CME Kinematics with Optical Flow: Multi-Coronagraph Insights into Internal Velocity Dispersion

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Abstract

Coronal Mass Ejections (CMEs) are large-scale eruptions of magnetized plasma that drive severe space weather disturbances. Understanding their kinematics in the middle corona is essential for linking CME initiation to interplanetary evolution. Traditional methods based on manually tracking features at selected position angles are subjective and often obscure velocity differences between CME components such as the core and leading edge. Here, we apply optical flow (OF) techniques to derive two-dimensional velocity fields of CMEs from coronagraph observations, capturing spatiotemporal intensity variations across the entire CME structure rather than isolated points. We implement OF on datasets from SOHO/LASCO C2, STEREO/COR1, **Solar Orbiter/METIS, and PROBA3/ASPIICS**, spanning a wide range of coronal heights and viewing geometries. Robust pre- and post-processing is employed to suppress instrumental noise and enhance CME–background contrast, particularly in the faint middle corona. Through case studies, we compare OF-derived velocities with traditional methods, identifying regimes where OF improves measurements and highlighting its limitations. A key result is the detection of internal velocity dispersion within CMEs, providing new insight into their expansion and deformation. Ultimately, this work aims toward an automated, objective CME detection and characterization pipeline based on OF velocity distributions, supporting continuous monitoring and improved space-weather forecasting.

Introduction

- Optical flow (OF) estimates motion by tracking how image intensity patterns shift between two consecutive images separated by a time interval Δt. The resulting two-dimensional vector field represents projected velocities of evolving coronal structures and provides a direct view of CME dynamics across the entire field of view. The method assumes that intensity remains approximately constant as structures move:

$$f(s+\Delta t w, t+\Delta t) \approx f(s,t)$$

- Linearizing this condition yields the Optical Flow Constraint Equation (OFCE),

$$\nabla f \cdot w + f t \approx 0,$$

- where ∇f and f_t are the spatial and temporal intensity gradients. Solving this equation produces dense velocity maps, enabling us to capture internal CME expansion, deformation, and velocity dispersion—beyond what feature tracking can provide.

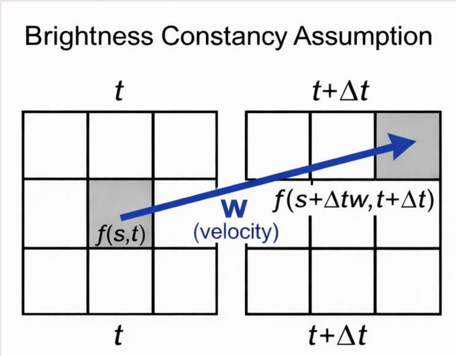


Figure: Optical Flow Illustration

Orthodox Methods for CME Kinematics

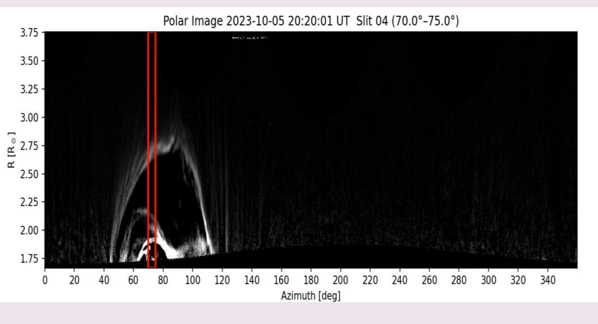


Figure: *Polar transformed image of a CME observed through METIS visible light channel. Red box denotes a slit placed at some position angle.*

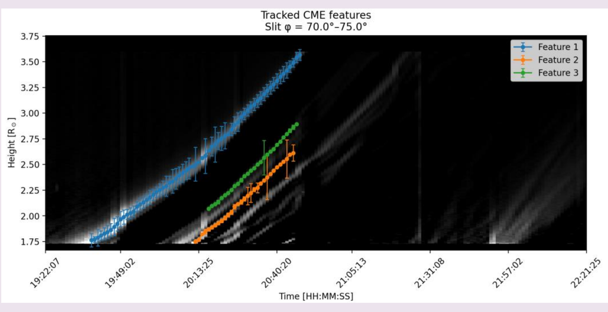


Figure: *Tracked CME features from Height-Time map using our* ***semi-automated tracking technique****.*

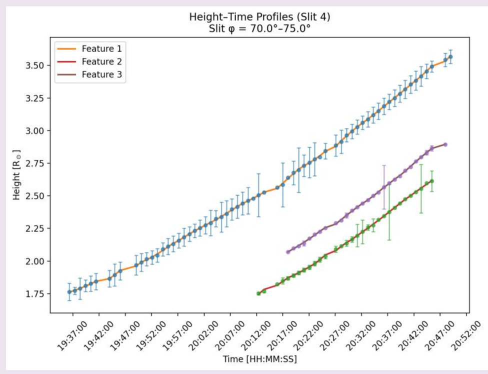
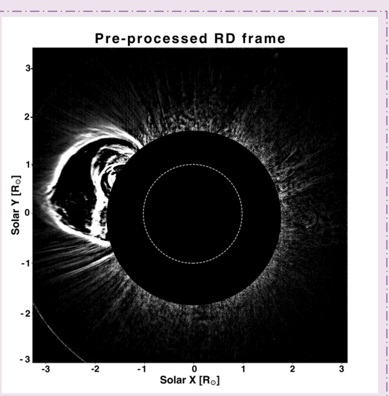


Figure: *Plotting and fitting the height-time profile.*

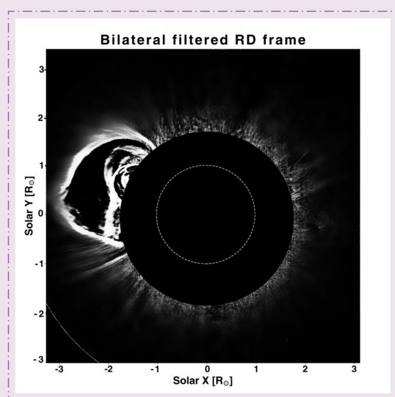
- Methods like the one shown above are not only time taking but also lead to subjectivity in measurements. Moreover, they are limited to measuring the velocity at only limited position angles and CME features.

Methodology

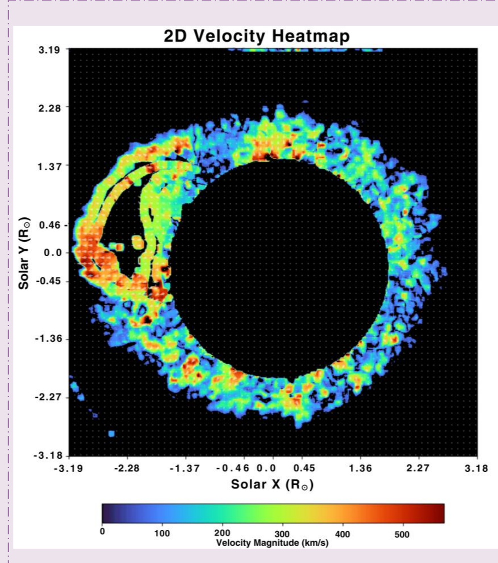
Pre-processing: Background removal and running difference → **Post-processing:** Removing noise while preserving edges → **Generating Optical Flow velocity field:** Using Gunnar-Farneback method (Dense OF) → **Overplotting OF vectors on the CME image:** Color coded velocity vectors



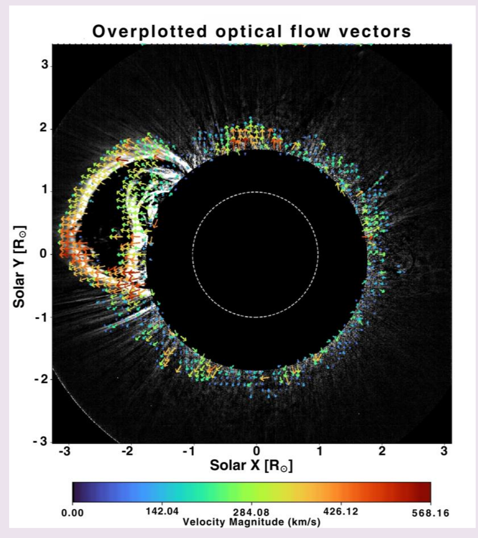
- Running difference image of a CME observed from METIS's visible light channel onboard Solar Orbiter.



- The running difference images consists of noise which will introduce errors in measuring the optical flow field between two consecutive frames. Hence, we smooth the image without compromising on the dynamic sub-structures of the CME, i.e., preserve the edges while smoothening.

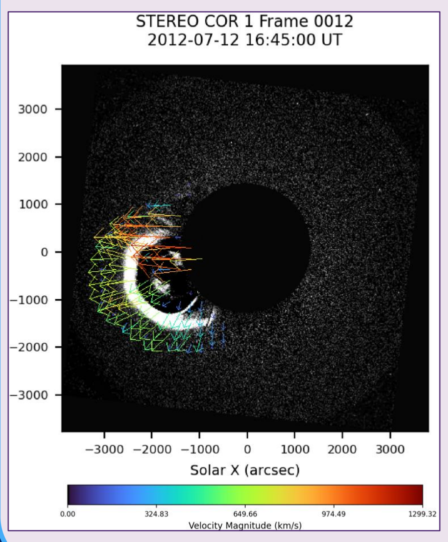


- Velocity heat map

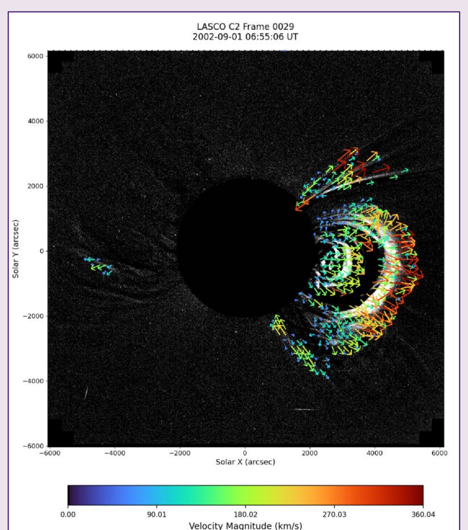


- Overplotted OF vectors on the METIS image.

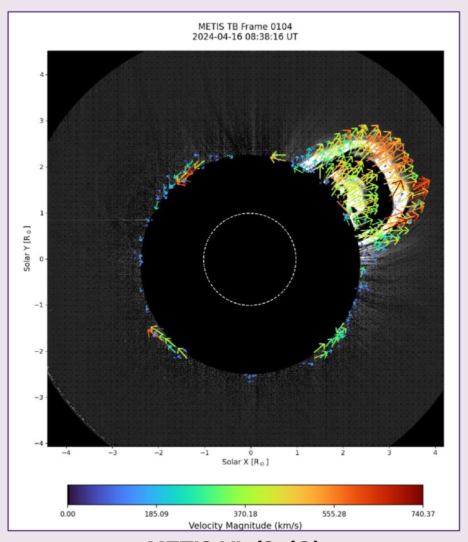
Optical Flow on Multi-Coronagraph Data



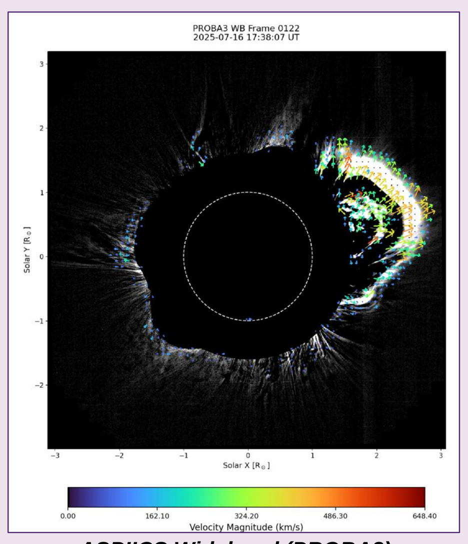
STEREO A COR 1



LASCO C2

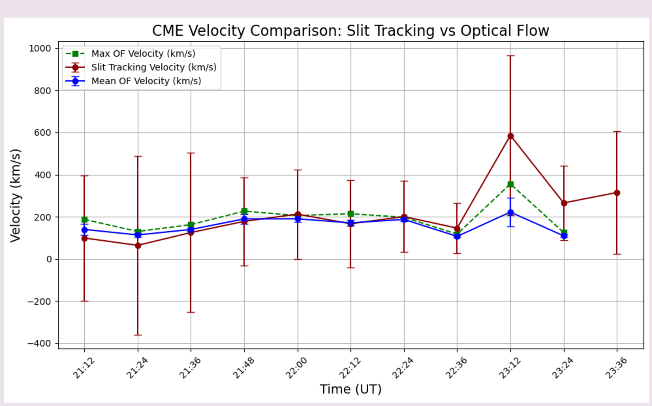


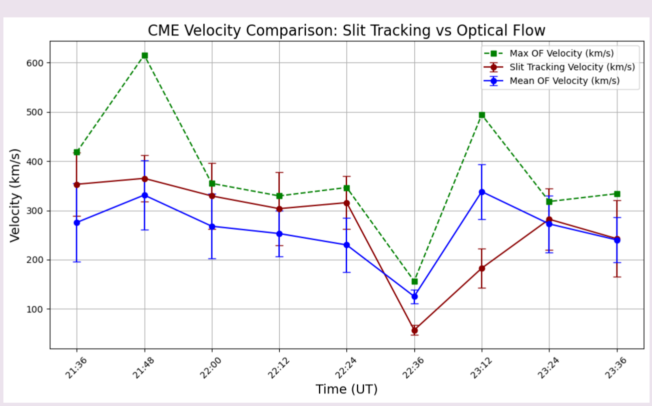
METIS VL (SolO)



ASPIICS Wideband (PROBA3)

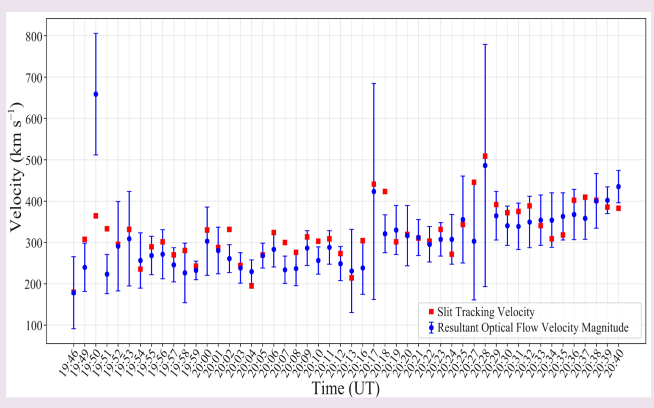
Validating the Optical Flow Method



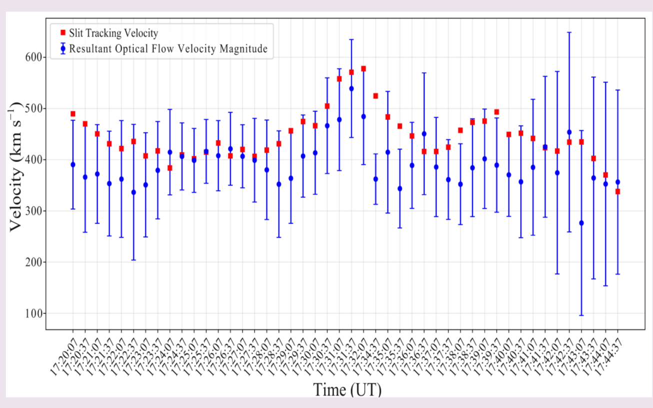


CMEs observed using the LASCO C2 instrument

Figure: *Comparing the velocity-time profile of the CME(s) leading edge between the Optical Flow method and XT-map tracking method (leading edge only)*



CME observed using the METIS (visible light instrument)

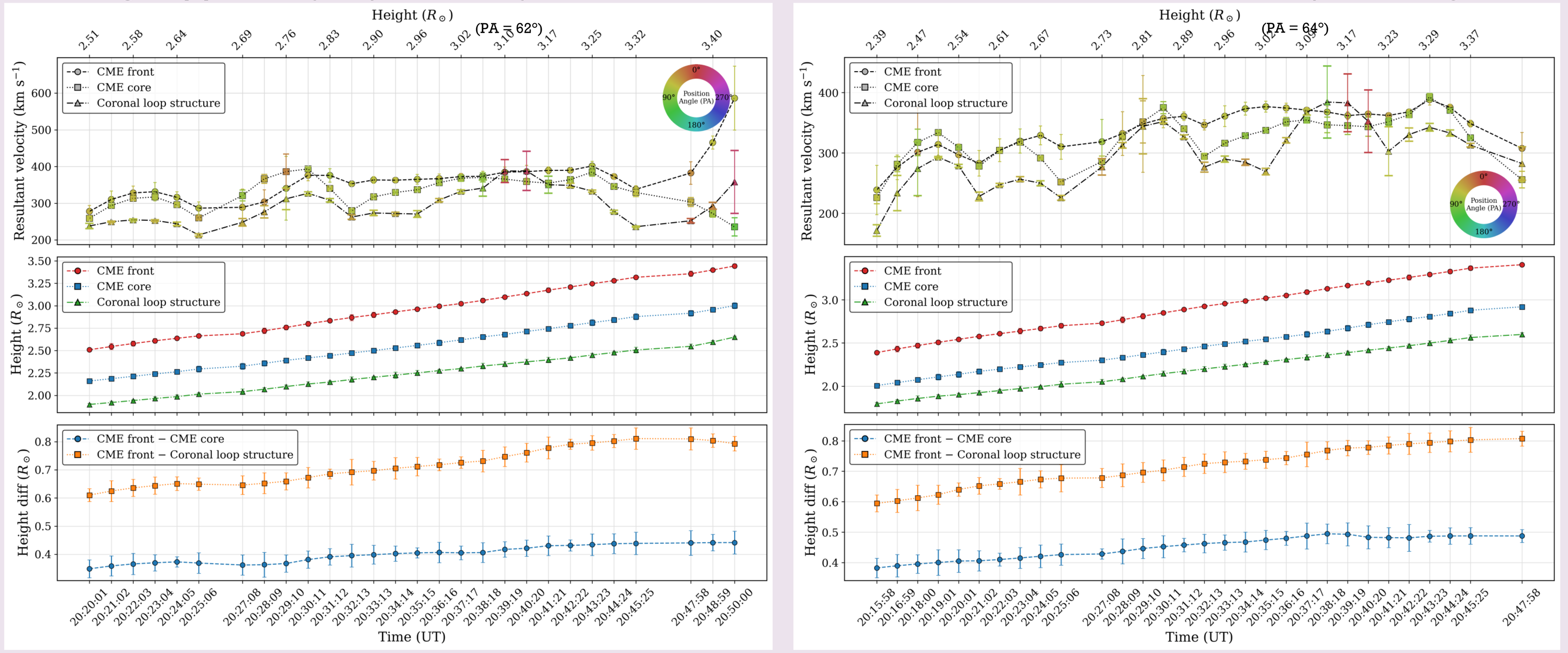


CME observed using the ASPIICS (Wideband Channel)

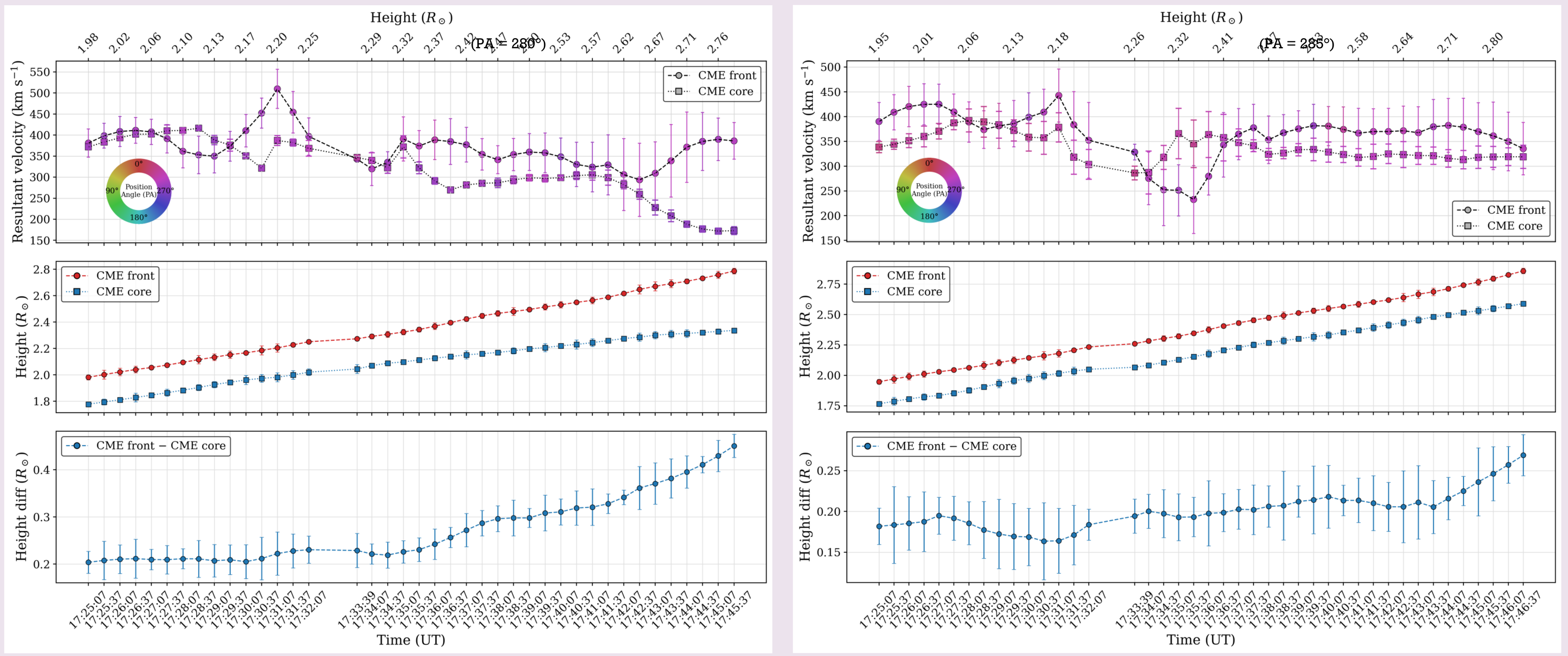
- The velocity-time profiles of the Optical Flow method matches quite well with the manual XT map tracking method. The **match is close** when the CME's calculated velocity is **not showing** any impulsive variation or when the velocity is too fast.
- However, any impulsive variation in the intensity (either because of noise or uncertainty in height-time measurements) leads to a mismatch (as expected).

CME Velocity Dispersion and Analysing the Velocity Field

Figure(s): *Velocity dispersion analysis between the CME front and other sub-structures at different position angles.*



A CME event observed on 2023 Oct 10 using ***METIS/SolO*** *with clearly visible front, core, and coronal loop substructure.*



A CME event observed on 2025 July 10 using ***ASPIICS/PROBA3*** *with clearly visible front and core.*

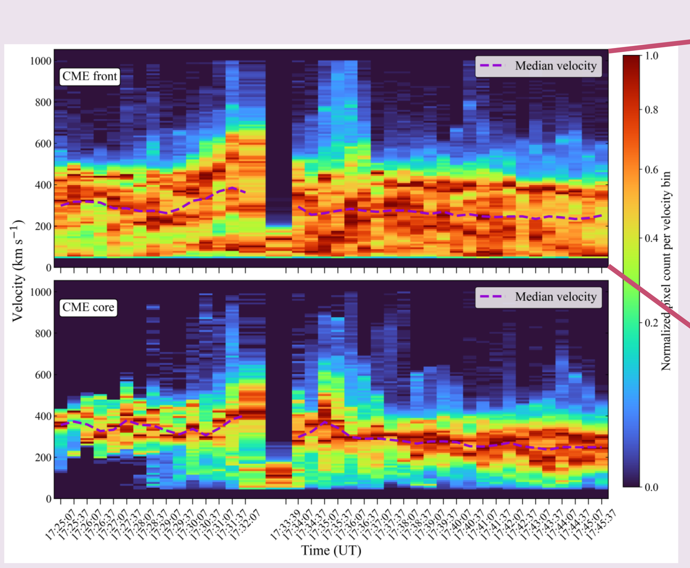


Figure: *Exploring the velocity dispersion inside the CME front and the core structure (left).*

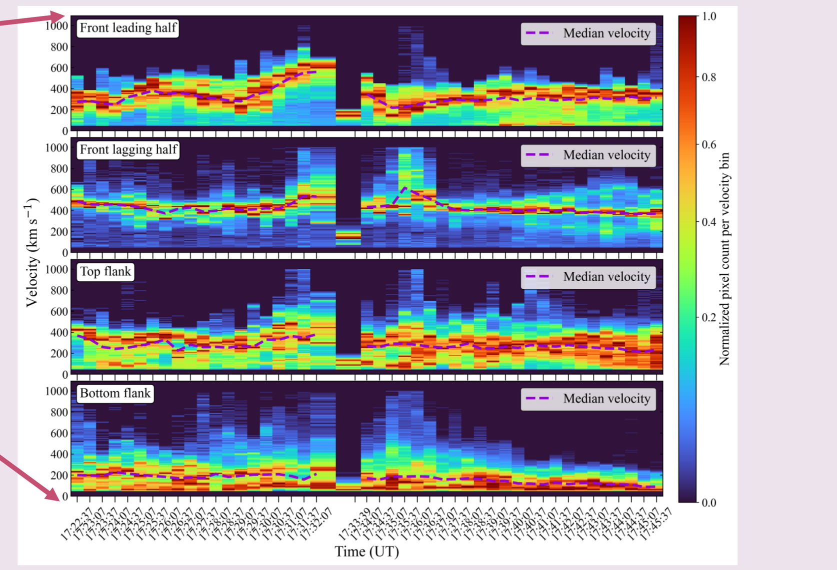


Figure: *Detailed analysis of dispersion inside the CME front sub-structures (right).*

Towards Automated CME detection

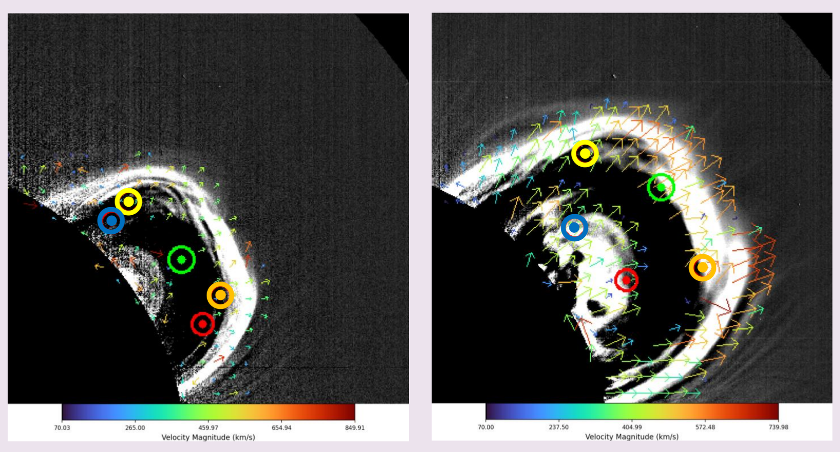


Figure: *A CME evolving with time. The green dot shows the auto-detected Center of motion and the other coloured dot shows the auto-detected expansion points. Earlier frame (left), later frame (right).*

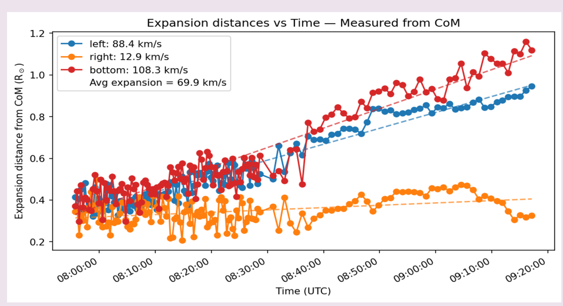


Figure: *CoM height-time profile fitted with a linear fit.*

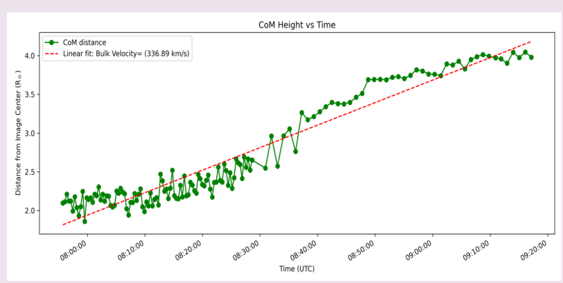
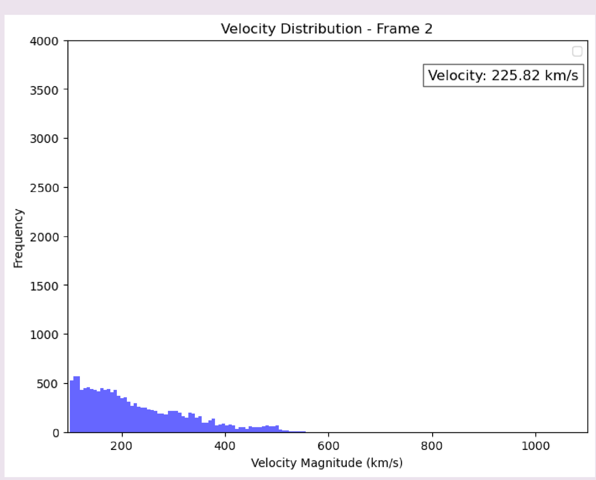
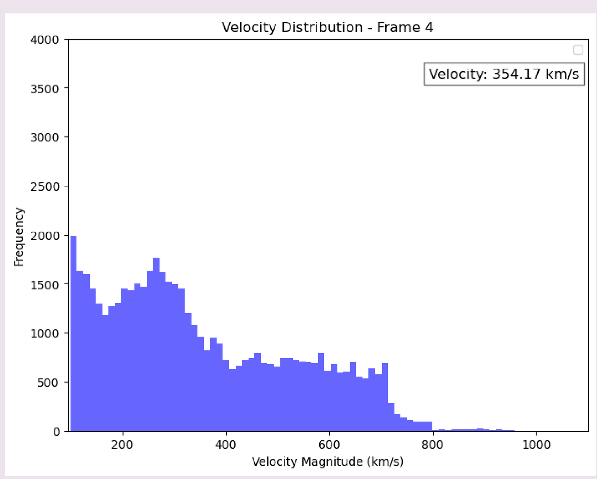


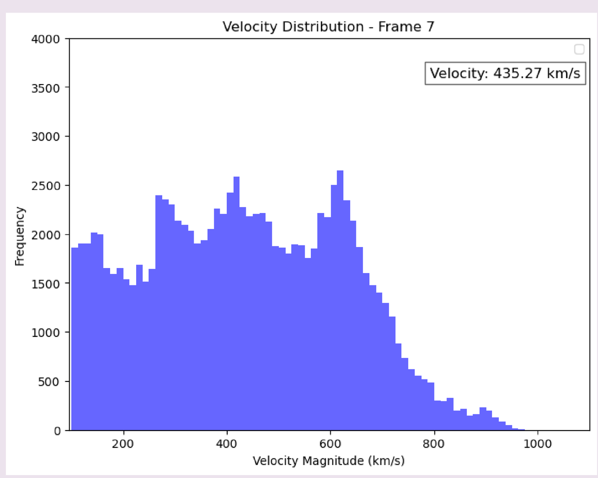
Figure: *Expansion (relative to CoM) height-time profile fitted with a linear fit.*



Velocity distribution of pre-CME frame *- solar winds and other features are present. No CME.*



Velocity distribution during CME frame *- there is a visible increase in incidence of higher velocities after the CME erupts*



Velocity distribution of the frame where the CME is last visible.

As the CME erupts, there is a notable increase in the incidence of higher velocities, as evident in the time evolution of the Histogram distribution. Based on this concept, we are training a ML model to detect CME, which is different from traditional image based detection algorithms.

Results and Summary

- Optical flow analysis reveals strong spatial and temporal variability in CME internal dynamics, with front and core showing non-self-similar, direction-dependent evolution.
- Height dispersion between CME substructures typically begins after impulsive acceleration, indicating internal restructuring in the middle corona.
- Significant intra-structural velocity differences confirm that CME fronts are kinematically heterogeneous.
- A future automated CME detection method is proposed using velocity distribution changes as a physics-based indicator.

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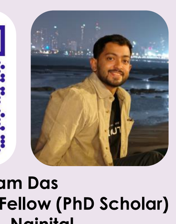

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