Coronal Mass Ejection Reconstruction using the new HeXCor model with Multi-Spacecraft In-Situ Fittings

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Introduction

Coronal mass ejections (CMEs) are eruptions of plasma and magnetic field from the Sun. They are primary drivers of space weather and can cause disruptions of Earth's magnetosphere. CMEs close to the Sun are observed by remote sensing instruments (e.g., coronographs) and enable modeling of their global structure (e.g., Graduated Cylindrical Shell model[1], FRI3D[2]). Interplanetary CMEs (ICMEs) are observed by in-situ instruments; their magnetic structures can be modeled (e.g,. cylindrical models, 3DCORE[3], FRI3D). Modeling of CME/ICME propagation and magnetic fields is important to understanding CMEs and how they will impact Earth and satellites.

Motivation: Disparity of CME/ICME Reconstruction

Traditional reconstruction methods model CMEs (remote sensing) and ICMEs (in-situ) separately. They do not directly connect remote sensing and in-situ observations and modeling.

HeXCor: Heliospheric ConneXions of observations for Coronal mass ejections

- The Graduated Cylindrical Shell (GCS) Model produces geometry to describe the global CME structure from remote sensing measurements. It is commonly used to describe the size, orientation, and propagation direction of CMEs as seen close to the Sun.
- **HeXCor** combines GCS geometry with a warped cylindrical magnetic flux rope. This flux rope can be fitted to in-situ magnetic field observations by space probes (e.g. the Wind spacecraft near Earth)
- **HeXCor incorporates remote sensing and in-situ data simultaneously. This enables direct comparison of remote-sensing and in-situ observations to better understand CME structure and evolution.**

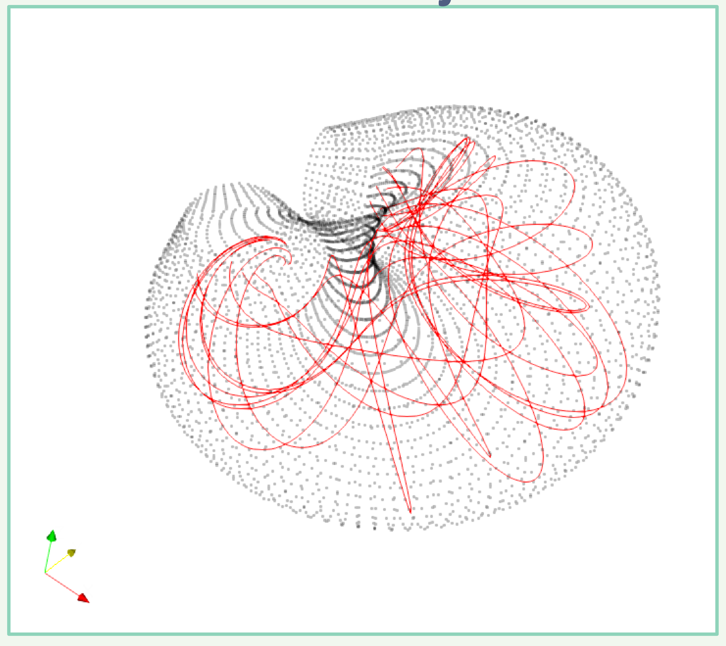
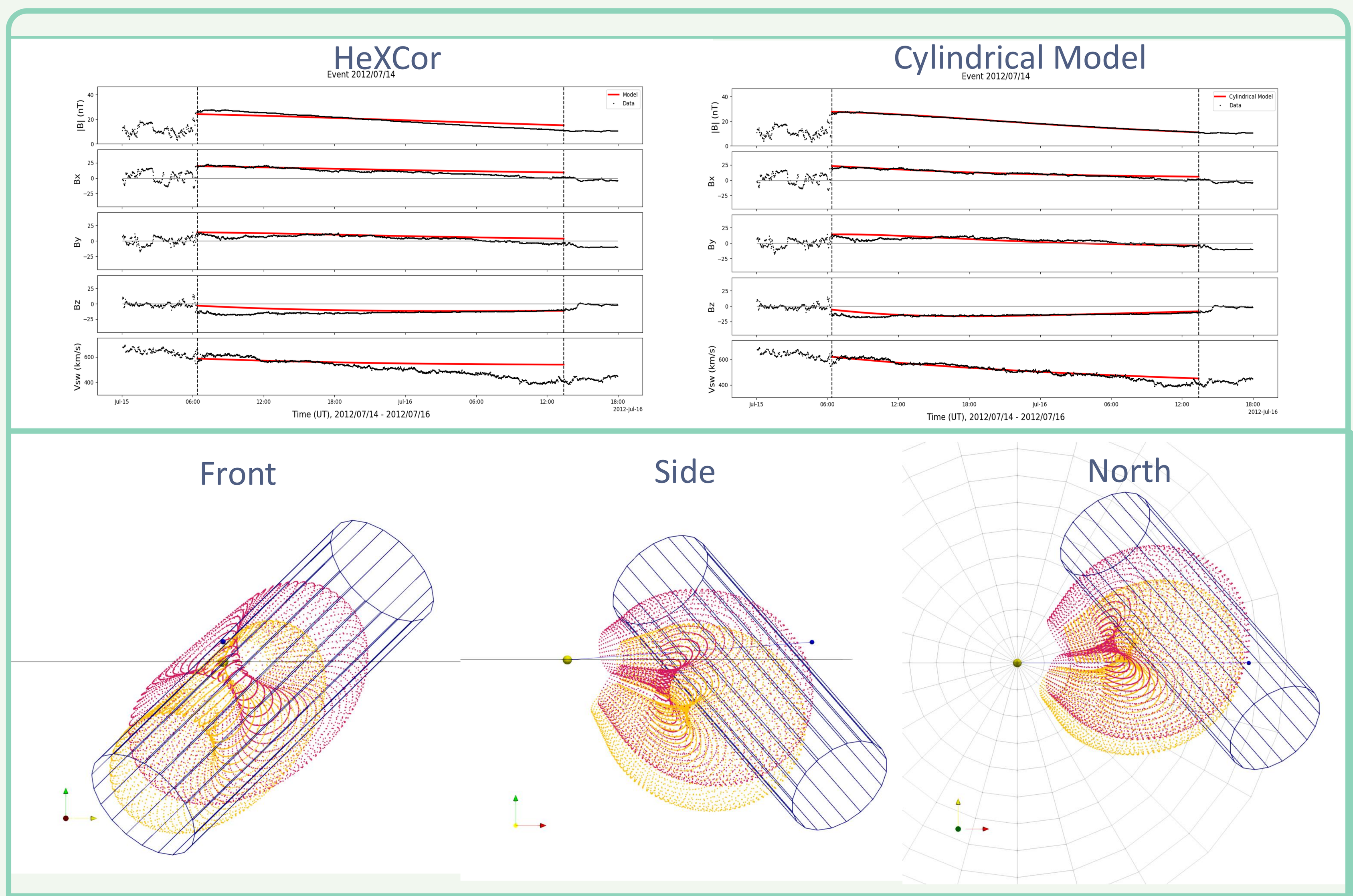


Figure: Graduated Cylindrical Shell (black) with magnetic flux rope (red).



Remote sensing (red) HeXCor (yellow) Cylindrical model (blue)

HeXCor Model Parameters and Fitting

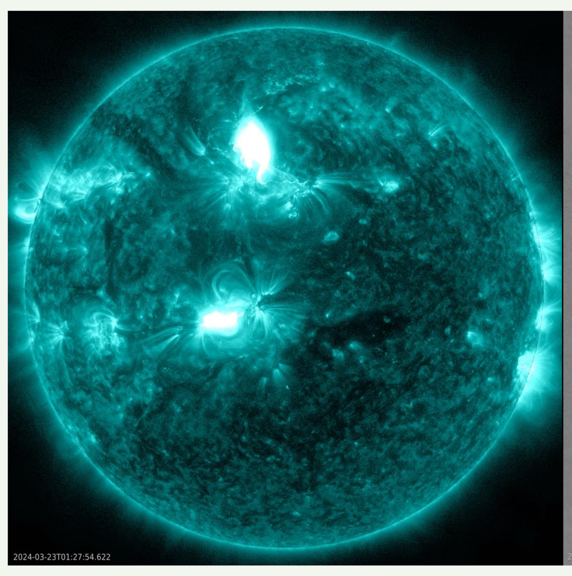
- **6 free parameters** are used in total.
- GCS Parameters: **Longitude, latitude, tilt angle**, **aspect ratio**
- Flux rope parameters: **Magnetic field strength**, **bulk velocity**,
- Half-angle, chirality, and axial direction are inferred from data.
- Model is fit using in-situ total magnetic field, magnetic field x-y-z-components, and solar wind speed.

Proof of concept with July 12 2012 CME

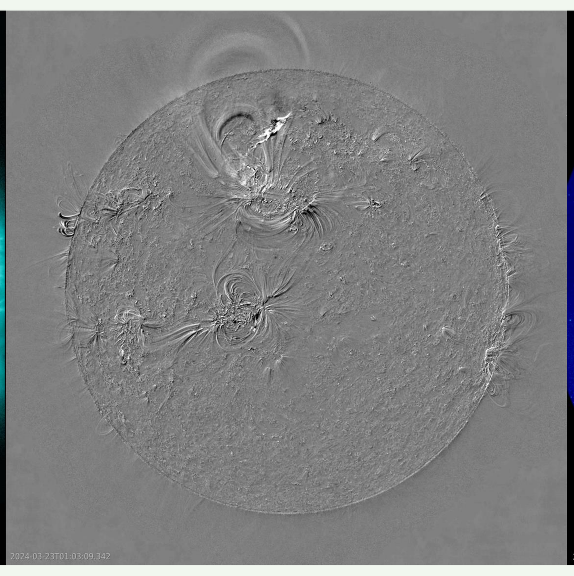
- This is an ideal event for remote sensing measurement (as Earth and STEREO A/B are all 120° separated from each other reducing uncertainty in measurement) and it has a strong in-situ signature at Earth.
- In-situ fitting with HeXCor compares well to the more conventional Marubashi[4] cylindrical model
- Orientations of HeXCor, remote-sensing GCS reconstruction, and cylindrical model are very closely aligned. **This provides good validation of the HeXCor approach.**
- This event appears to follow assumption of radial self-similar expansion well with agreement across models. Deflection and deformation during propagation are not apparent.

BUT NOW WE TO NEED RECONSTRUCT CME WITH MULTIPLE IN-SITU SPACECRAFT TO IMPROVE ANALYSIS

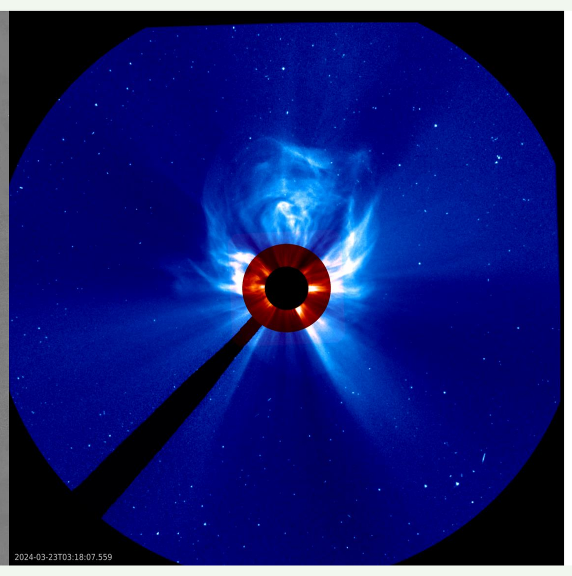
Multiple In-situ Spacecraft Case Study: 23 March 2024



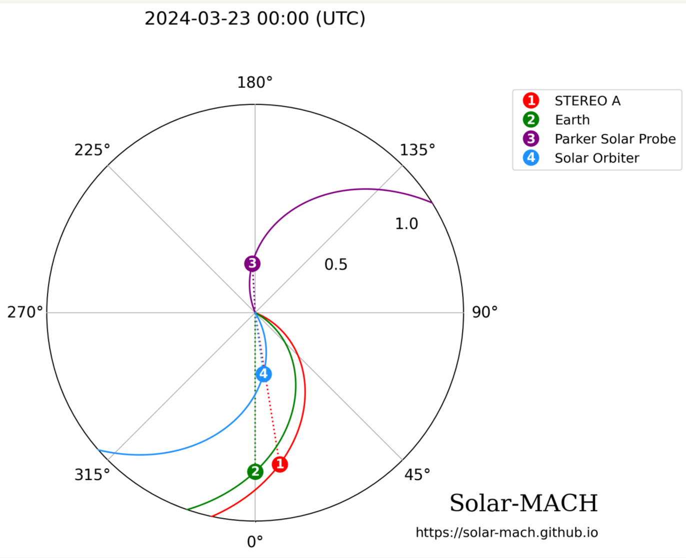
AIA 131 image showing location of the flare and eruption (upper middle)



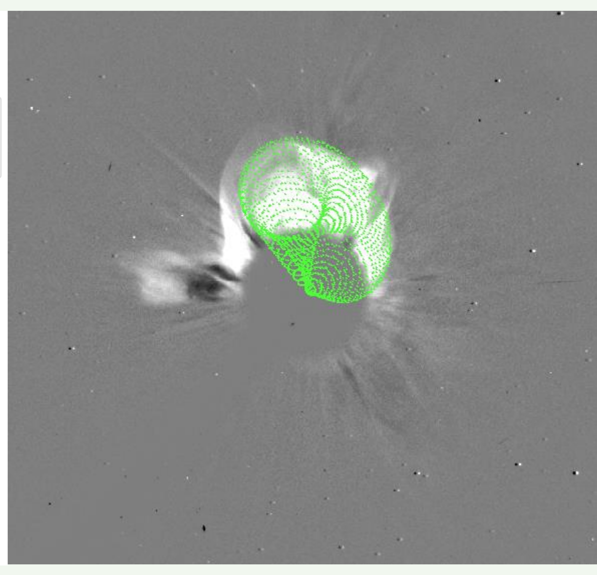
AIA 171 base difference image highlighting expanding magnetic loops during eruption (top middle)



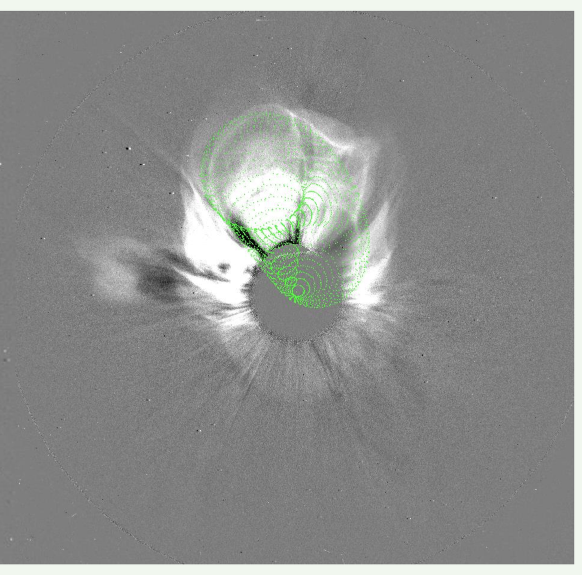
LASCO C2/C3 image showing CME



Location of Earth (with Wind), STEREO-A, Solar Orbiter, and Parker Solar Probe[5]. Solar Orbiter, Wind, and STEREO-A impacted by CME.



LASCO C3 difference image of CME with overlaid GCS point cloud



STEREO-A COR2 difference image of CME with overlaid GCS point cloud

Preliminary Results and Discussion

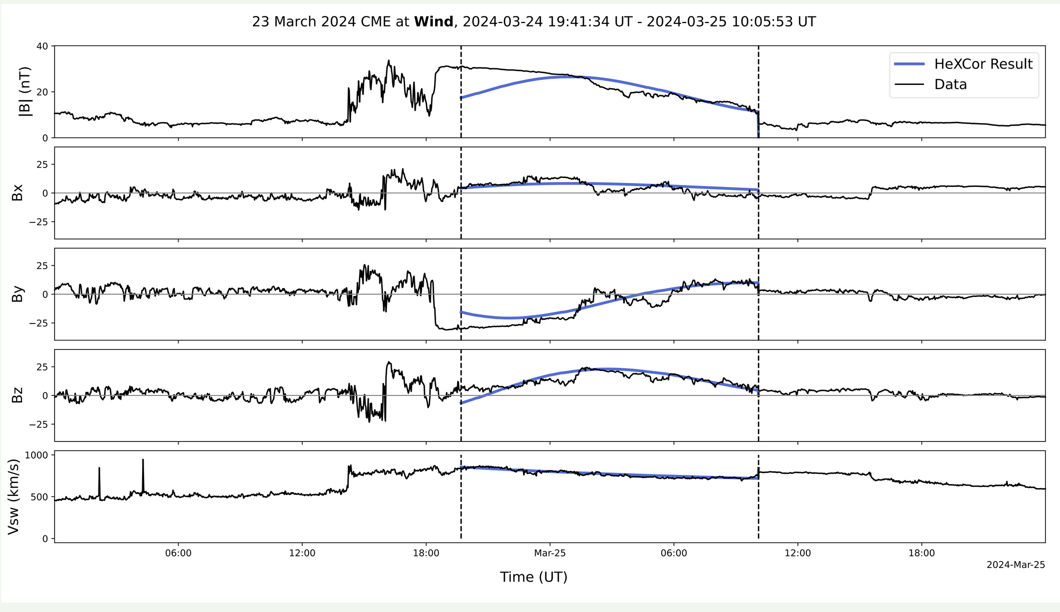
Eruption Time:	2024-03-23 00:50UT
Solar Orbiter Ejecta Impact Time:	2024-03-23 15:10UT
Wind Ejecta Impact Time:	2024-03-23 19:41UT
STEREO-A Ejecta Impact Time:	2024-03-23 21:00UT

The remote sensing observations and measurements of this CME are shown in the images above. Start and End times of ejecta are preliminary estimates.

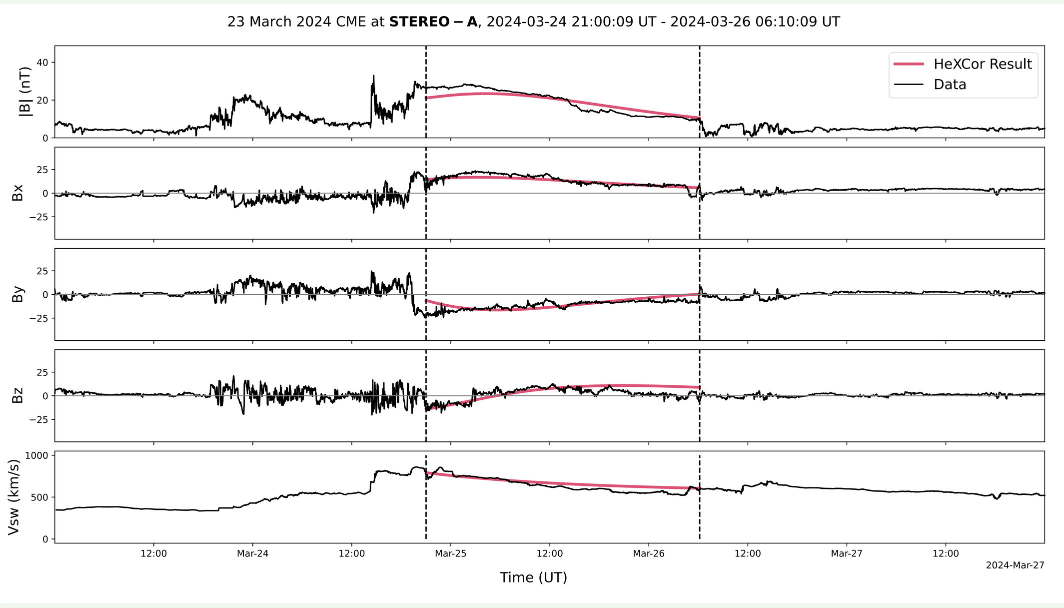
This is a large full-halo CME that impacted Solar Orbiter, Wind, and STEREO-A, making it a great example for multi-spacecraft in-situ reconstruction. HeXCor was used to fit each spacecraft individually (Solar Orbiter results excluded for further development). The HeXCor results for Wind and STEREO-A both fit the in-situ data well (shown middle right) but produce CME profiles with significantly different orientations (shown bottom right). The remote sensing measurement (shown bottom right) has similar orientation to the Wind result with elevated latitude.

These preliminary results, particularly the disagreement between Wind and STEREO-A, could suggest significant differences in the CME magnetic structure across only 9° of longitudinal position. Coronagraph images also indicate significant writhe in the structure, which could influence these results. Additionally, the in-situ solar wind data shows more complexity than expected of a clean CME, indicating effects of deformation or the presence of multiple structures.

Further development of HeXCor will fully incorporate Solar Orbiter and all solar probes, as well as *simultaneous* multi-spacecraft in-situ fitting.

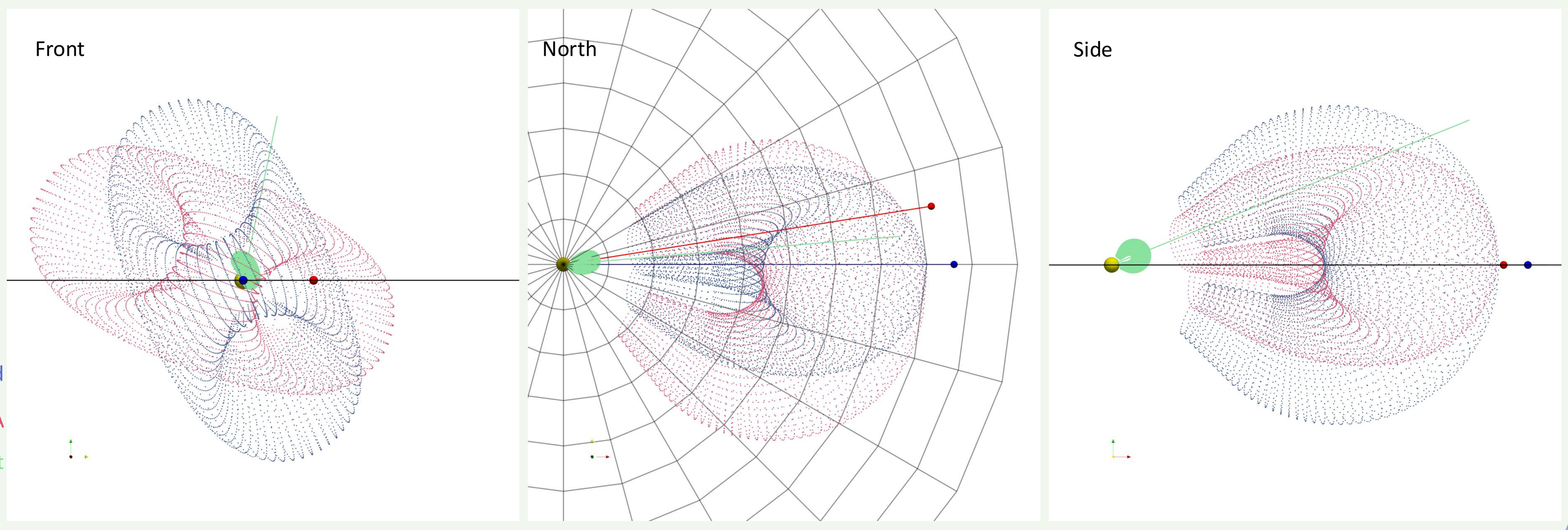


HeXCor result for Wind in-situ fitting. Vertical dashed lines mark start and end times of ejecta.



HeXCor result for ST-A in-situ fitting. Vertical dashed lines mark start and end times of ejecta.

HeXCor result for Wind
HeXCor result for STEREO-A
Remote Sensing Measurement



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References [1]A. Thernisien, 2011 *ApJS* [2]Isavnin, 2016 *ApJ* [3]Möstl et. al., 2018 *Space Weather* [4]Marubashi and Lepping, 2007 Ann. Geophys [5]Gieseler et. al., 2023, *Front. Astronomy Space Sci.*