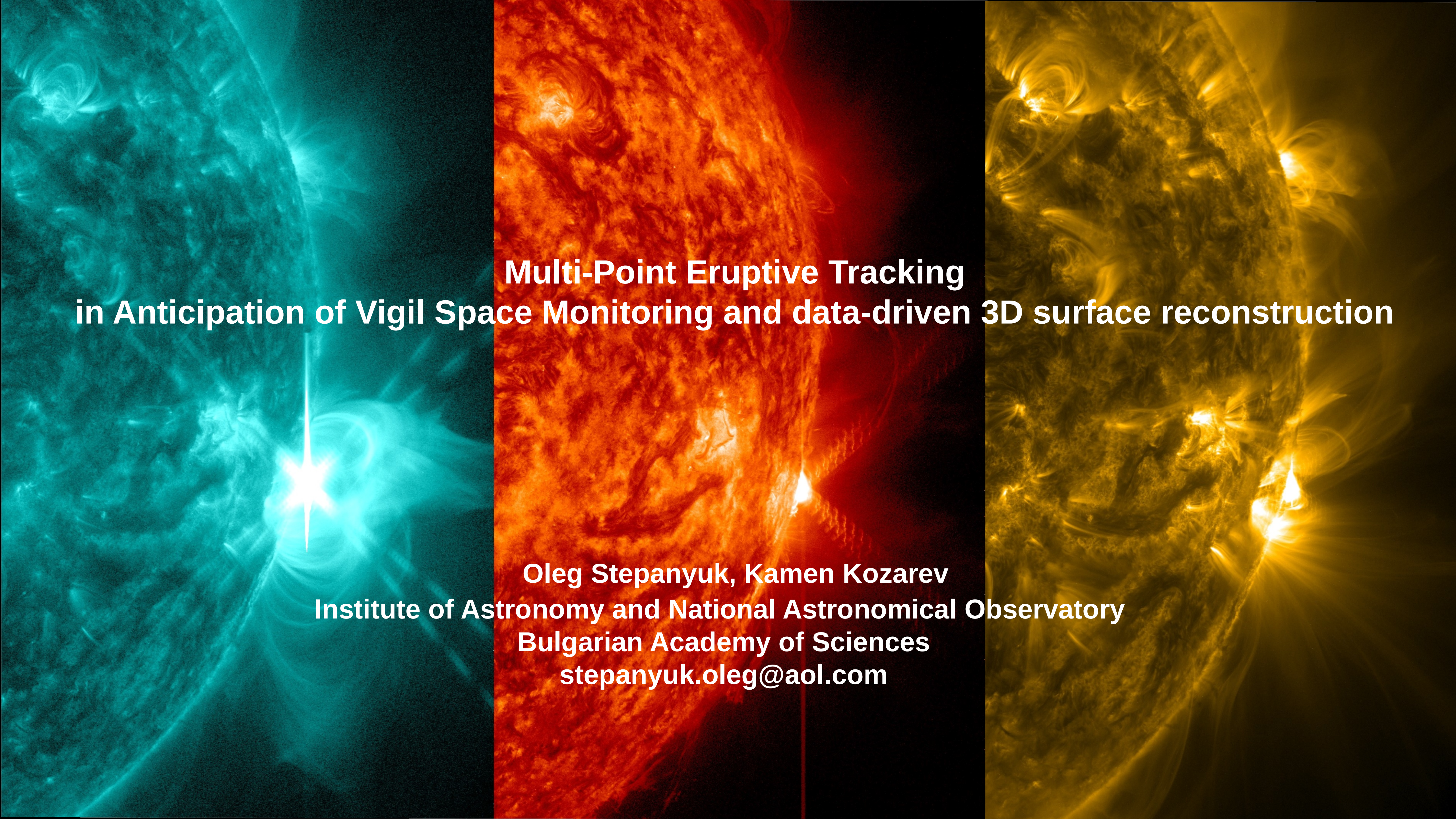

Multi-Point Eruptive Tracking in Anticipation of Vigil Space Monitoring and data-driven 3D surface reconstruction

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J. Space Weather Space Clim. 2022, **12**, 20
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Research Article — Open Access

Multi-scale image preprocessing and feature tracking for remote CME characterization

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J. Space Weather Space Clim. 2024, **14**, 2
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Topical Issue - CMEs, ICMEs, SEPs: Observational, Modelling, and Forecasting Advance

Research Article — Open Access

Multi-instrument observations and tracking of a coronal mass ejection front from low to middle corona

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INSTITUTE OF ASTRONOMY
NATIONAL ASTRONOMICAL OBSERVATORY

A&A, 684, L7 (2024)

Letter to the Editor

Tracking the motion of a shock along a channel in the low solar corona

J. Rigney[1,2,3], P. T. Gallagher[1], G. Ramsay[2], J. G. Doyle[2], D. M. Long[4,3], O. Stepanyuk[5] and K. Kozarev[5]

+

Received: 31 October 2023
Accepted: 21 March 2024

Abstract

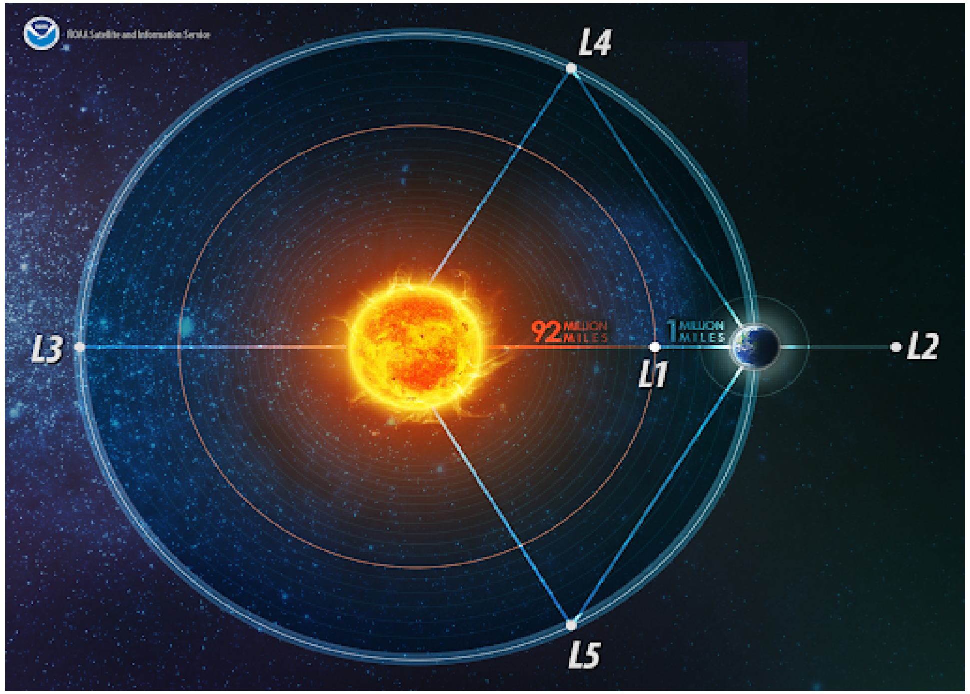
Context. Shock waves are excited by coronal mass ejections (CMEs) and large-scale extreme-ultraviolet (EUV) wave fronts and can result in low-frequency

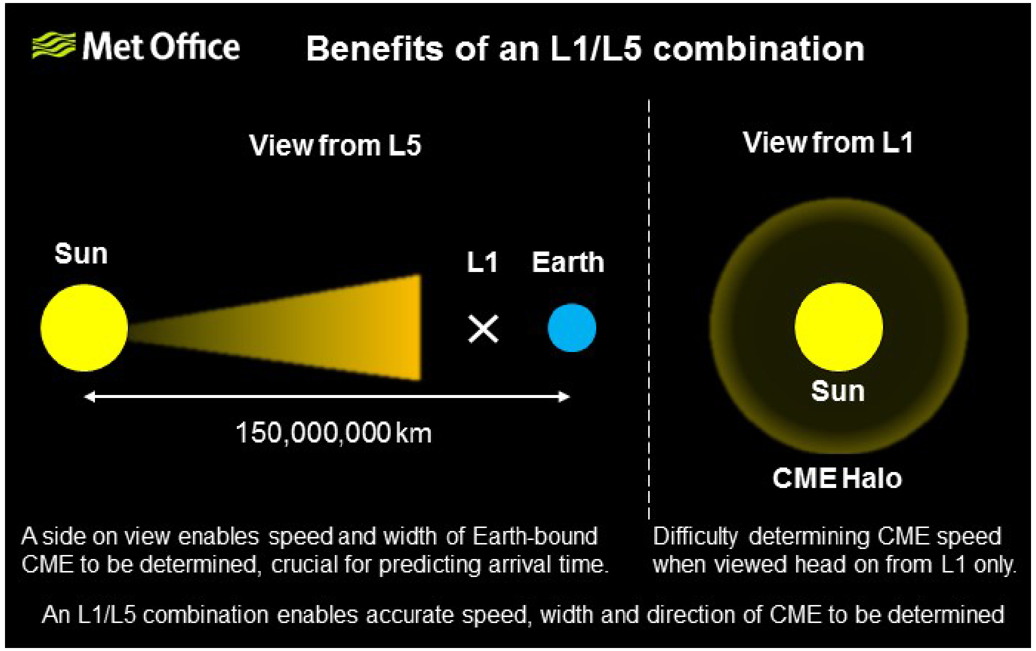
Motivation. What do we do

- Kamide [2001] and Akioka et al. [2002] -- the first to discuss an L 5 concept

- We apply our feature tracking methods to Compact Coronagraph (CCOR) data,

- In perspective: extend our approach to study events simultaneously observed from L1/Earth (by SDO and SOHO instruments) and near the L5 point (by STEREO-A and STEREO-B instruments), approximating the expected geometric configuration between Vigil and the Earth/L1.



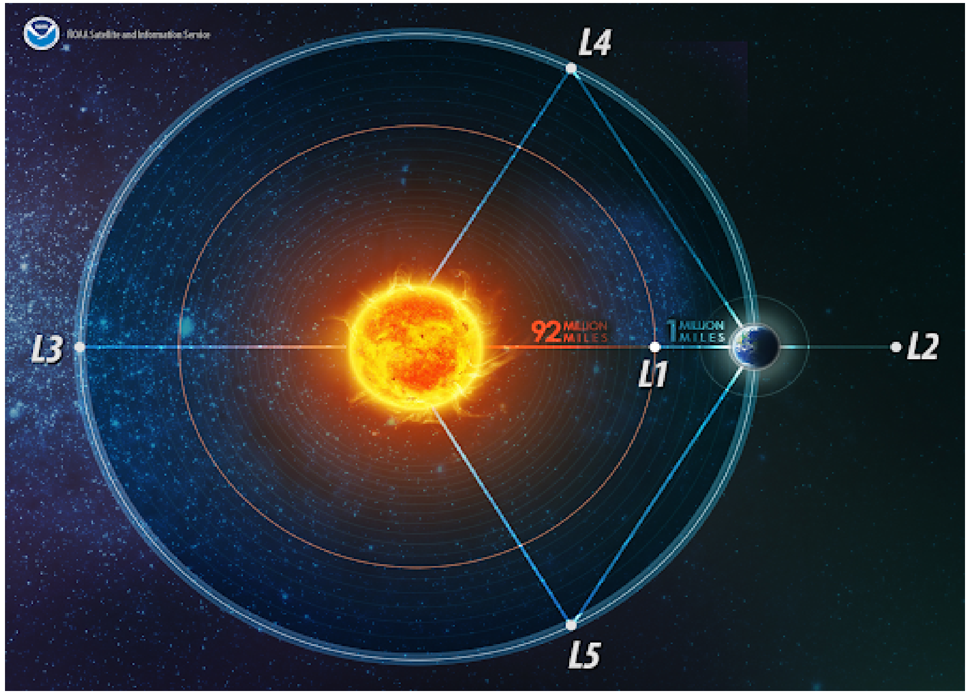


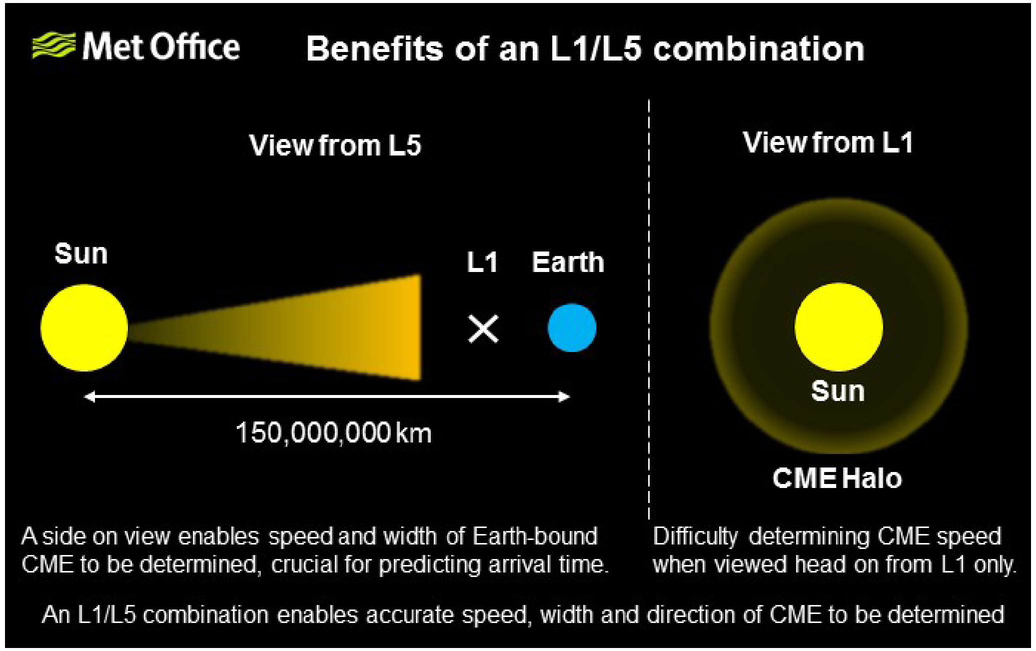
Motivation. What do we do

Develop data-driven tracking models for single-point CME observations in order to get CME projected structure over time, giving evolution in and off the equatorial plane

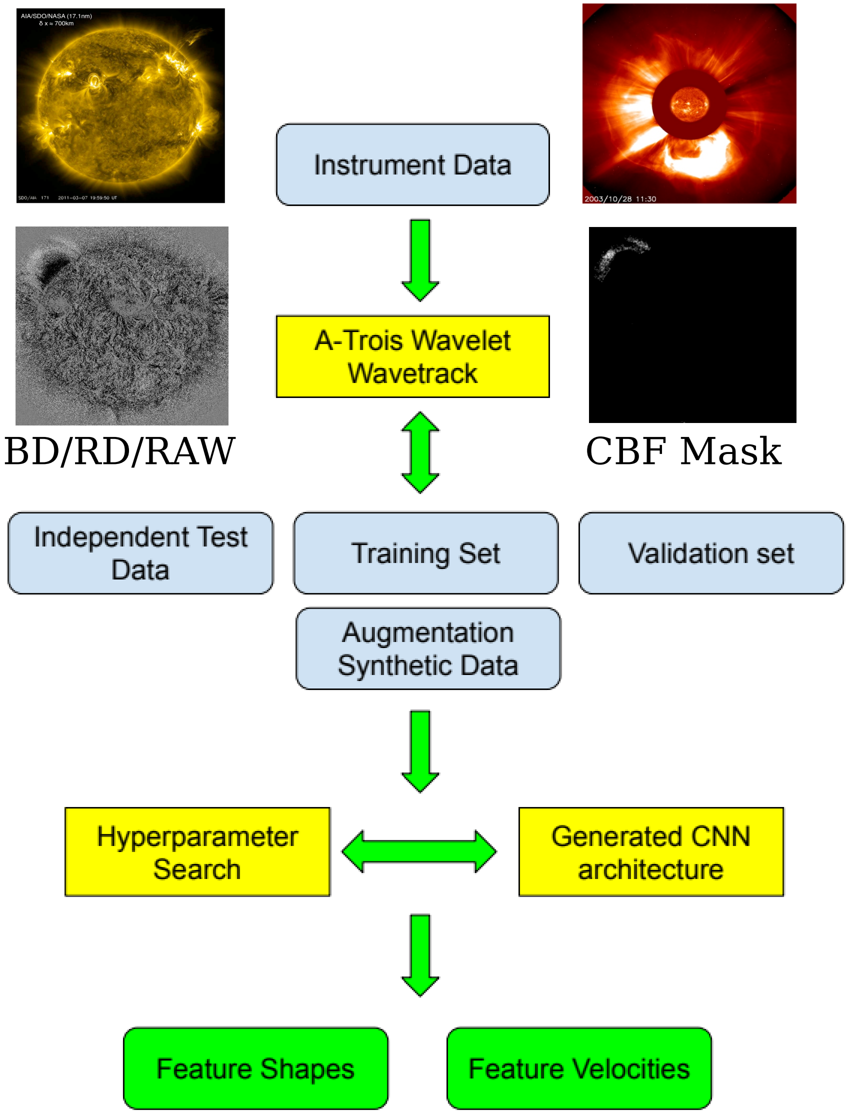
Multi-point tracking gives a better estimation of the 3D structure of CMEs and their fronts
1) Useful for studying CME evolution in the corona and heliosphere
2) Provides realistic conditions for modeling the diffusive shock acceleration of solar energetic particles.

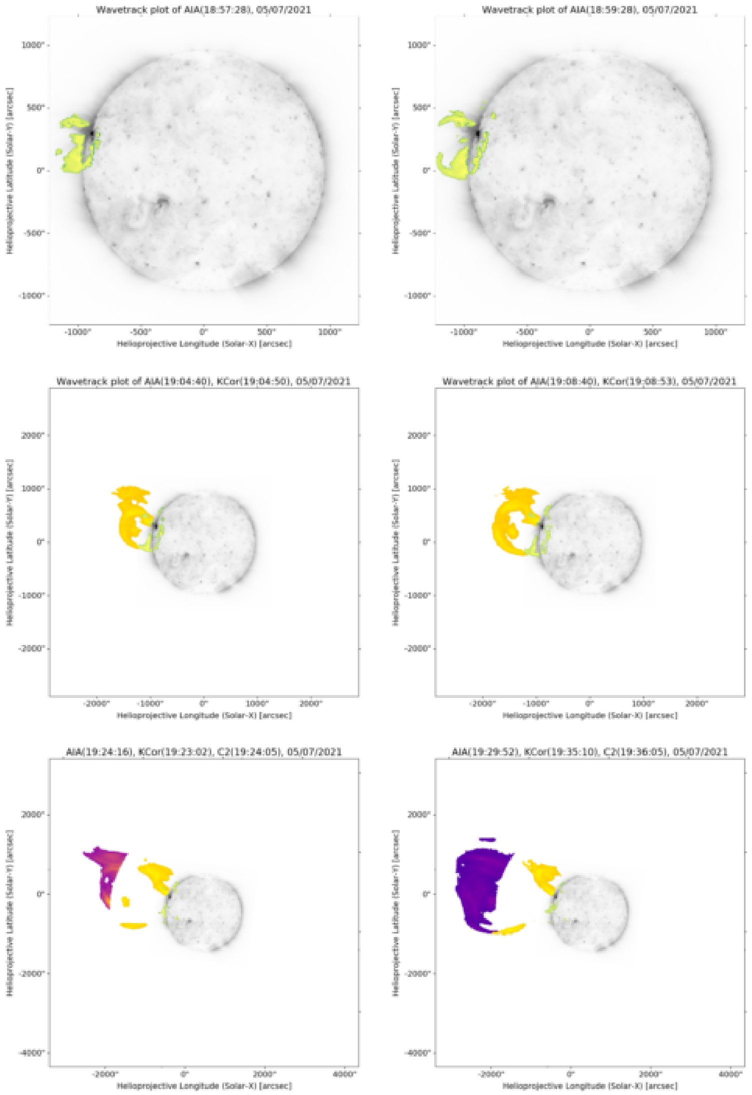
Currently, very simple analytic models (spheroid, ellipsoid, etc.) are used for shock front fitting. Our aim is to move away from analytic models and manual fitting.

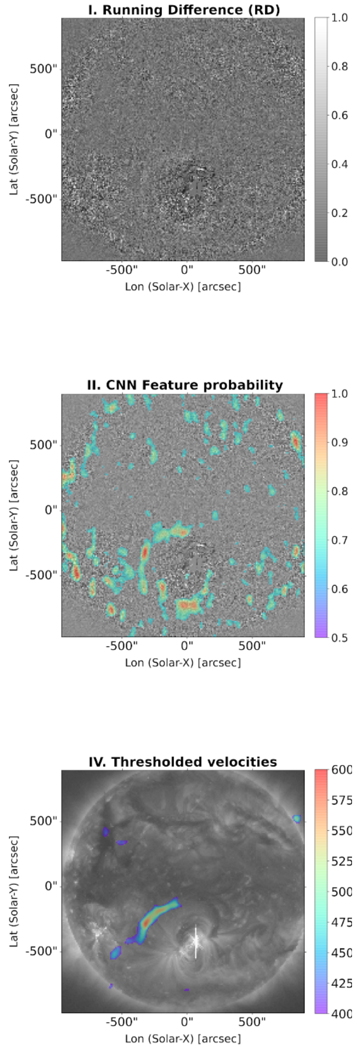




The Method: Hybrid algorithmic / data driven approach. Emphasis on the training data quality







Stepanyuk O., Kozarev K., J. SWSC (2024) | JGR (2025) Under Review

The Method: Hybrid algorithmic / data driven approach. Emphasis on the training data quality

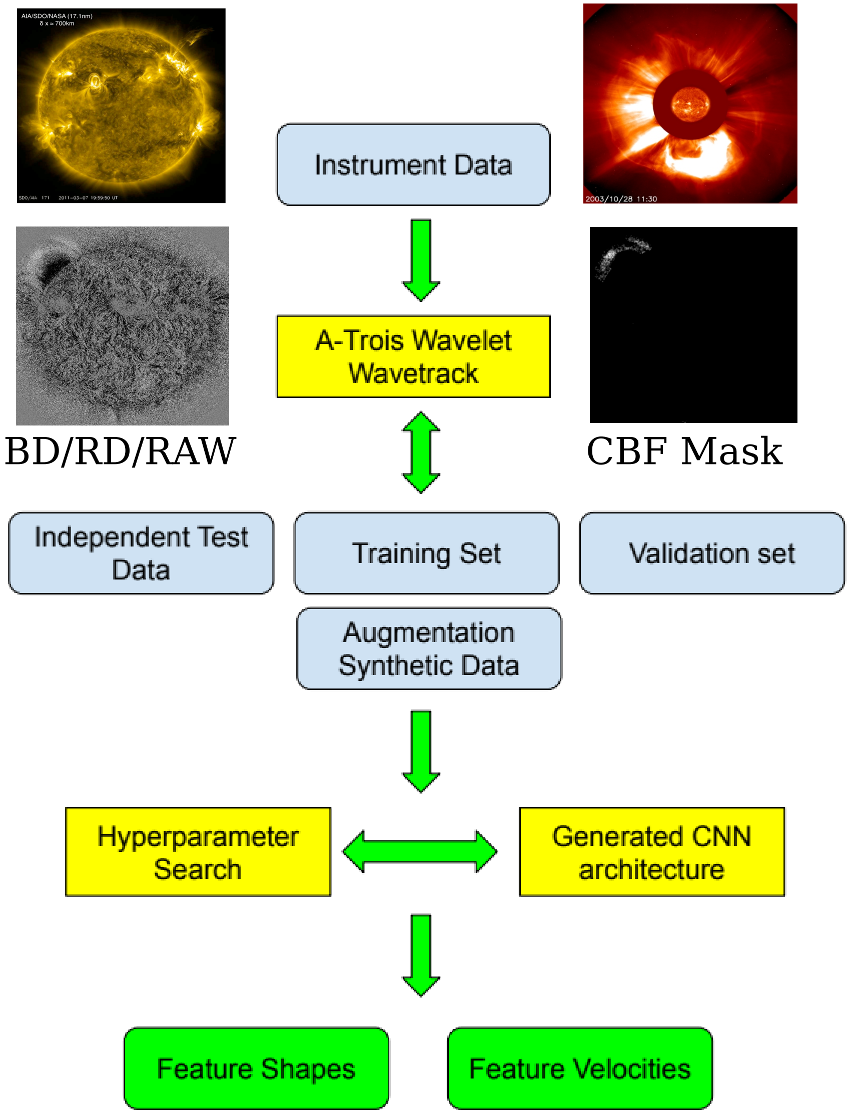


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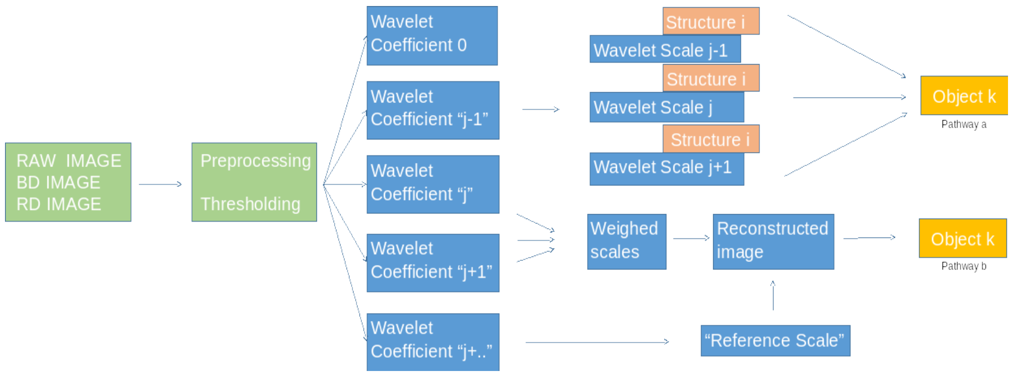
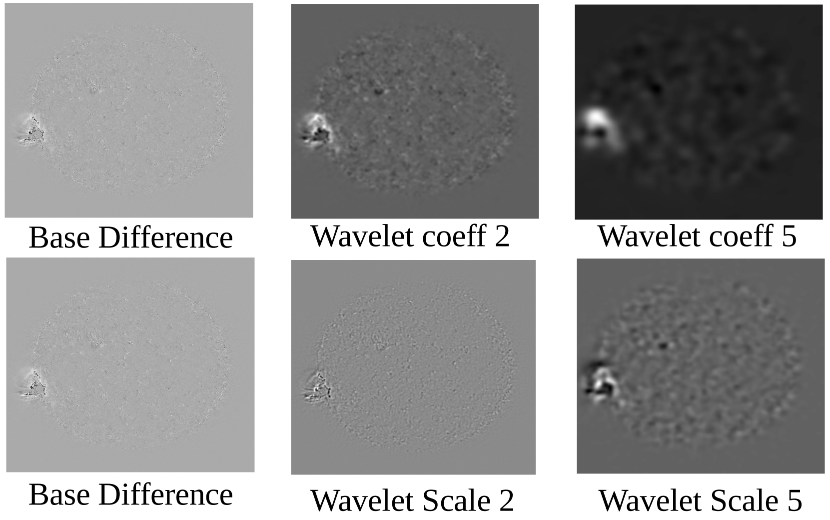
Image Processing stages with Wavetrack software



à trous wavelet decomposition



Object condition for a structure:

$$w_j^m > w_{j-1}^m \quad w_j^m > w_{j+1}^m$$

The Method: Hybrid algorithmic / data driven approach. Emphasis on the training data quality

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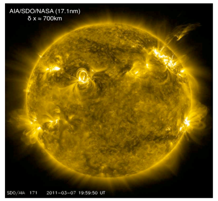
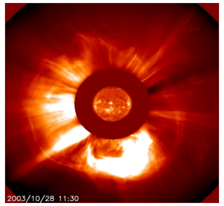
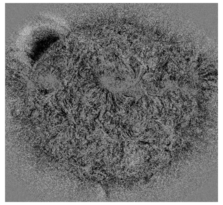


Instrument Data



A-Trois Wavelet Wavetrack



BD/RD/RAW

CBF Mask

Independent Test Data

Training Set

Validation set

Augmentation Synthetic Data

Hyperparameter Search

Generated CNN architecture

Feature Shapes

Feature Velocities

Basic Idea: Hilbert space decomposition as a subset of orthogonal subspaces (with corresponding scaling functions):

$$V_2 \subset V_1 \subset V_0 \subset V_{-1} \subset V_{-2} \subset \ldots, \bigcap_{m \in Z} V_m = \{0\}, \bigcup_{m \in Z} = L^2(R)$$

Image decomposition as:

$$I(x,y) = \sum_{i=1}^{n} O_i(x,y) + F(x,y) + B(x,y)$$

(Objects (O), background(F) and noize (B))

Structures by definition:

$$S_{j,k} = \{w_j[k_1,l_1], w_j[k_2,l_2], \ldots, w_j[k_p,l_p]\}$$

Objects by definition:

$$O_l = \{S_{j_1,k_1}, \ldots, S_{j_n,k_n}\}$$

Object condition for a structure:

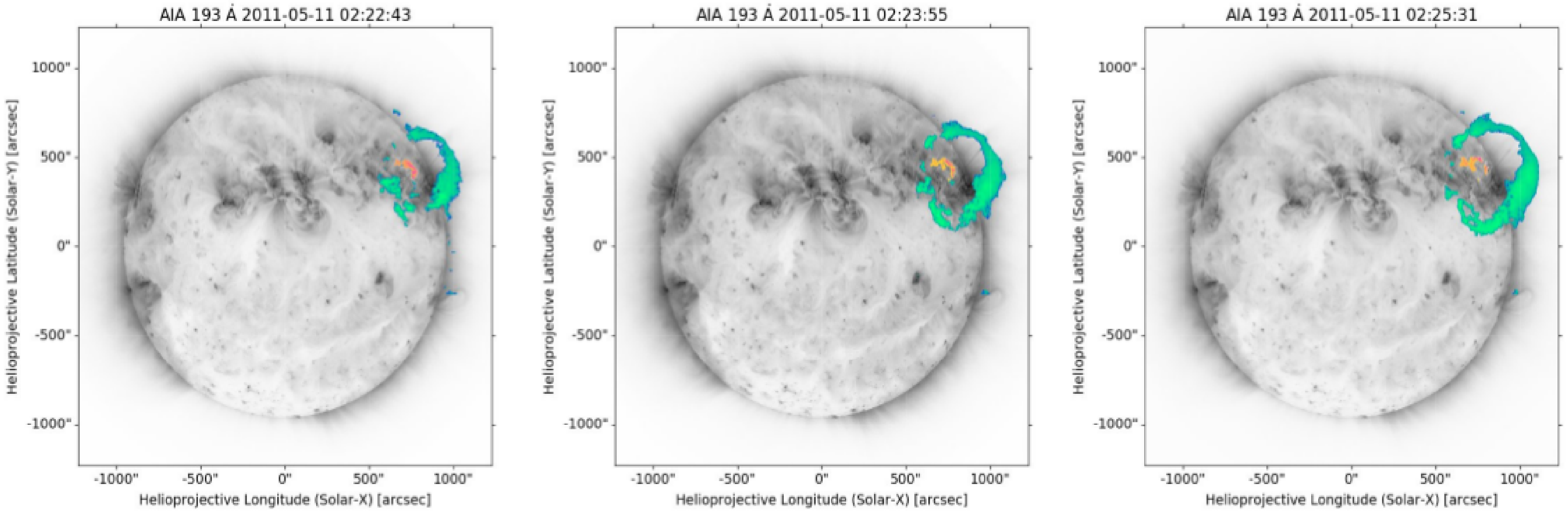
$$w_j^m > w_{j-1}^m \quad w_j^m > w_{j+1}^m$$

Where:

$$w_{j+1}^m = max\{w_{j+1,x_1,y_1}, \ldots, w_{j+1,x_n,y_n}\},$$
$$w_{j,x,y} \in S_{j,k}$$

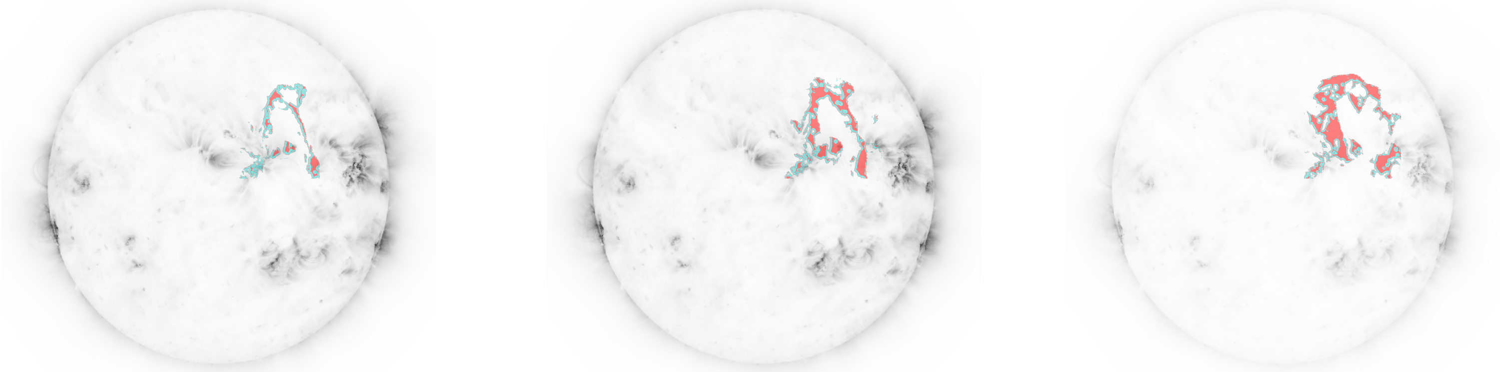
** See later. *JL. Starck, Handbook of Astronomical Data Analysis - 2002

Segmentation and Tracking. Filaments SDO (Training Metrics)



CBF and the filament: Combined tracking of the May 11, 2011 event

AIA193: 21:31:06 AIA193: 21:39:54 AIA193: 21:49:06



Gigantic filament: Tracking of the September 29, 2013 event

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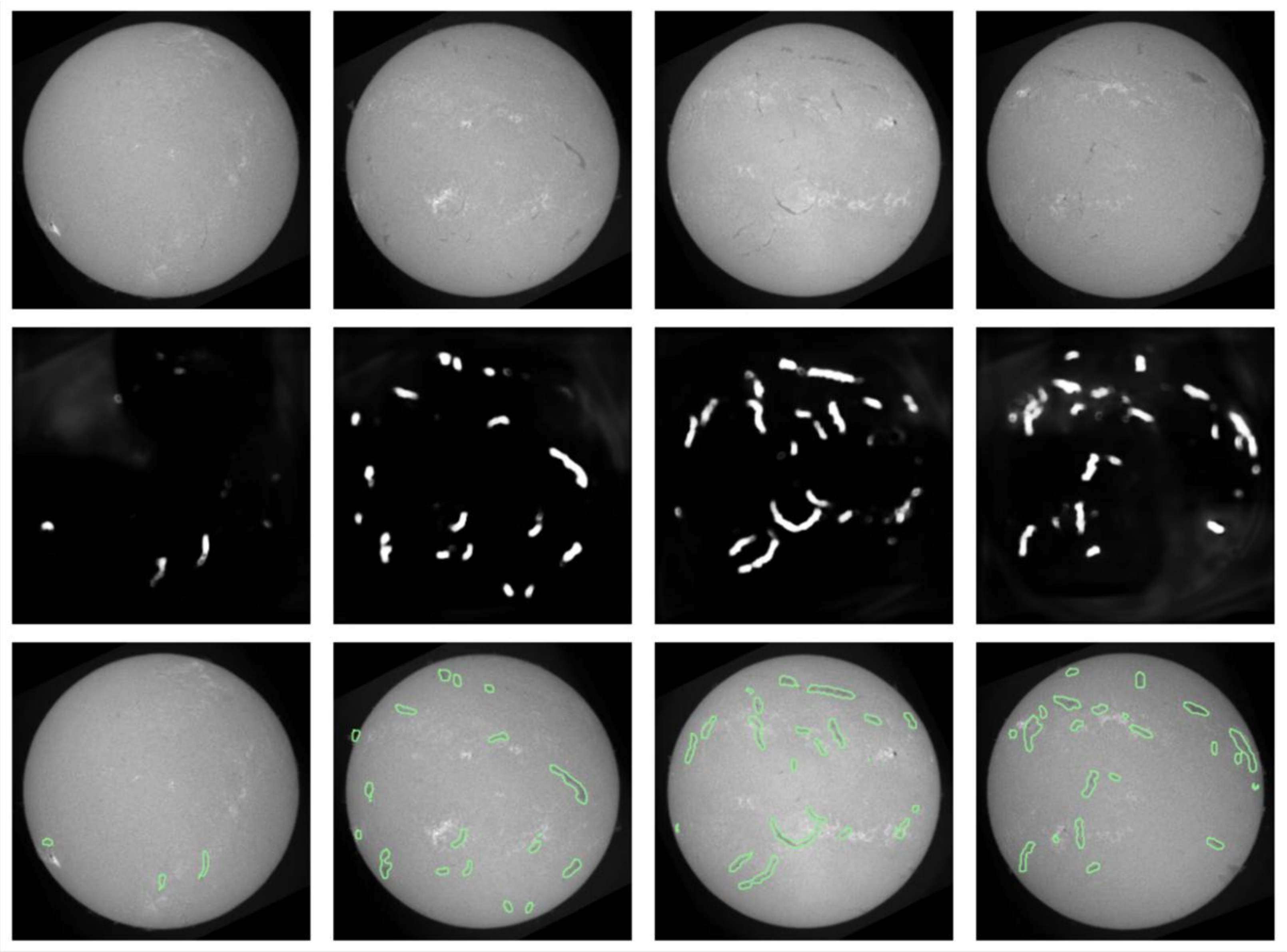
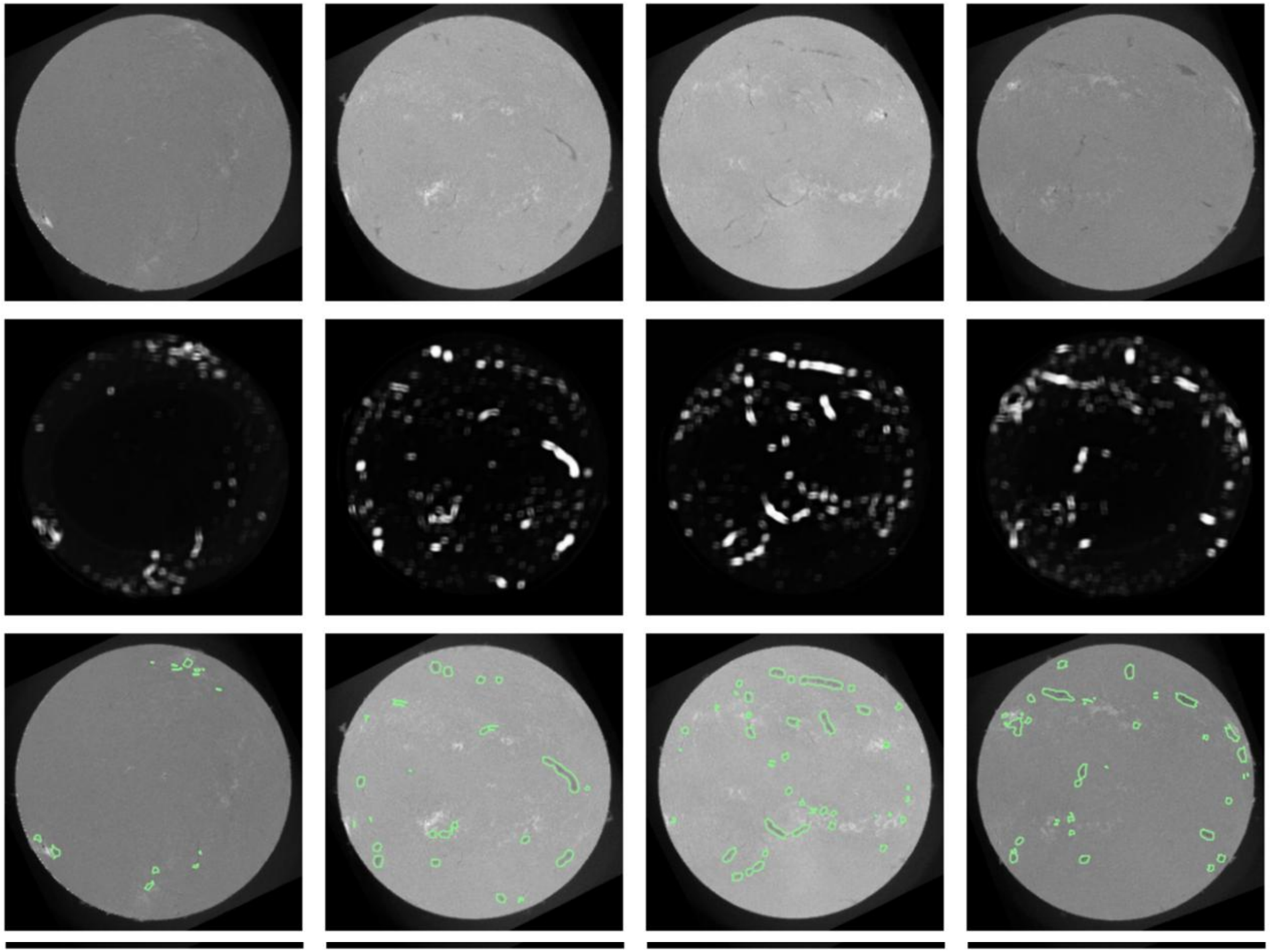
Segmentation and Tracking. Filaments. Kanzelhöhe Observatory Data (Synoptic)



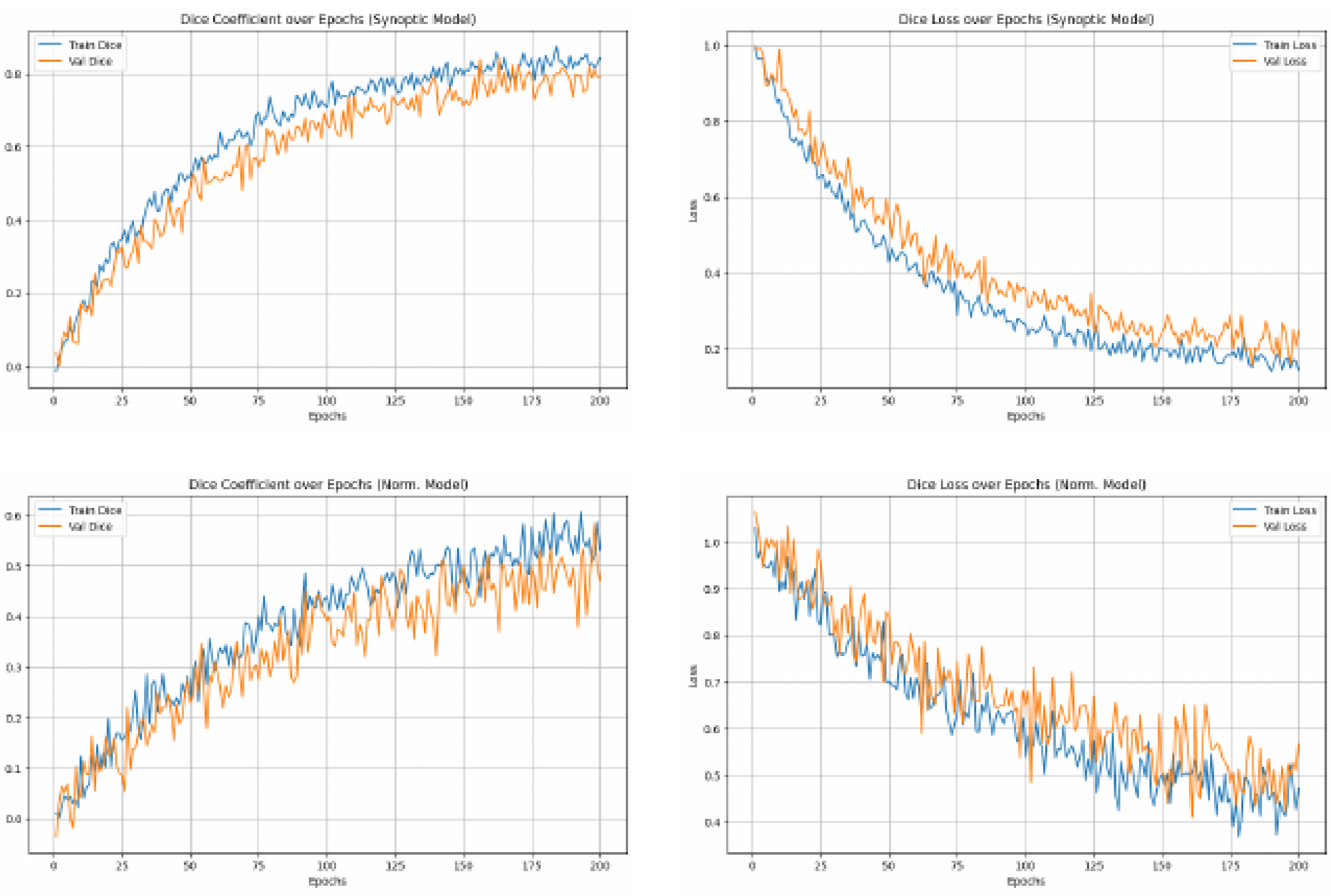
This research was funded by the Bulgarian National Science Foundation project No. KP-06-Austria/5 (14-08-2023) and Austria's Agency for Education and Internationalisation (OeAD) project No. BG 04/2023

Segmentation and Tracking. Filaments. Kanzelhöhe Observatory Data (Normalized)



This research was funded by the Bulgarian National Science Foundation project No. KP-06-Austria/5 (14-08-2023) and Austria’s Agency for Education and Internationalisation (OeAD) project No. BG 04/2023

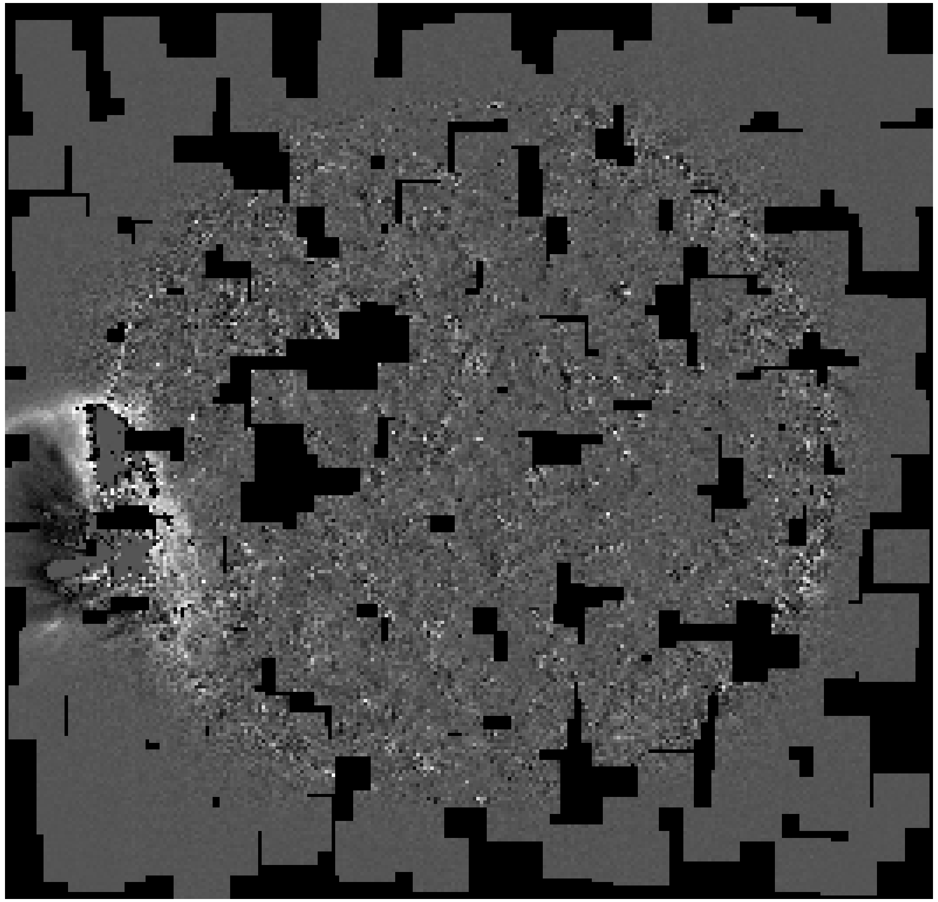
Segmentation and Tracking. Filaments. Kanzelhöhe Observatory Data (Training Metrics)



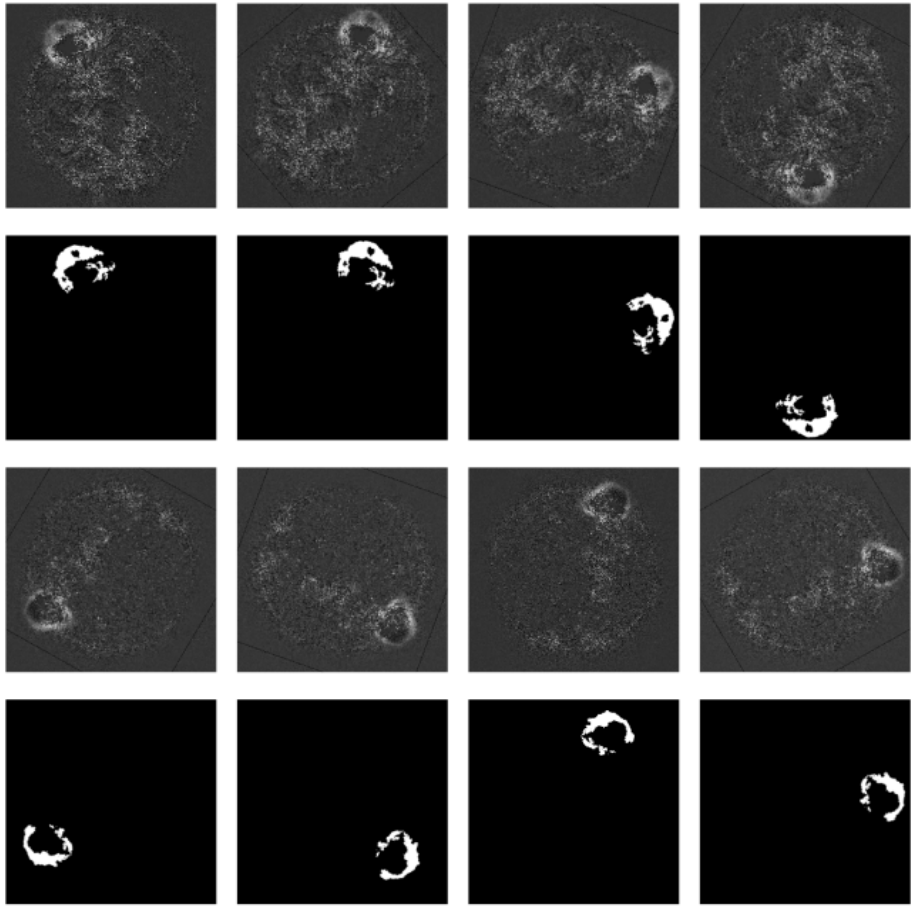
This research was funded by the Bulgarian National Science Foundation project No. KP-06-Austria/5 (14-08-2023) and Austria’s Agency for Education and Internationalisation (OeAD) project No. BG 04/2023

SDO AIA: Synthetic data and augmentation

Data Augmentation

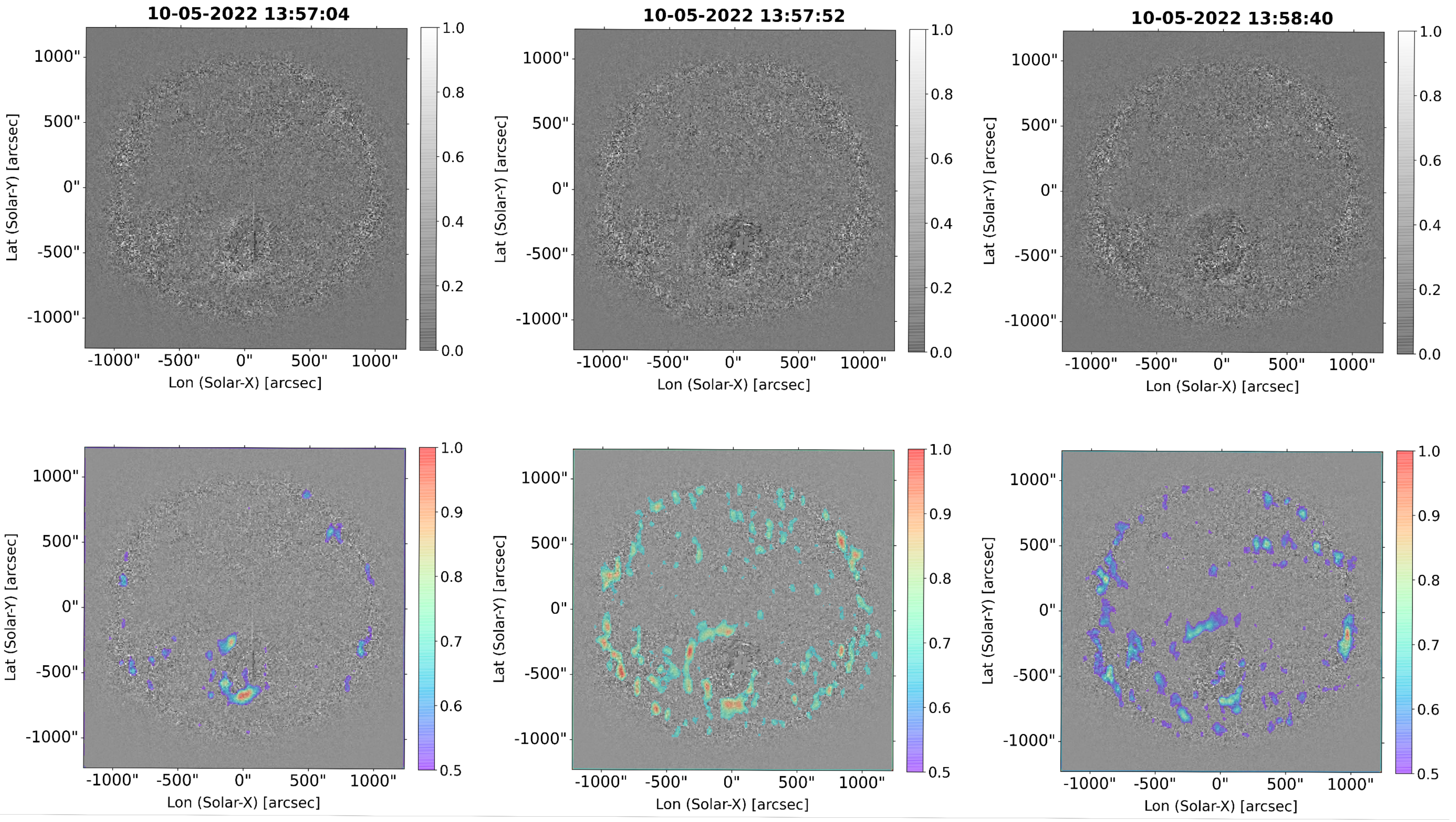


Patches



Geometrical / intensity

Case Study: An early Solar Cycle 25, X1.5-class event



1. O. Stepanyuk, K. Kozarev “Segmentation and Tracking of Eruptive Solar Phenomena with Convolutional Neural Networks”, ournal of Geophysical Research - Machine Learning and Computation. (Under Review)

2. J. Rigney, P. T. Gallagher, G. Ramsay, J. G. Doyle, D. M. Long, O. Stepanyuk and K. Kozarev. "Tracking the motion of a shock along a channel in the low solar corona", A&A, Letters to Editor, 684, L7 (2024)

Velocity field estimation. Space-time context

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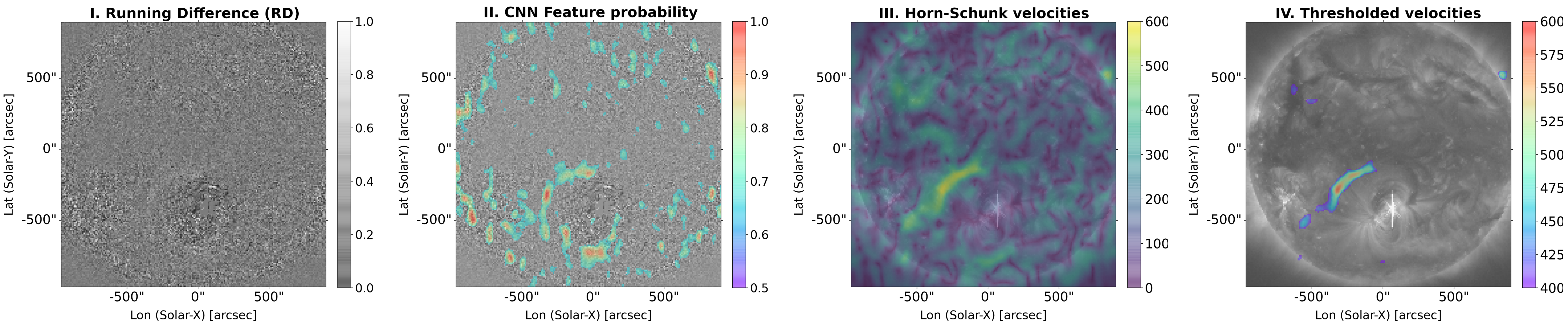

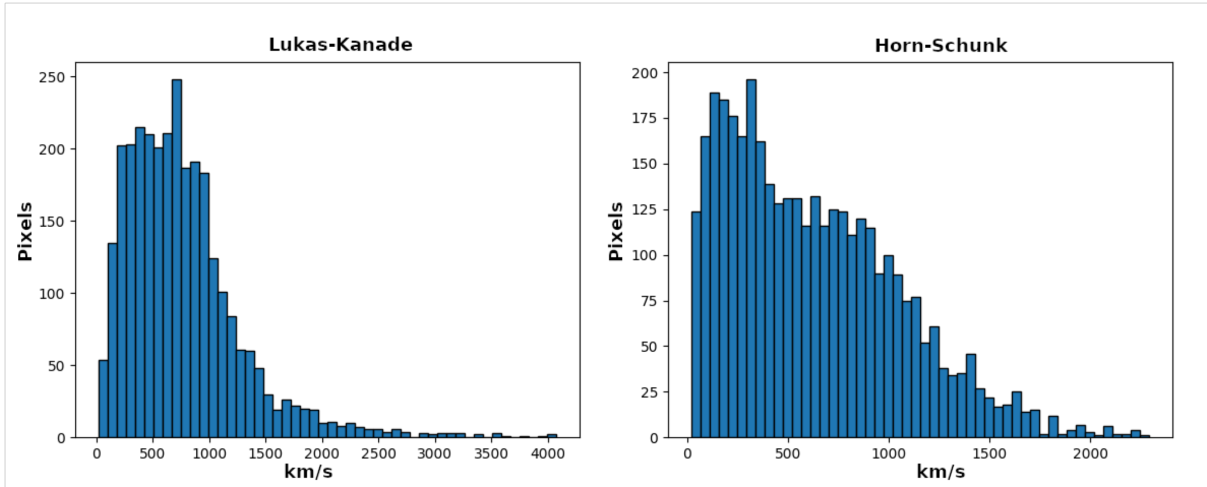

Image-by-image segmentation -> spatial aspects of image features, overlooking their temporal evolution. (Information not utilized)

Velocity field estimation to operate within a space-time context rather not being limited to purely spatial processing.

Velocity field estimation. Lukas-Kanade, Horn-Schunk methods

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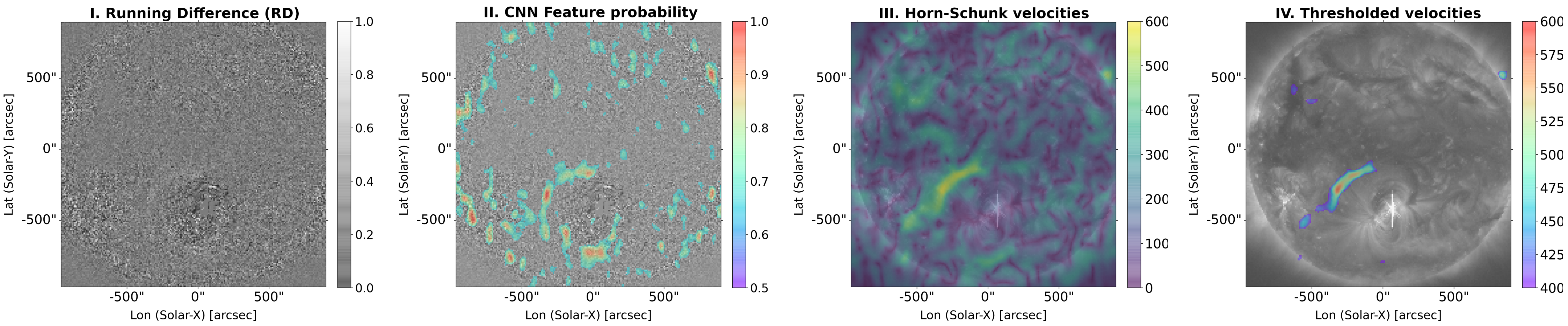
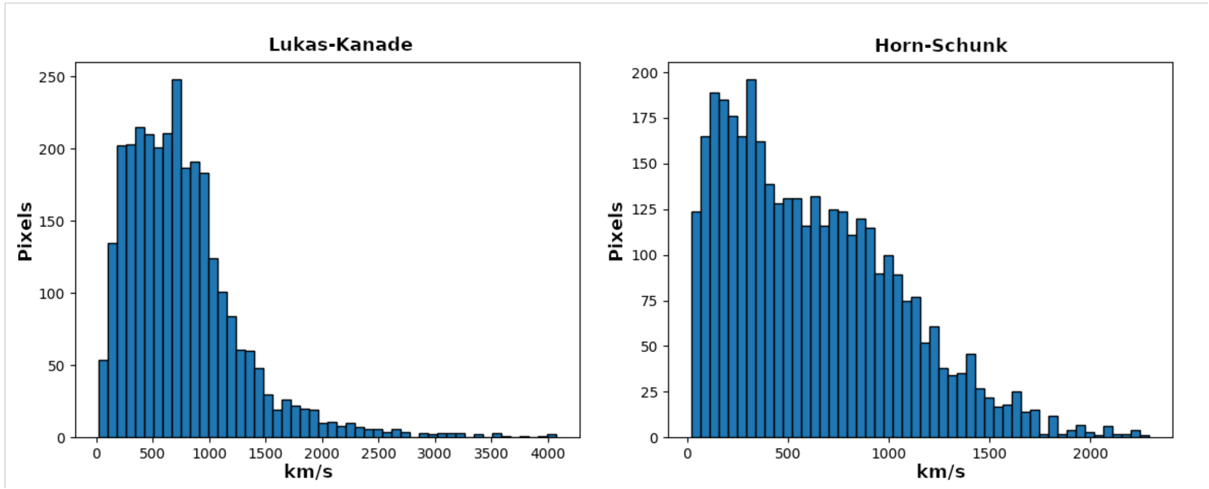
The Institute of Astronomy and National Astronomical Observatory, Bulgarian Academy of Sciences





Lucas-Kanade - differential, local-based. approximates motion by assuming constant flow in a small neighborhood, + least-squares approach over local patches.

Horn-Schunk is a global-based approach .Smooth optical flow field by integrating intensity variation constraints across the entire image + adding a regularization term that enforces flow smoothness and continuity.

Velocity field estimation. FLCT limitations, Sampling Cadence Problem

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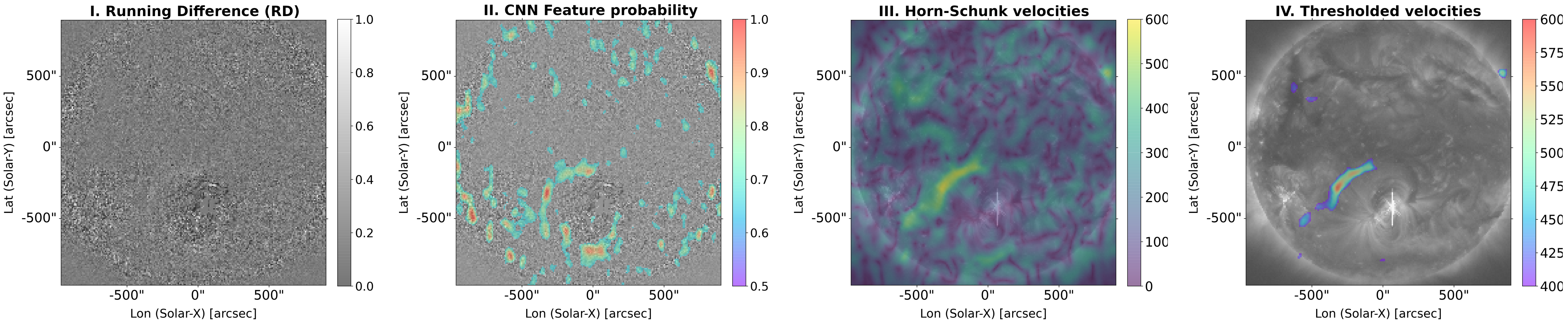
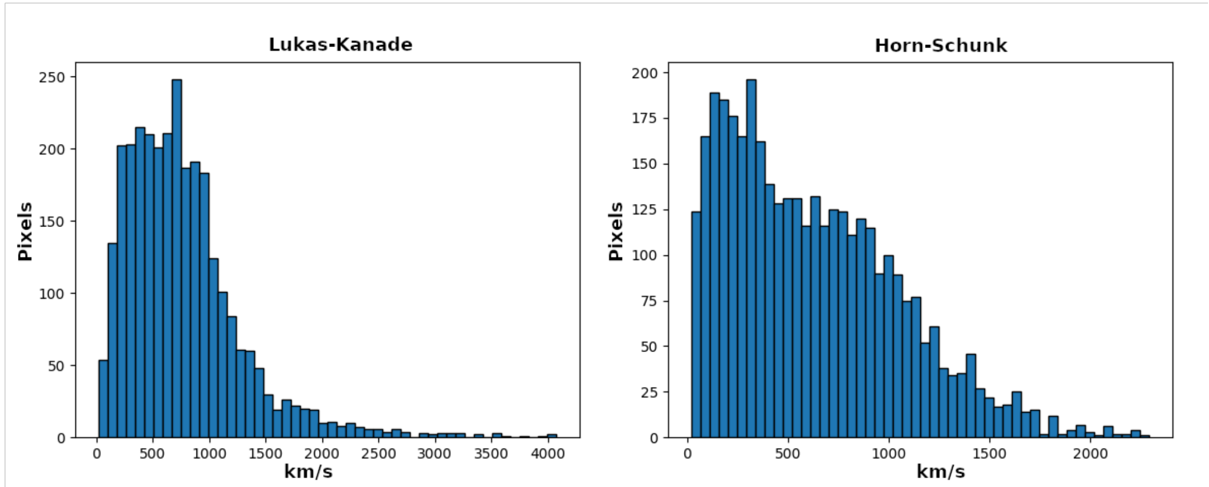
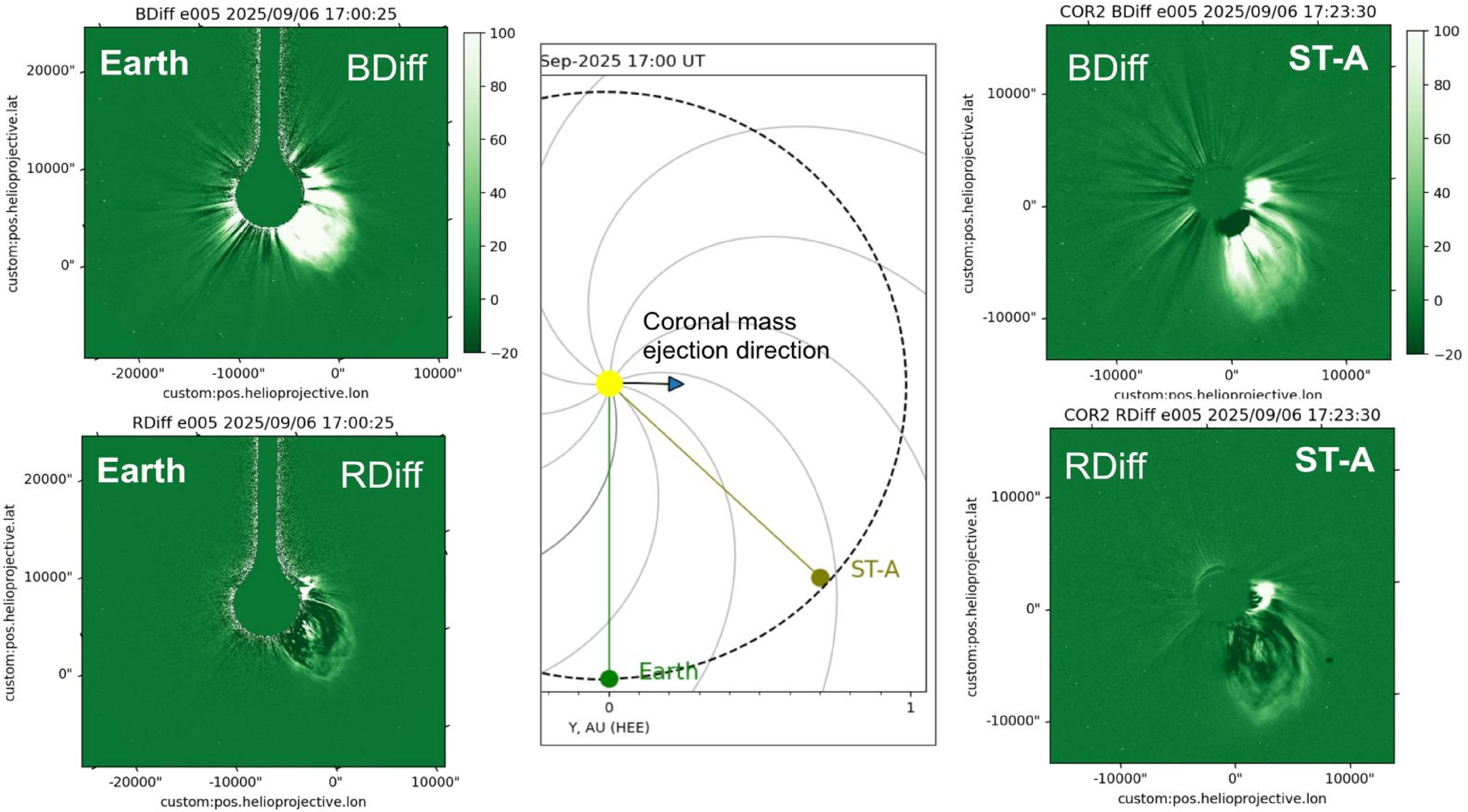
The Institute of Astronomy and National Astronomical Observatory, Bulgarian Academy of Sciences





FLCT (Cross-correlations in the Fourier space)

Sampling Cadence problem:
Infrequent / irregular data -> errors in differentiation teqniques (simple difference formulas fail). Possible Solution: higher-order polynomial fits or alternative/adaptive numerical schemes, or ….:



BDiff e005 2025/09/06 17:00:25
Earth
BDiff
RDiff e005 2025/09/06 17:00:25
Earth
RDiff
custom:pos.helioprojective.lat
custom:pos.helioprojective.lon
Sep-2025 17:00 UT
Coronal mass ejection direction
ST-A
Earth
Y, AU (HEE)
COR2 BDiff e005 2025/09/06 17:23:30
BDiff
ST-A
COR2 RDiff e005 2025/09/06 17:23:30
RDiff
ST-A

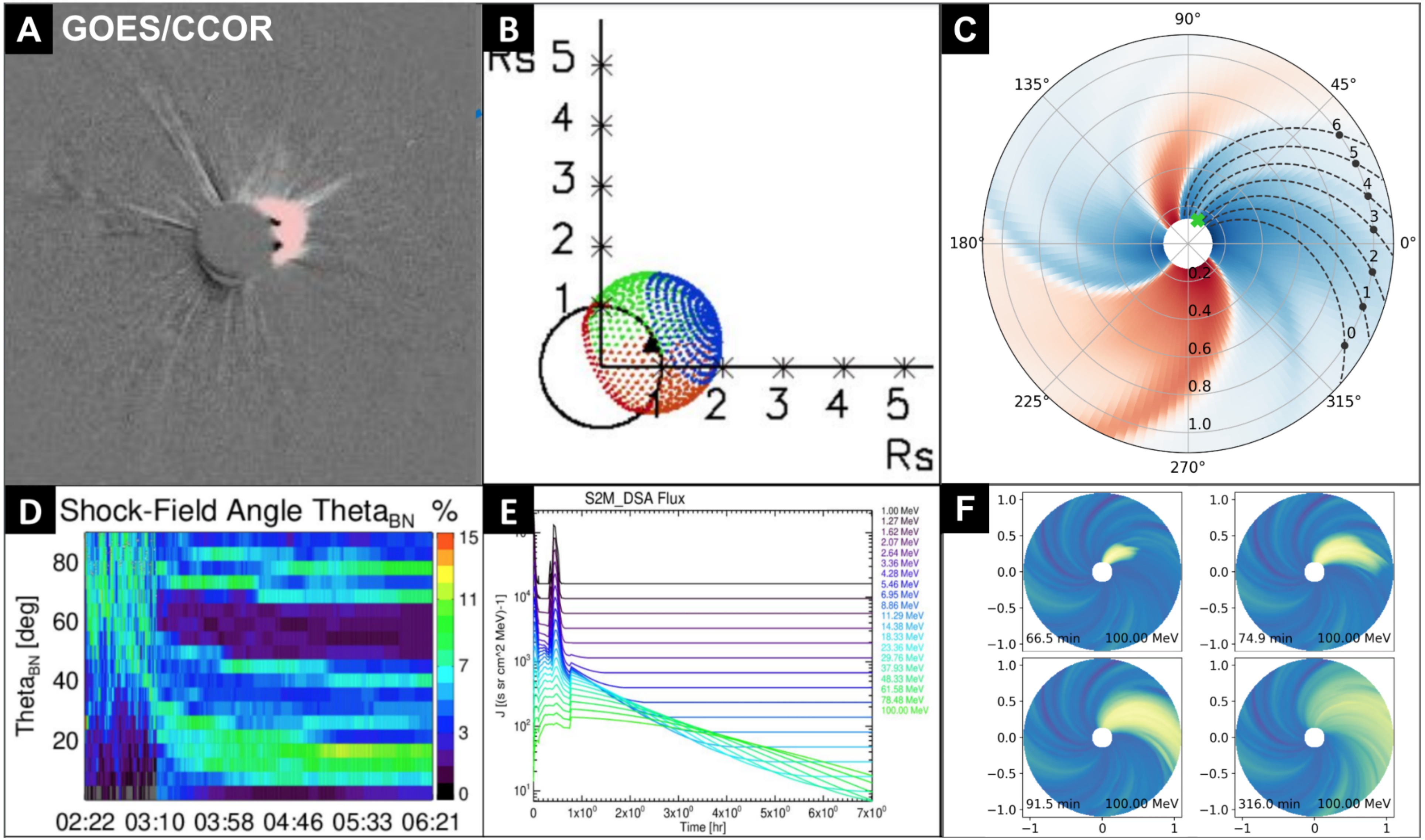
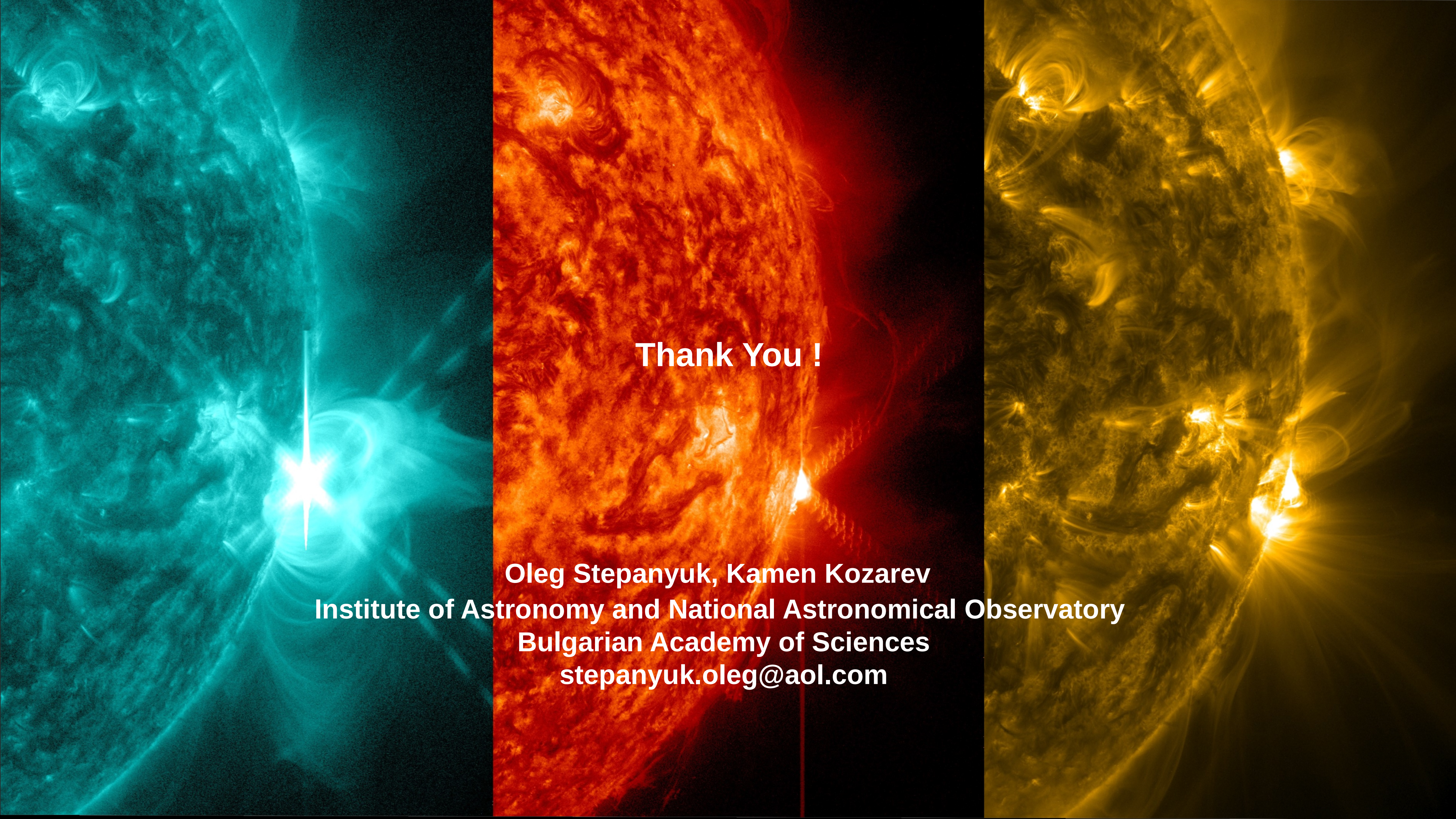


Fig. 2 - Envisioned intermediate outputs from, and inputs to, the upgraded SPREAdFAST2.0 framework, from the telescopic observations to global heliospheric SEP fluxes

Algorithmic VS Data Driven 3D reconstruction. PINNs ?

Component	Classic deformable mesh prior (e.g., SMPL/FLAME)	NeRF-based deformable prior (2023–2025 era)
Shape representation	Explicit triangle mesh	Implicit signed distance field or density field (MLP or triplane / 3D GS)
Learned prior	PCA or VAE in vertex or latent space	Trained on thousands of simulated CME density volumes → learns a latent space of plausible 3D CME structures
Deformation parameters	Low-dim latent code (32–256 dims) that deforms a template mesh	Low-dim latent code that conditions the NeRF → generates different CME morphologies
Differentiable rendering	Rasterize mesh + Thomson-scattering shader	Neural volume rendering of density + brightness model (Thomson scattering)
Single-view reconstruction	Yes (very common now)	Yes (and often even better because no mesh topology issues)


Thank You !
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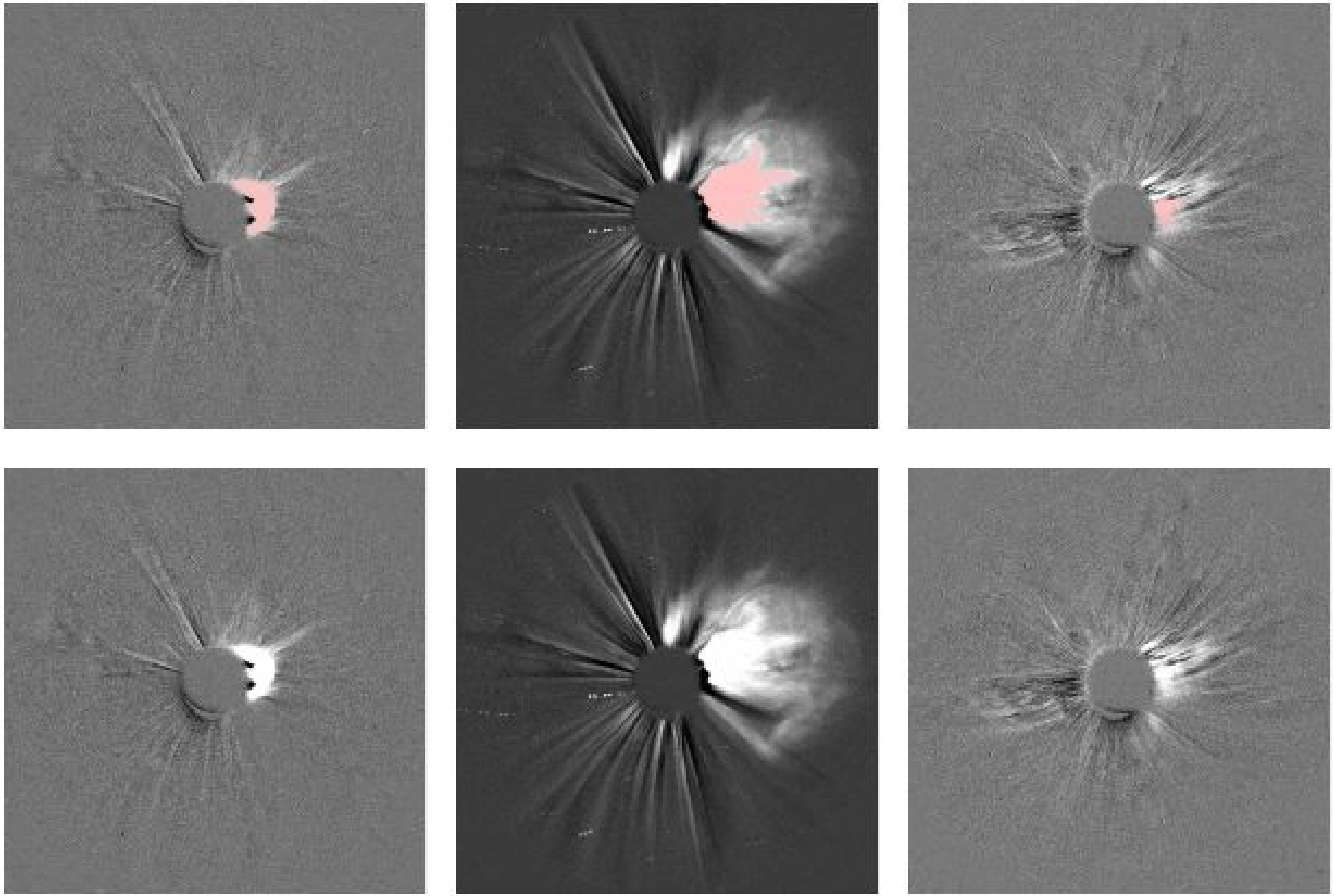
stepanyuk.oleg@aol.com

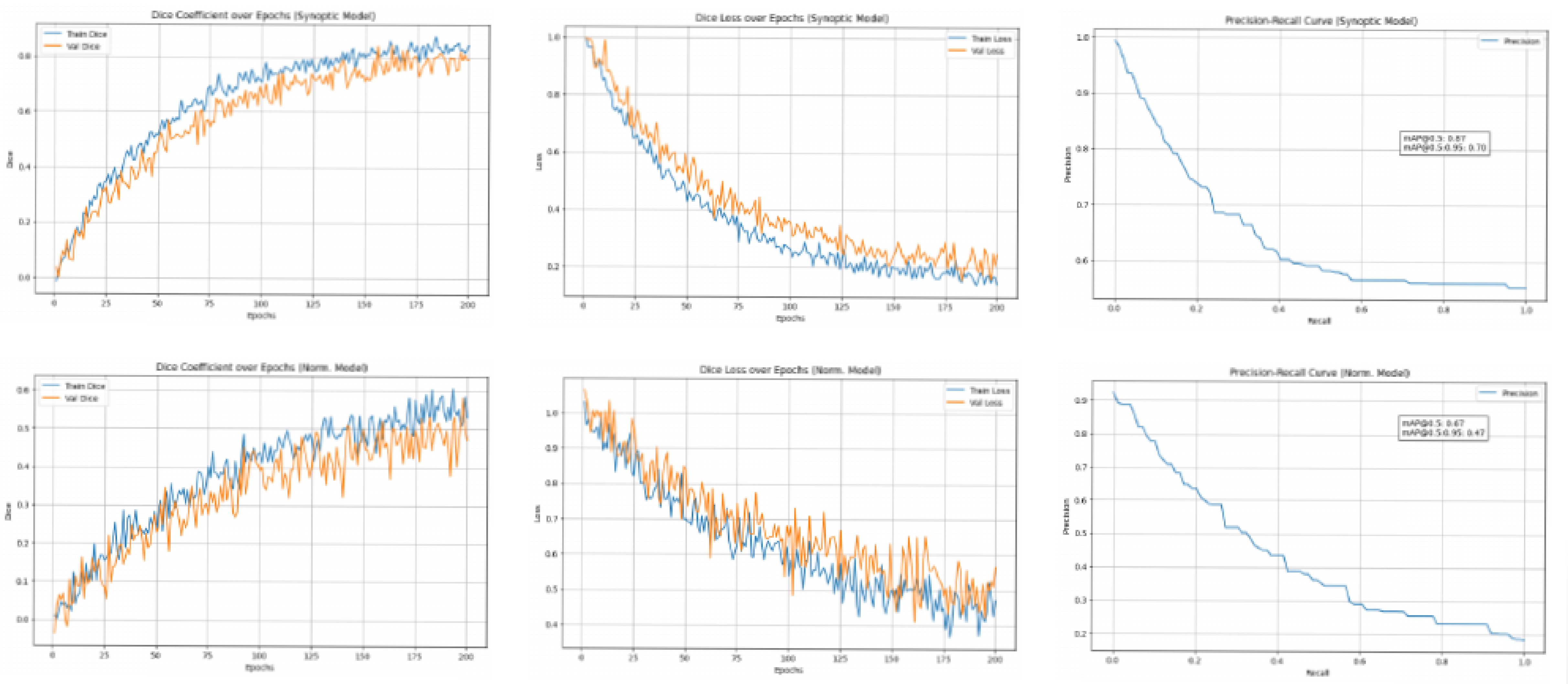
Additional Slides (discussion)

C-COR Algorithmic Tracking (Wavetrack. Proof of Concept)



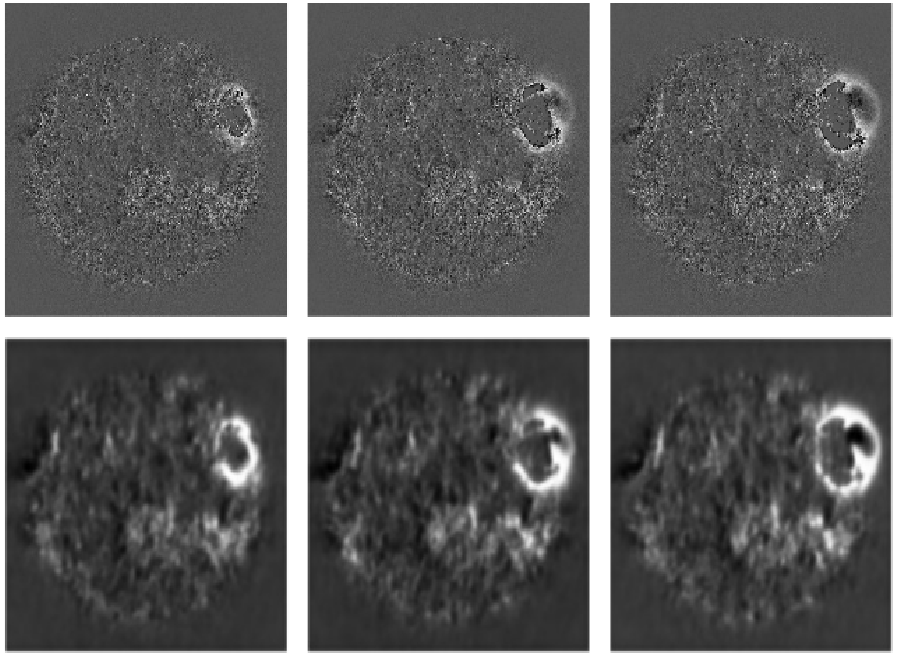
20250724_175330 20250724_212330 20250810_162330

Segmentation and Tracking. Filaments. Kanzelhöhe Observatory Data (Training Metrics)

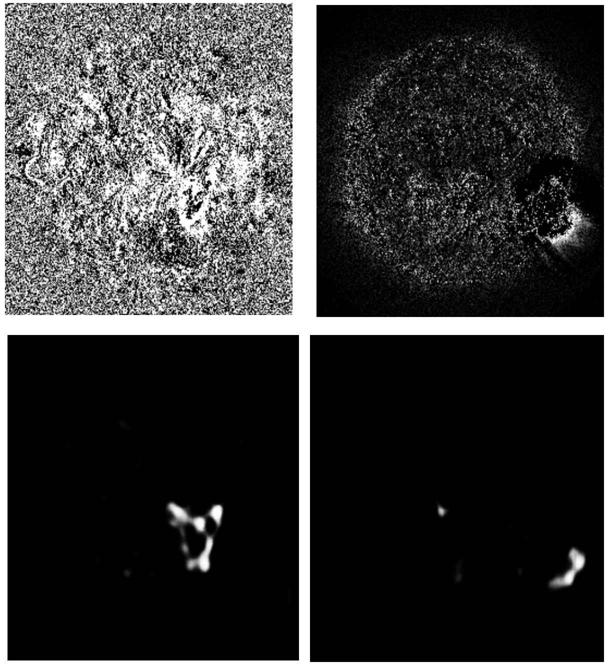


Segmentation and Tracking, previous results. SDO AIA segmentation performance

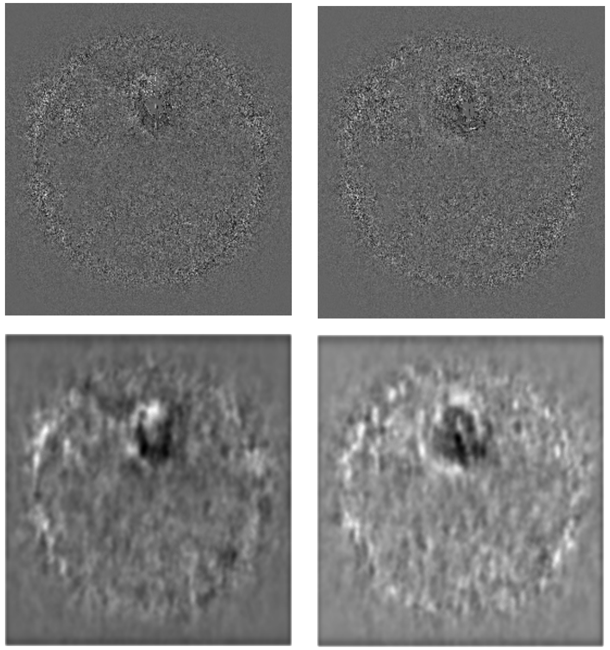
Under Review



2011-06-07. AIA 193 A. CBF evolution. Probabilistic masks (softmax)



29-09-2013/11-05-2011
Filament on disk / on limb recognition



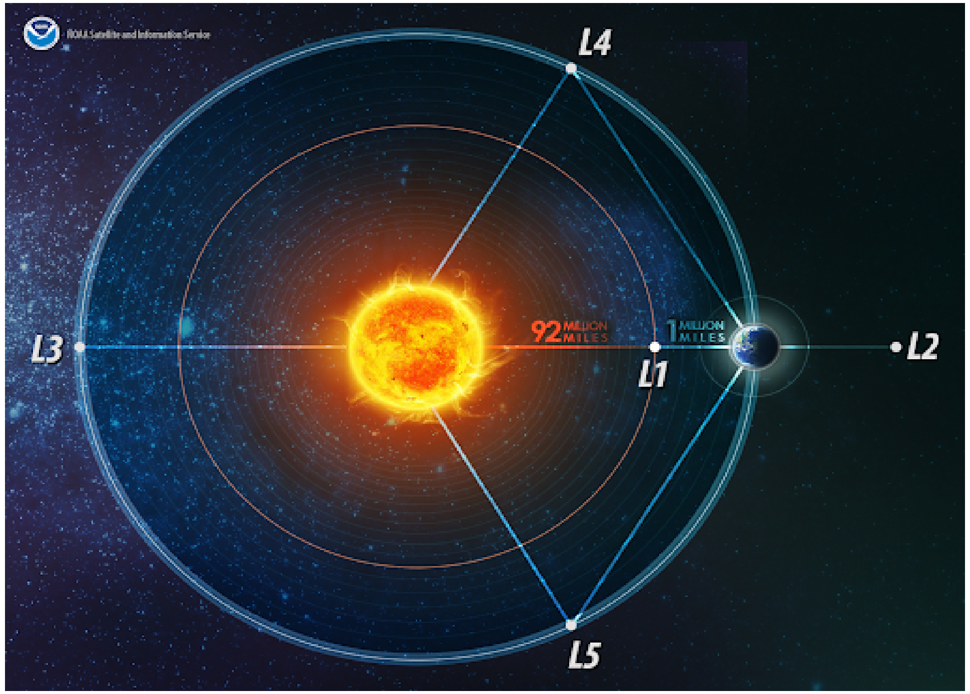
10-05-2022 Shock in the Low Corona
(we previously studied in Rigney at al, A&A L7 (2024))

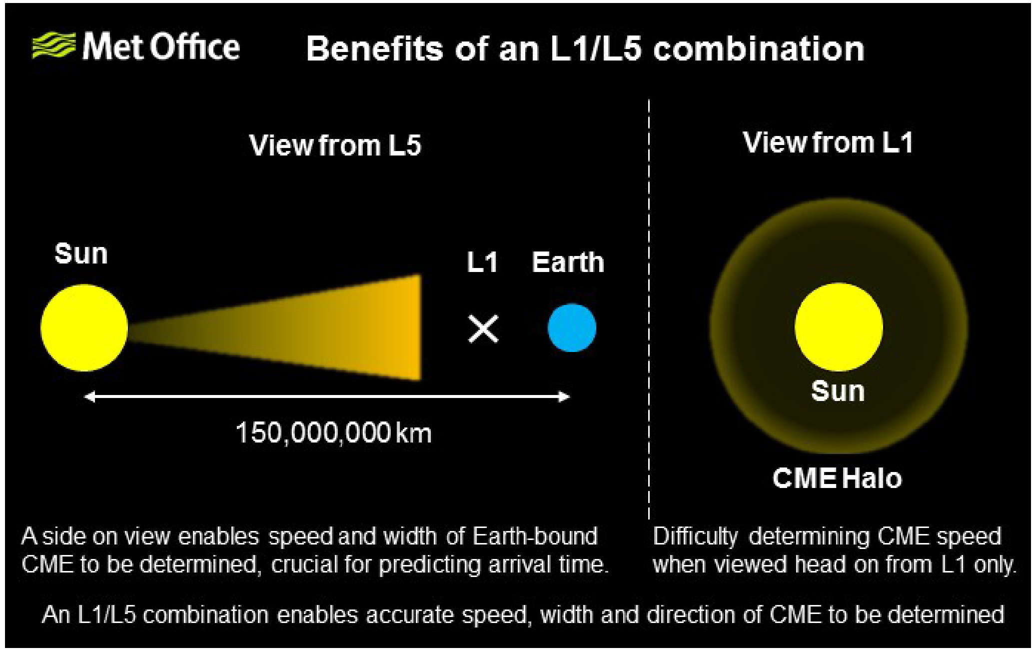
Models testing by comaring with validation sets according to IoU and Dice metrics: $\mathrm{IoU} = \frac{|A \cap B|}{|A \cup B|}$ $\mathrm{Dice} = \frac{2|A \cap B|}{|A| + |B|}$

https://gitlab.com/iahelio/helios_cnn/
Pre-trained models for segmentation and tracking of Coronal Bright Fronts from SDO AIA Base Difference images

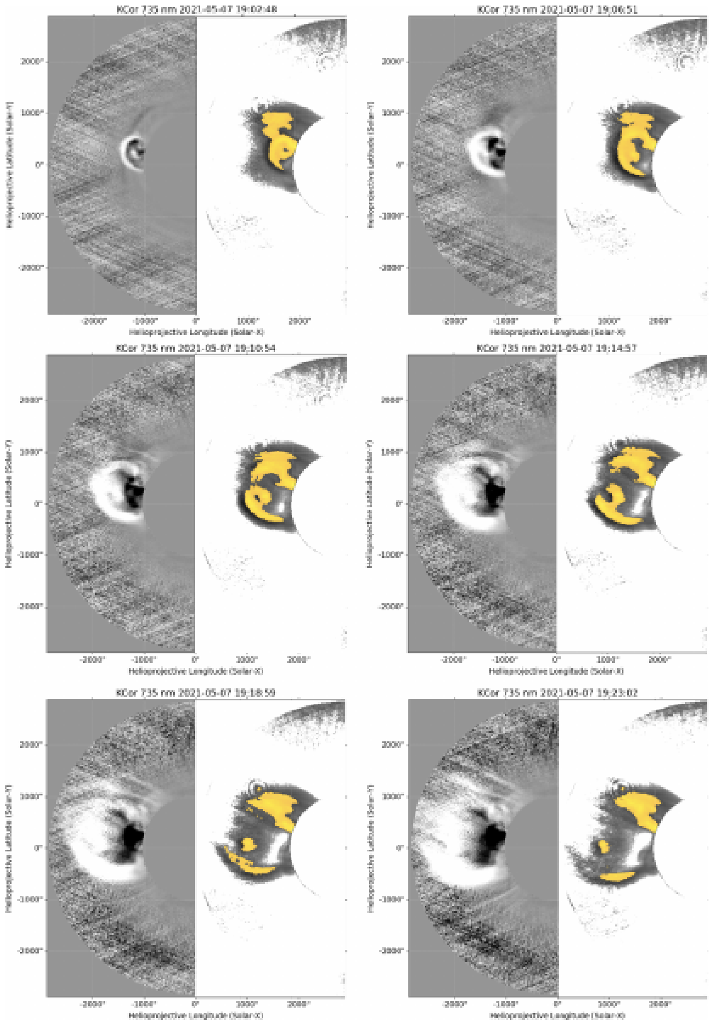
Motivation. What do we do

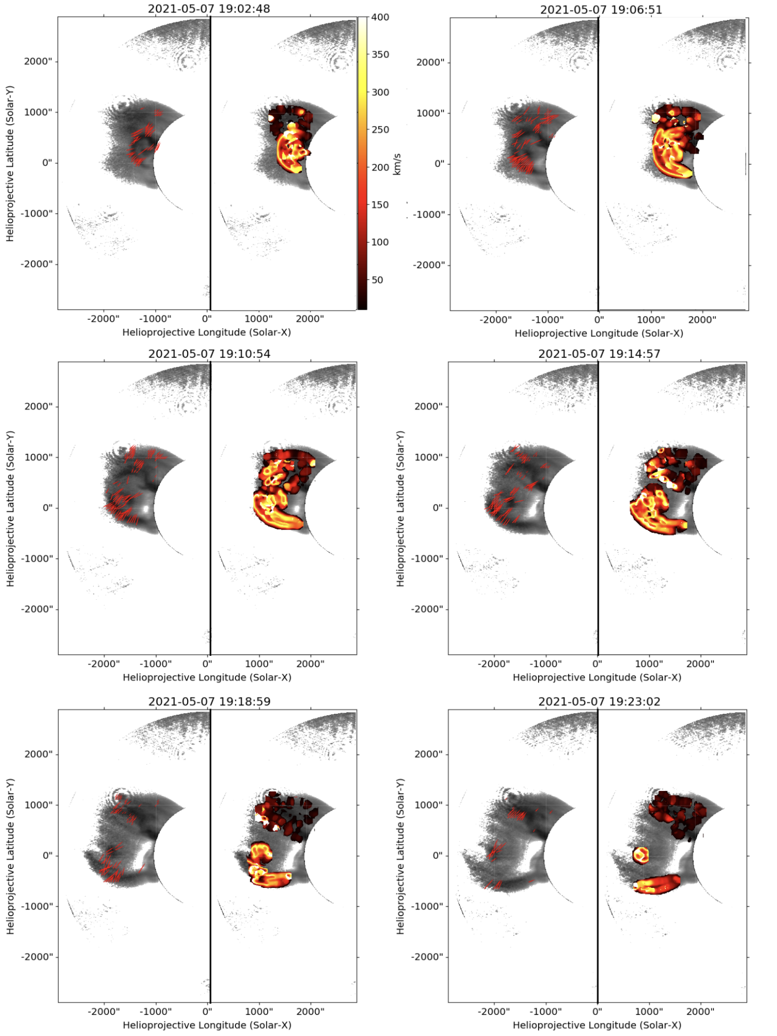
- Kamide [2001] and Akioka et al. [2002] -- the first to discuss an L 5 concept
- L 5 location is optimal: CME within the -- Thomson surface of maximum scattered brightness
- Stereoscopic VS. reconstruction from a single viewpoint (j-map technique [e.g., Möstl et al., 2014]
- We apply our feature tracking methods to Compact Coronagraph (CCOR) data,
- In perspective: extend our approach to study events simultaneously observed from L1/Earth (by SDO and SOHO instruments) and near the L5 point (by STEREO-A and STEREO-B instruments), approximating the expected geometric configuration between Vigil and the Earth/L1.

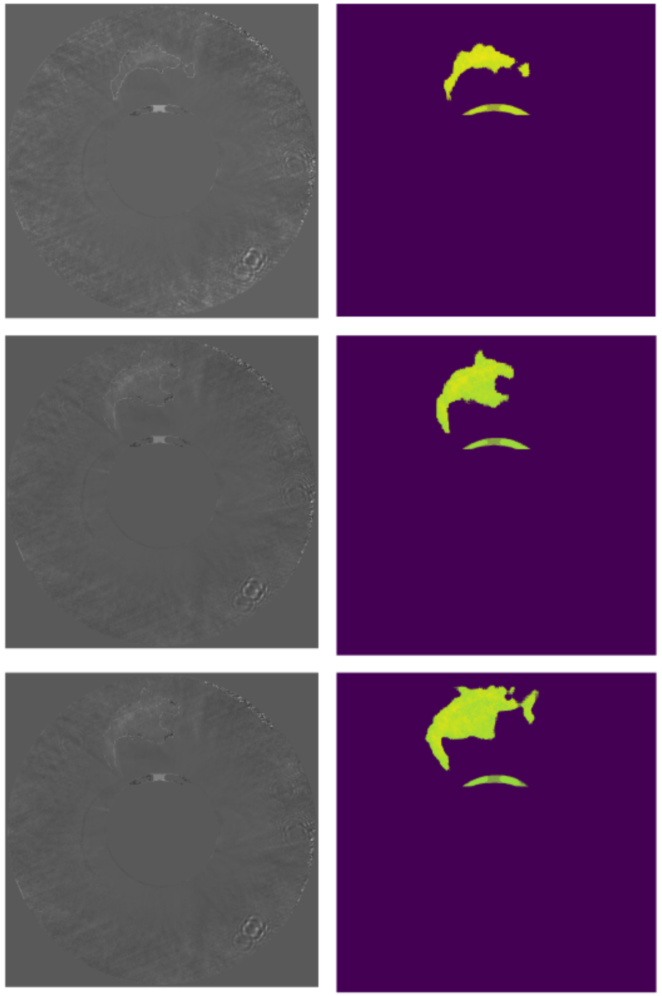




Training data (limb) : Wavetrack feature masks (K-Cor),







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Stepanyuk O., Kozarev K "Multi-Instrument Tracking and Observations of a Coronal Mass Ejection Front From Low to Middle Corona". J. SWSC (2024)