar wind signatures at the L1 location by systematically characterizing variations in plasma and particle parameters associated with CME-driven disturbances. The analysis of these dynamically significant but short-lived features described in this work thus enhances our capability for distinguishing anomalous solar wind conditions from ambient backgrounds, strengthening the physical interpretation of CME–solar wind interactions as well as underpinning the development of reliable space-weather forecasting frameworks.

Dataset Required:

1. **SWIS Level-2 data (flux, number density, temperature, speed) from Aug 2024 onward, available at ISSDC**

   The study uses SWIS Level-2 scientific data products, which include ion flux, number density, temperature, and bulk solar wind speed, collected from August 2024 onwards and are obtained from the Indian Space Science Data Centre (ISSDC). The in-situ measurements are quality-controlled and fully calibrated, thus making them the primary dataset to characterize the solar wind conditions and identify the CME-driven disturbances.

2. **Halo CME event timestamps and properties from CACTUS CME database**.

The Halo CME event timestamps and physical properties are taken from the CACTUS CME catalogue. This provides automated, standardized detections of CME events derived from SOHO/LASCO coronagraph observations. These include onset time, angular width, central position angle, and apparent speed. These halo CME records are used as reference labels for event verification, temporal alignment with in-situ solar wind observations, and supervised model training and validation.

Suggested Tools/Technologies:

Development of the automated Halo CME detection system is based on a modern, efficient, and reliable technology stack. Each component, from the backend processing right to frontend visualization, was carefully chosen in order to guarantee high performance, scalability, stability, and ease of integration. This chapter explains in detail the technology stack used throughout the system, giving reasons why each one fits best in this project. The chosen technology stack covers scientific computing requirements, large-scale data processing, and visualization with interactive user access toward a complete space-weather analysis solution.

Programming Language and Core Libraries:

Python is the principal programming language used in this system because of the vast scientific computing ecosystem that has been built around it, flexibility, and robust support for data processing. Python can handle array manipulation and all sorts of large datasets along with time-series structures quite effectively, making it suitable for solar wind data. Its readability and easiness for development promote Python in research-oriented projects, one example of which is CME detection.

Several libraries form the backbone of the data processing pipeline. These libraries allow the system to handle the complexity and volume of Aditya-L1 particle data in an efficient and structured manner.

These Libraries Are:

- **NumPy for numerical computations**
- **Pandas for DataFrame-based data manipulation**
- **SciPy for signal processing and statistical operations**
- **SpacePy / cdflib for reading CDF (Common Data Format) files used**
- **SWIS-ASPEX(Aditya Solar Wind Particle Experiment)**
- **Matplotlib for visualization of solar wind parameters and event plots**
- **Requests for retrieving CACTUS CME catalogue data**

Backend Framework

The system backend will be implemented with FastAPI, a fast, modern Python framework. The reason for using FastAPI is because:

- It offers high performance, close to Node or Go
- It supports asynchronous processing
- It has automatic API documentation via OpenAPI
- It integrates smoothly with Python data models
- It is ideal for lightweight scientific APIs.

The backend handles tasks such as:

- Serving detected events
- Triggering data processing jobs
- Providing access to visual plots
- Managing metadata

FastAPI performs under high loads of information without leading the system to lag.

Data Processing and Worker Execution

Heavy computation tasks are executed by standalone Python worker scripts, residing in the backend scripts directory. Worker responsibilities include:

- Loading data
- Preprocessing
- Feature extraction
- Detection and scoring
- Generating visualization images

This separation ensures that the backend API remains lightweight and responsive while the worker handles computationally intensive tasks.

Worker tasks can be executed using scheduling or manual triggers. This makes the processing pipeline flexible, capable of handling various requirements from real-time to batch-processing.

Frontend Framework

The UI is developed in React - a modern JavaScript library, which is used for developing interactive web interfaces. React provides:

- Component-based architecture
- Fast rendering by using virtual DOM
- Flexibility in building dashboards

The frontend dashboard displays:

- Event Summaries
- Time-series plots
- Detection scores

Data visualization

It provides smoothness, responsiveness, and friendliness to the dashboard using React.Storage and File Management

Outputs of each processing, such as JSON summaries, detection results, image plots, and score graphs are organized under a structured directory. The storage layer includes:

- A results directory for CME detection outputs
- A data directory for SWIS and CACTUS input datasets
- A logs directory for debugging and monitoring

This file-based storage approach provides a reliable solution in research systems, where datasets are stored locally and repeatedly analyzed.

The system may, if required in the future, integrate with:

AWS S3

Azure Blob Storage

Google Cloud Storage

Due to the modular design of the storage module.

Configuration and Environment Management

The project handles the threshold values, data paths, time windows, and settings of the detection through YAML configuration files. This will enable researchers to change model parameters without having to delve into the code. Virtual environment support in Python ensures that dependencies remain isolated and reproducible.

Visualization Tools

The main visualization library will be Matplotlib because it's the best choice for scientific plotting and is capable of producing high-quality, publication-grade graphs. It allows:

- Multi-panel comparison plots
- Anomaly region highlighting
- Saving high-resolution images for dashboards

Further visualization enhancements could be added in the future using libraries such as Plotly or Seaborn.

Justification of the Technology Stack

The selected technology stack offers robust scientific computing, rapid API speed, and a state-of-the-art UI. Other benefits of using this technology are:

- Stability: Python + scientific libraries are used throughout the space science community
- Scalability: React and FastAPI can scale to serve multiple users.
- Flexibility: Modular design makes it easy to replace or enhance components.
- Performance - Python workers do heavy computations API remains responsive
- Portability: It can run locally, on servers, or cloud platforms.

The technology stack is well-matched to the computational and scientific requirements of Halo CME detection.

Software Requirements –

- Programming Languages – Python
- Libraries: ISRO SPDF CDF Libraries
- Data Analysis & Processing – Pandas, NumPy, SciPy
- Visualization – Matplotlib, Plotly
- Signal Processing – SciPy, NumPy

- Machine Learning – scikit-learn, Random forest

Expected Solution / Steps to be followed to achieve the objectives:

1. **Identify halo CME timestamps using CACTUS CME database –**

   Systematic identification of Halo CME timestamps is performed using the CACTUS CME database: this provides automated detections of coronal mass ejections based on coronagraph observations. The first appearance time, angular width, and kinematic properties are listed in this database for each CME, allowing for proper temporal tagging of halo events. These timestamps then provide the reference markers, allowing the correlation of remote-sensing CME observations with in-situ solar wind measurements and the construction of labeled datasets for subsequent analysis and model development.

2. **Extract corresponding SWIS Level-2 data for identified CME windows-**

   The halo CME timestamps were identified from the CACTUS CME database, following which the corresponding SWIS Level-2 data from the ASPEX payload onboard Aditya-L1 were extracted. This extraction was done over CME time windows carefully defined for each event to span the pre-event phase, the main impact, and the recovery phase.

   The parameters extracted included:

   - Ion flux
   - Plasma number density
   - Ion temperature
   - Solar wind bulk speed

   These parameters were then synchronized with the CME arrival times at the L1 point to ensure accurate temporal alignment. This dataset was used to study transient variations in solar wind properties caused by the propagation of halo CMEs and their space weather impact.

3. **Analyse flux, density, temperature, and speed parameters during these windows.**

Quantitative temporal and statistical analysis was carried out on the SWIS Level-2 measurements of ion flux, plasma number density, ion temperature, and solar wind bulk speed for each of the CME impact windows. This was to identify enhancements driven by CMEs, compressions, heating signatures, and velocity disturbances in the upstream solar wind, so as to comprehensively characterize the plasma dynamics throughout the pre-impact, sheath, and magnetic cloud phases.

4. **Derive new time-series features (e.g., moving averages, gradients, combined metrics).**

From raw time-resolved ion flux, plasma number density, ion temperature, and solar wind bulk speed measurements, a detailed set of derived time-series features was created. These included multiscale moving averages, temporal derivatives, variance measures, normalized ratios, and composite plasma indices. The derived features were chosen to accentuate dynamic transitions, shock-associated discontinuities, and sustained CME-driven enhancements in the solar wind.

5. **Determine statistical thresholds on derived parameters that signal CME presence**

Statistical thresholds were determined on the derived time-series parameters (e.g., moving averages, gradients, and composite indices) to flag intervals whose values deviate significantly from background solar wind conditions, thereby indicating the likely presence of CME-related disturbances.

For each derived parameter, the background solar wind distribution was characterized using historical non-CME intervals. From these distributions, statistical thresholds were computed. Time samples for which the derived features exceeded these thresholds were tagged as ‘anomalous’ and treated as potential CME candidates. These candidate intervals were then cross-validated against known CME event lists to refine the threshold levels and to optimize the trade-off between false positives and missed event

6. **Validate thresholds against confirmed CME occurrences for accuracy and robustness.**

The derived time-series parameters, including moving averages, gradients, and composite indices, were subjected to statistical thresholds so that intervals could be flagged whose values deviate significantly from background solar wind conditions, thereby pointing to the likely presence of CME-related disturbances.

The background solar wind distribution for each derived parameter was characterized using historical non-CME intervals. From these distributions, statistical thresholds were computed. Time samples for which the derived features exceeded these thresholds were tagged as ‘anomalous’ and treated as potential CME candidates. Candidate intervals were then cross-validated against the known CME event lists to refine threshold levels and optimize the trade-off between false positives and missed events.

Evaluation Parameters:

1. **Correct identification of key signature patterns belonging to CME events.**
   This measures the ability of the detection framework to accurately recognize the characteristic solar-wind and plasma signatures that uniquely accompany the arrival and passage of a CME at the L1 location. Instead of using a sole dependency on individual parameter thresholds, this evaluation focuses on finding the multi-parameter physical pattern that defines a true CME-driven disturbance.

   The key CME signature patterns include:

1. Flux Enhancement: A sudden and significant rise in ion flux associated with the CME-driven shock front and compressed sheath region.
2. Density Compression: A steep increase of plasma number density, usually occurring at the front edge of the CME. This indicates shock arrival.
3. Temperature Increase: The ion temperatures are raised within the CME sheath due to shock heating and turbulence.
4. Bulk Speed Acceleration: The solar wind speed increases visibly when fast CME plasma overtakes the ambient slow wind.
5. Sustained Deviation: Prolonged parameters change during the magnetic cloud phase, comprising low temperature, smooth magnetic rotation, and reduced density.

2. Effectiveness of Derived Parameters and Thresholds in Distinguishing Transient Events

It evaluates the capability of derived time-series features and statistically defined thresholds to distinguish transient CME-driven disturbances from normal background solar wind variability and other non-CME solar wind fluctuations. Given that individual parameters may show some overlap in the characteristics of transient events such as CMEs, high-speed streams, and local compressions of the solar wind, this test focuses on the overall discriminatory performance provided by the combination of engineered features and thresholding strategy.

Effectiveness is examined by analysing:

1. The capability of the derived parameters-moving averages, temporal gradients, variance measures, and composite metrics-to accentuate the CME-specific signature while suppressing short-term noise and random fluctuations.
2. The ability of statistical thresholds to reliably distinguish disturbed solar wind conditions from quiet background intervals across multiple events and various regimes of the solar wind.
3. Temporal coherence and persistence of the threshold exceedances, which should be characteristic of true CME passages rather than spurious spikes.

   Performance is quantitatively evaluated by measuring:
   - True positive detection of transient CME events,
   - False alarm rate during non-CME periods,
   - Precision–recall balance, and
   - Event-wise detection consistency across different CME speeds and intensities.

3. Accuracy and reliability of detection methodology using time-series data.

This evaluation parameter quantifies the system's overall performance in terms of accuracy and operational reliability of the proposed CME detection methodology for continuous time-series solar wind data obtained from SWIS Level-2 measurements. It characterizes the system's capability to operate under consistent, correct detection of CME-driven transient disturbances across different background conditions in the solar wind for a wide range of event scenarios.

Accuracy is assessed regarding how well the system can perform in:-

4. Classify CME and non-CME intervals correctly,

5. Achieve high TPR for the confirmed CME events, and
6. Maintain strong precision to ensure that the detected events are physically meaningful and not dominated by false alarms.

Reliability can be gauged from:-

7. The stability of detection performance across different CME speeds, intensities, and solar wind regimes.
8. The consistency of threshold exceedances and feature behaviour across repeated events
9. Robustness of the system against instrumental noise, short-term fluctuations, and data gaps.
10. The capability of keeping the rates of false alarms and missed detections low on long-duration time-series datasets.

Performance is quantitatively validated using standard classification metrics, including:

- Accuracy
- Precision
- Recall (Sensitivity),
- F1-score
- False Alarm Rate FAR

Thus, the correctness and consistency of the detection framework are comprehensively reviewed.

A high score regarding this evaluation parameter confirms that the proposed time-series-based detection methodology is both statistically robust and physically reliable, suitable for real-time space-weather monitoring, early CME warning systems, and long-term operational deployment.

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