Tomographic Inversion of Synthetic White-Light Images: Observing Coronal Mass Ejections in 3D

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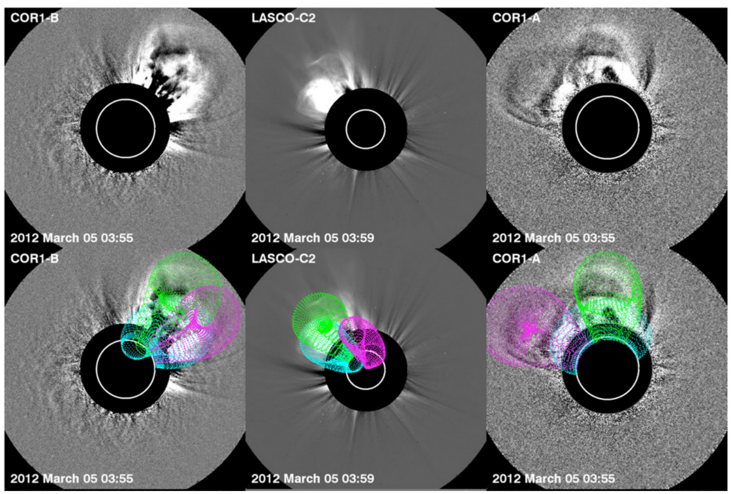
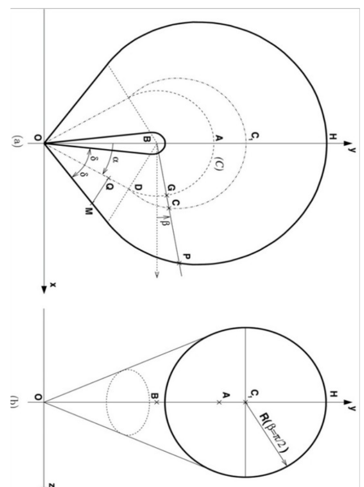
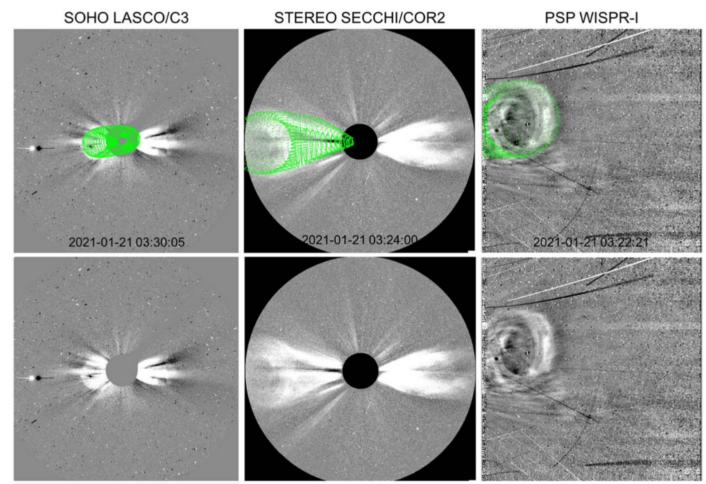
Introduction: Observing CMEs in White-Light

- CME parameters are typically derived using forward modelling and are often not well constrained and are associated with large uncertainties
- CME observations are made using white-light imagers: coronagraphs and wide-angle heliospheric imagers
- Forward modelling techniques are able to fit basic CME morphology, but give no information on internal structure and mass density
- Inverse modelling provides an alternative, but requires a large number of observing spacecraft in order to provide sufficient viewpoints



Colaninno+ [2015]


Thernisien [2015]



Braga+ [2022]

ISSI Team

"Tomographic Inversion of Synthetic White-Light Images: Advancing our Understanding of CMEs in 3D"

Led by E. Palmerio and D. Barnes

- We proposed an ISSI project, which was selected in 2023
- 1st meeting took place December 2023, 2nd meeting October 2024

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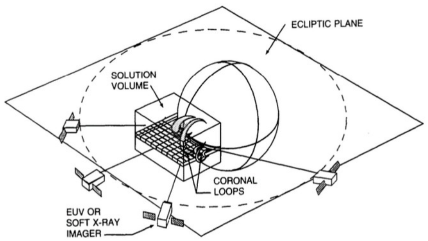
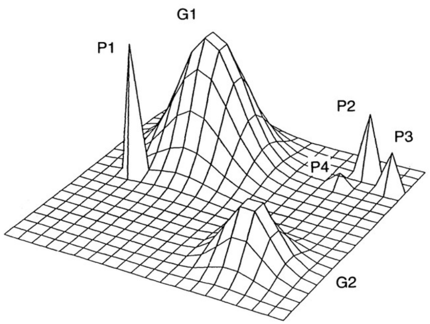
Team webpage

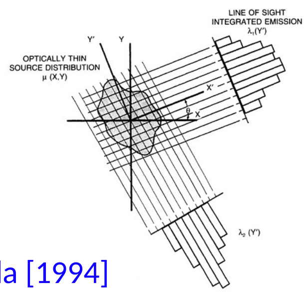
Page 1

Inverse Modelling: Discrete Tomography

- "Tomography" is applied to a broad range of inversion problems
- By defining a grid over the heliosphere the LOS integral from an image pixel can be approximated as a sum of finite elements
- Each spacecraft measures different radiance values depending on the angle from which it observes density structure
- Multiple vantage points can therefore be used to constrain 3D density distribution
- It is expected that a greater number of observers results in better reconstruction







Davila [1994]

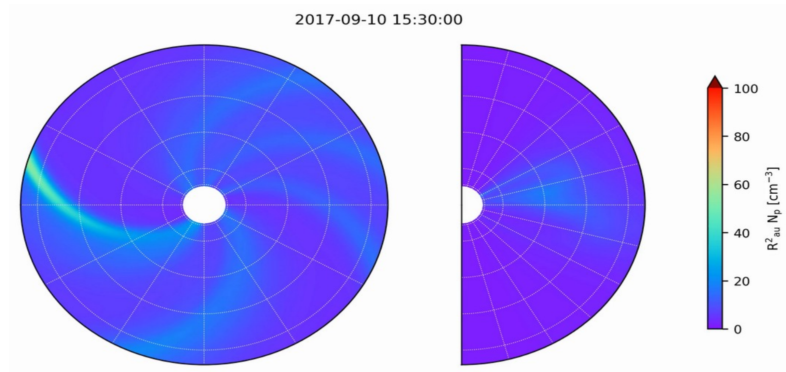
Discrete Tomography Method

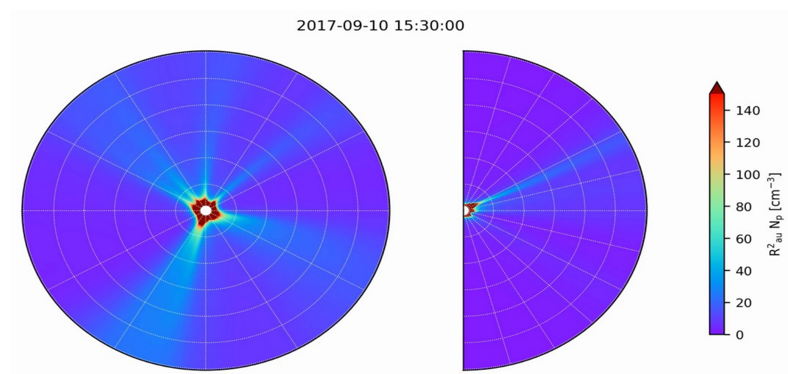
- goal is to formulate and solve inverse equation **y = H·x**
- **y** is array containing radiance values in every image pixel
- **x** is the unknown density distribution over pre-defined grid
- **H** is a physical operator based on the equations of Thomson scattering that relates elements of **y** and **x**

(1) Process images to reveal CME structure
(2) Calculate elements of **H** for given spacecraft setup
(3) Solve for **x** using iterative convergence algorithm

Simulating CMEs with the MAS/CORHEL Model

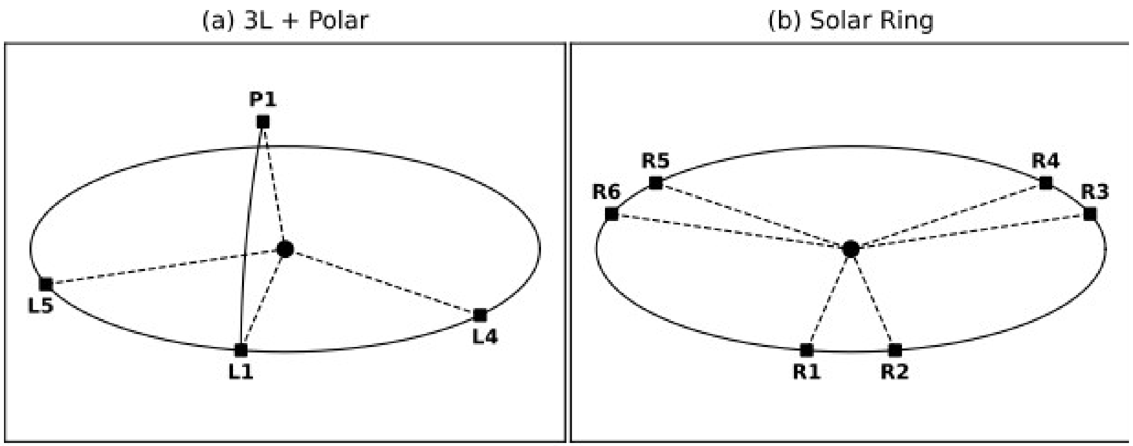
- **MAS – Magnetic Algorithm outside a Sphere**
- **CORHEL – Coronal Heliospheric**
- MHD simulation that models coronal magnetic field, solar wind and CME propagation
- 2 domains: COR (1–30$R_\odot$); HEL (28–230$R_\odot$)
- CMEs modelled from their eruption with full flux-rope (RBSL; Titov+ 2018)
- The runs used in this project utilised CORHEL-CME (Linker+ 2024), a tool to model the eruption and propagation of CMEs with MAS/CORHEL
- We simulate three separate CMEs based on real events: slow (~800km/s), medium (~1500km/s), fast (~2500km/s) CMEs based on 2021-10-28, 2020-11-29 and 2017-09-10





Synthetic Spacecraft

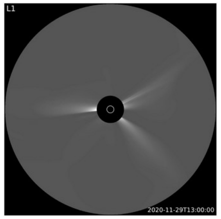
- Simulations allow us to create any number of synthetic spacecraft, which allows us to test different combinations
- We choose “plausible” spacecraft configurations; The L1, L4 and L5 points, a polar (P1) spacecraft 60° above the Ecliptic, and a six spacecraft ring (R1—R6), all at 1 au
- This results in nine possible observers, from which we choose five possible combinations in order to perform the inversion
- We can address questions; how does the number of observers influence the solution, how useful are out-of-ecliptic observations? How well are the results augmented using polarised brightness measurements?

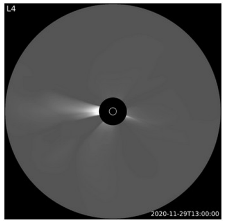


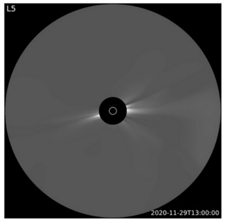
label	L1	L4	L5	P1	R2	R3	R4	R5	R6
3sc	✓	✓	✓						
3sc ring	✓					✓		✓	
4sc	✓	✓	✓	✓					
6sc ring	✓				✓	✓	✓	✓	✓
7sc	✓			✓	✓	✓	✓	✓	✓

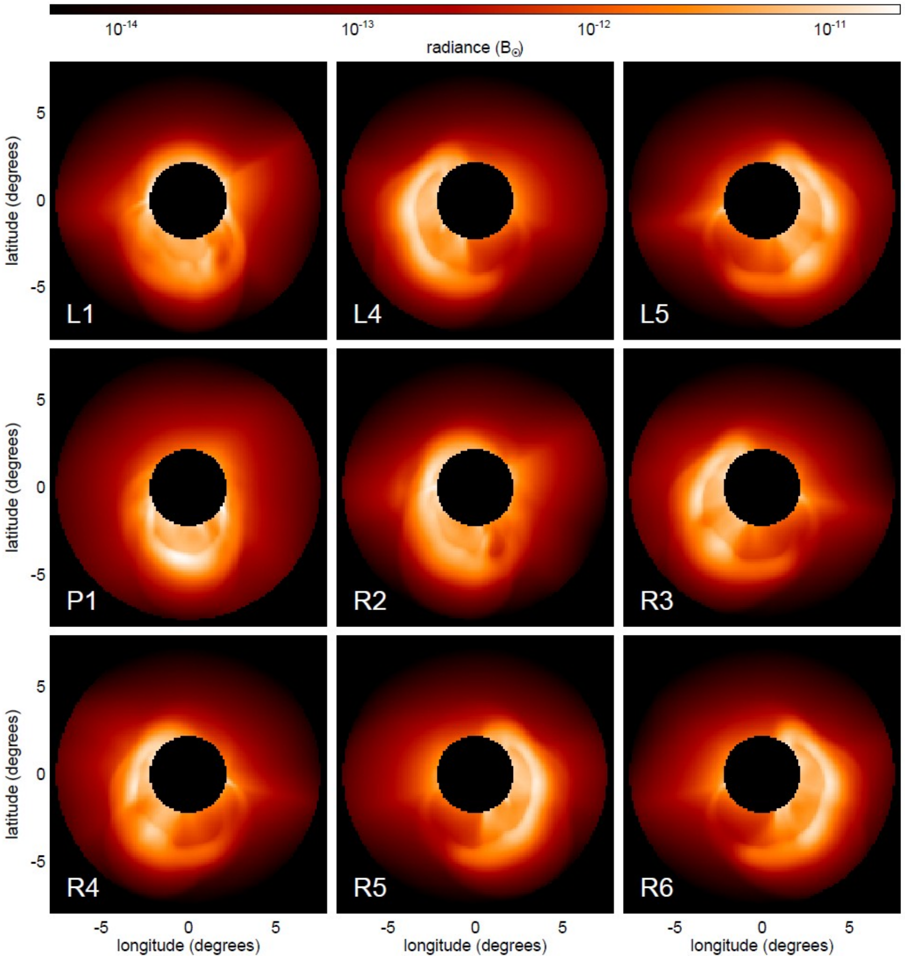
Synthetic White-Light Images

- Using Thomson scattering equations from Tappin & Howard [2009], we can create synthetic images for a specified instrument
- In this study we use a fake LASCO-C3 FOV, maximum 8° ($30R_{\odot}$)
- We create a sequence of images for each of the three CMEs as they pass through the FOV
- Images are processed; reduced resolution, background subtracted and a $4R_{\odot}$ is applied



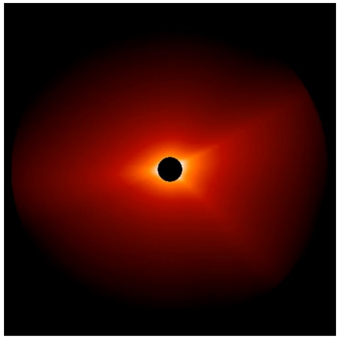


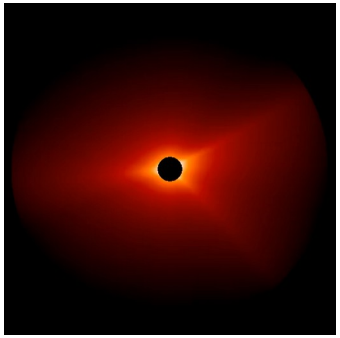


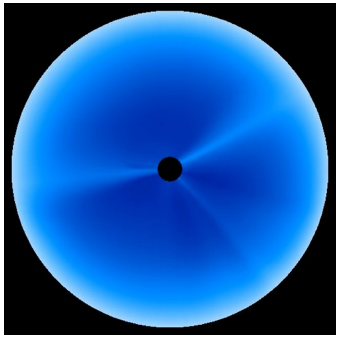


Polarised Brightness Images

L1

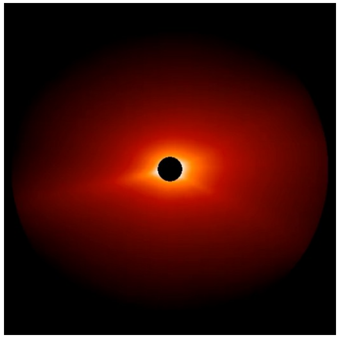


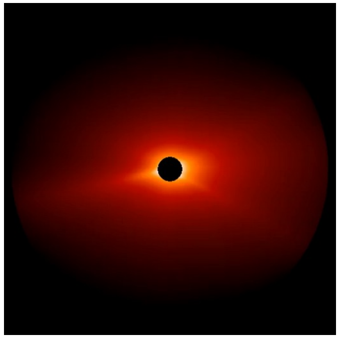


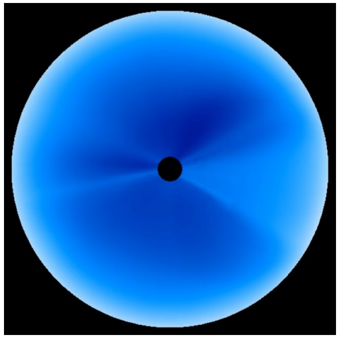


total brightness | polarised brightness | degree of polarisation

L5

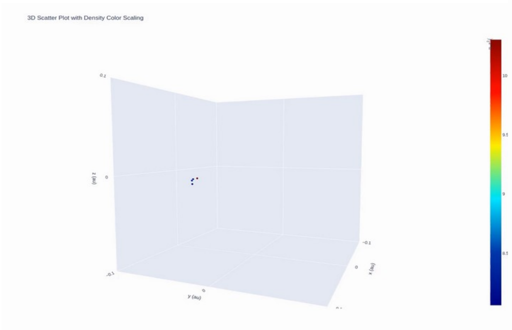




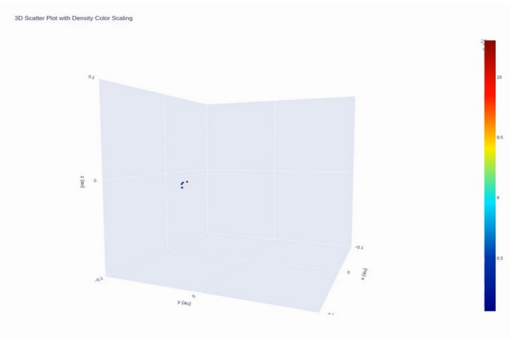


CME Densities

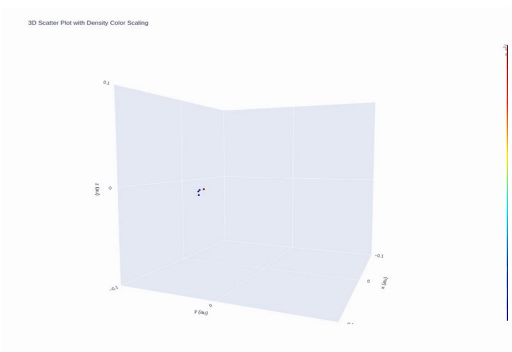
3 spacecraft



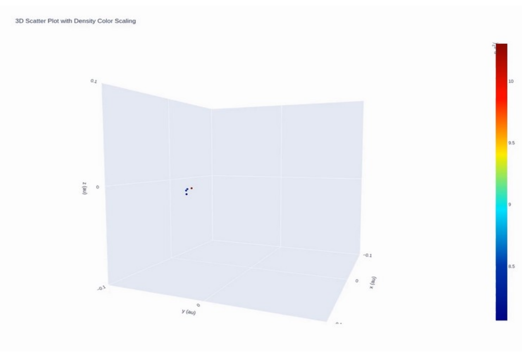
4 spacecraft



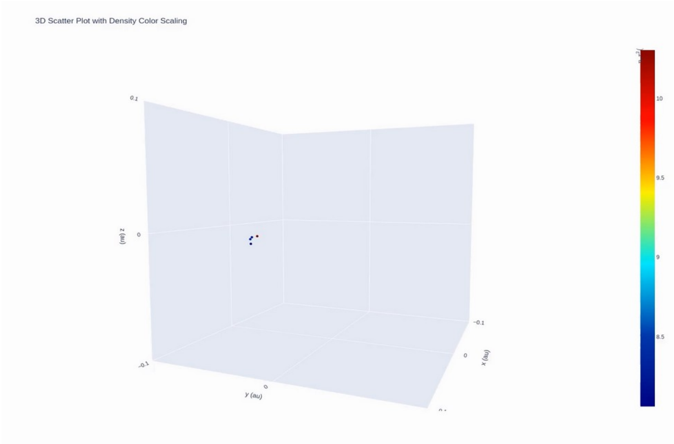
6 spacecraft



7 spacecraft



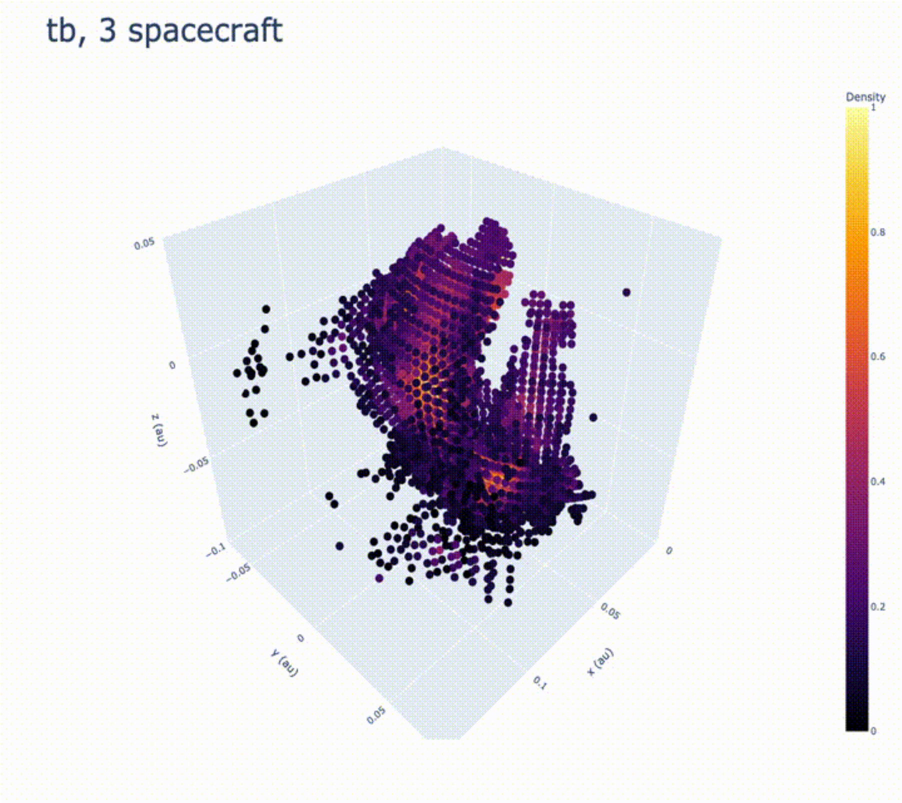
original MAS simulation

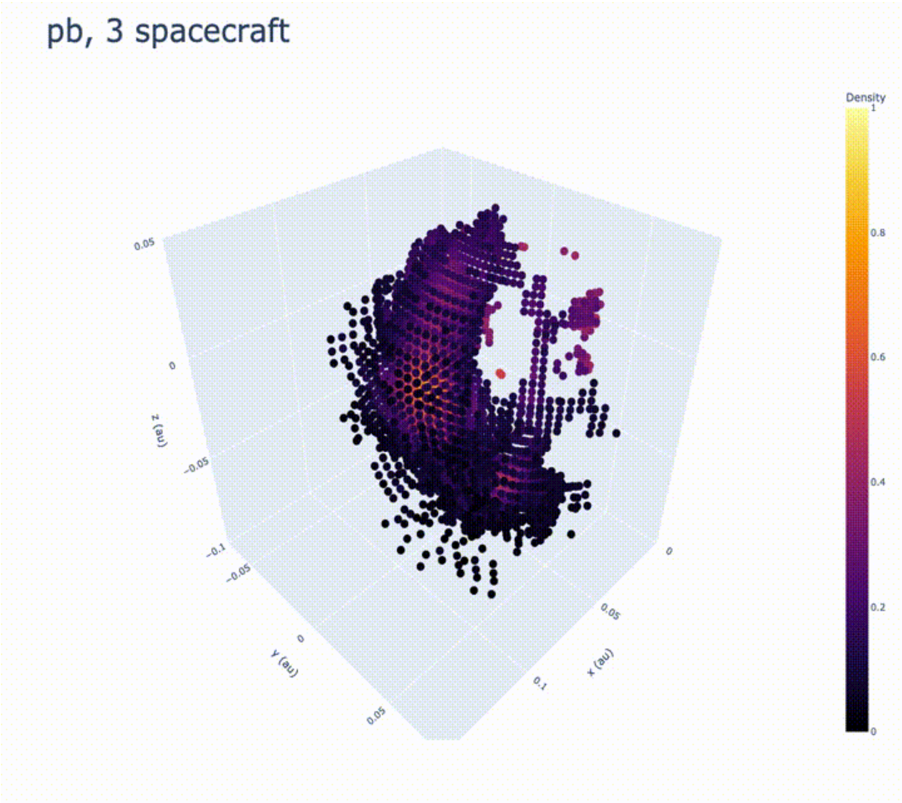


Page 1

Number of Spacecraft

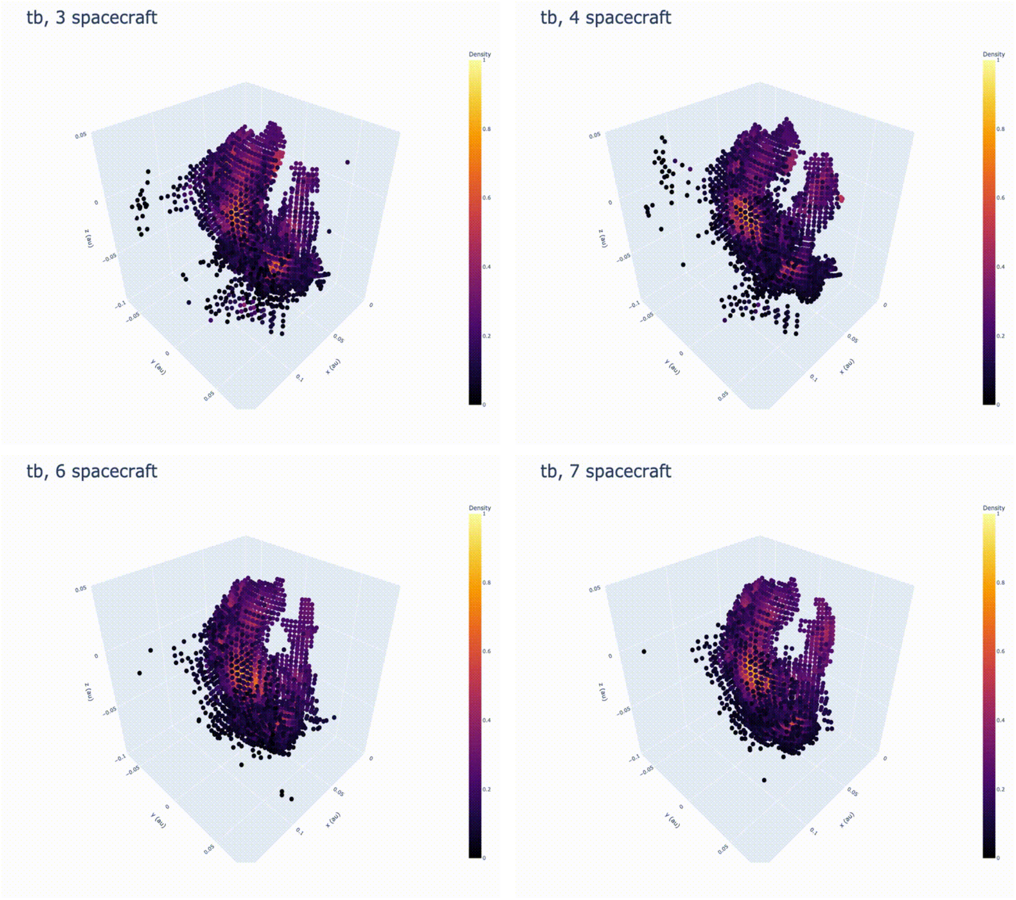
Increasing the number of spacecraft results in better agreement with the original CME density from CORHEL





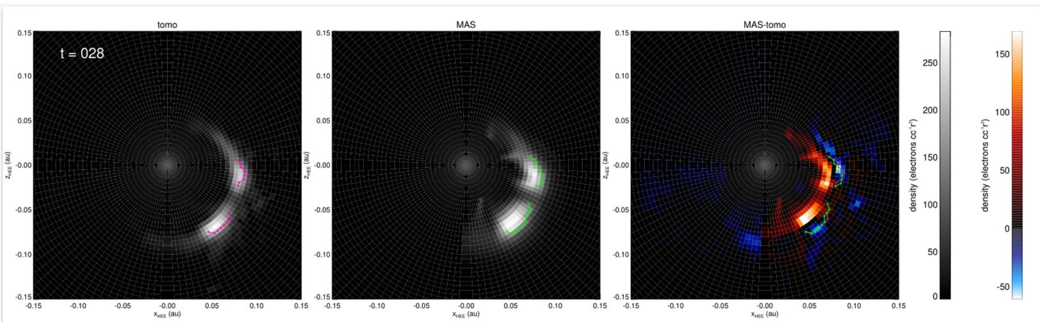
Polarimetric Reconstructions

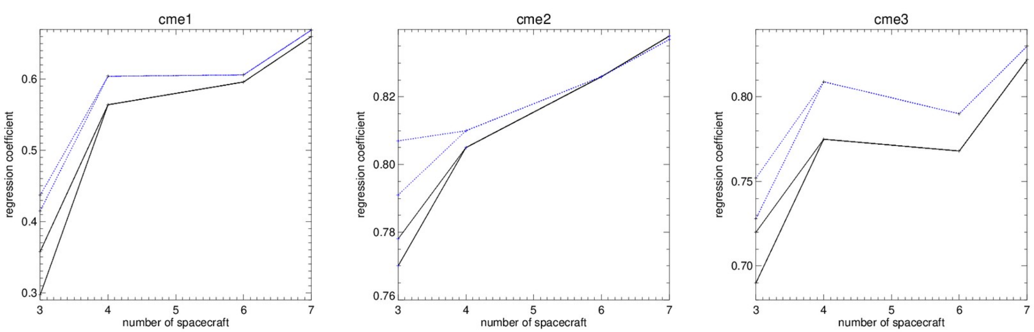
- Performing the inversion using tb vs using tb+pb shows that polarisation measurements improve our ability to constrain density
- However, the advantage of using pb measurements diminishes as the number of observing spacecraft increases
- This implies that we could perform the method well using just 3 or 4 observing spacecraft if they possess polarising imagers
- The most important factor is having a greater number of observing spacecraft; orbital configuration is less significant

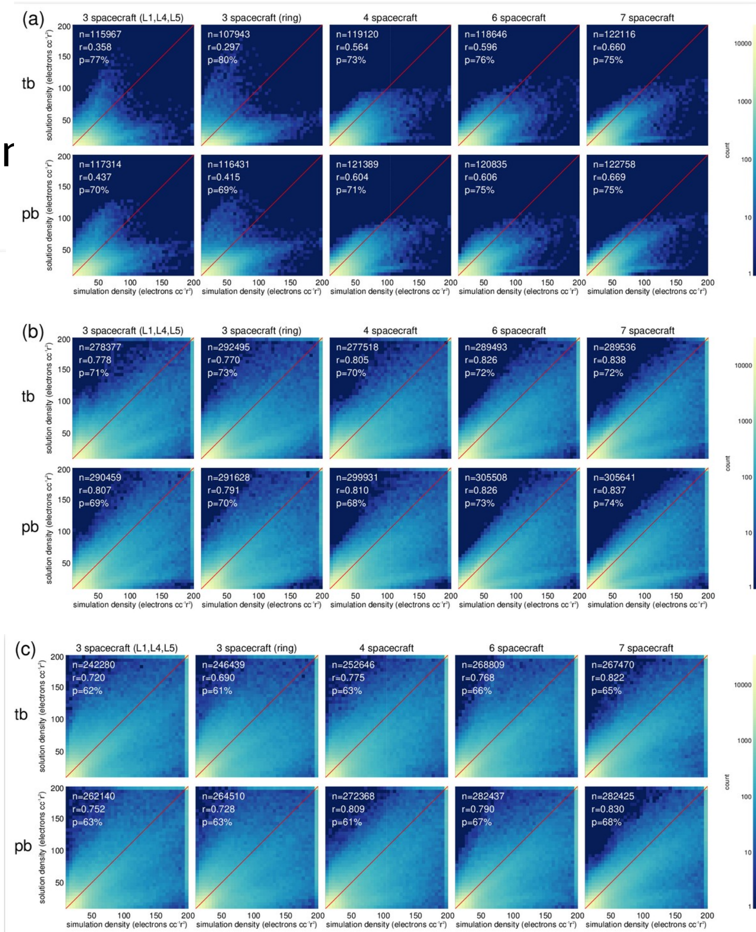


Results: Density Reconstruction

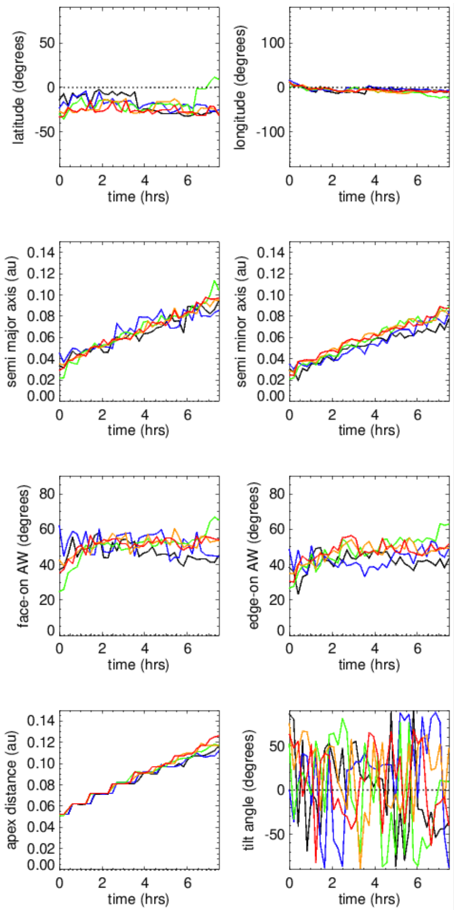
- We can perform a direct comparison between the 'real' density from the MAS simulations and the reconstructed densities from tomographic inversion



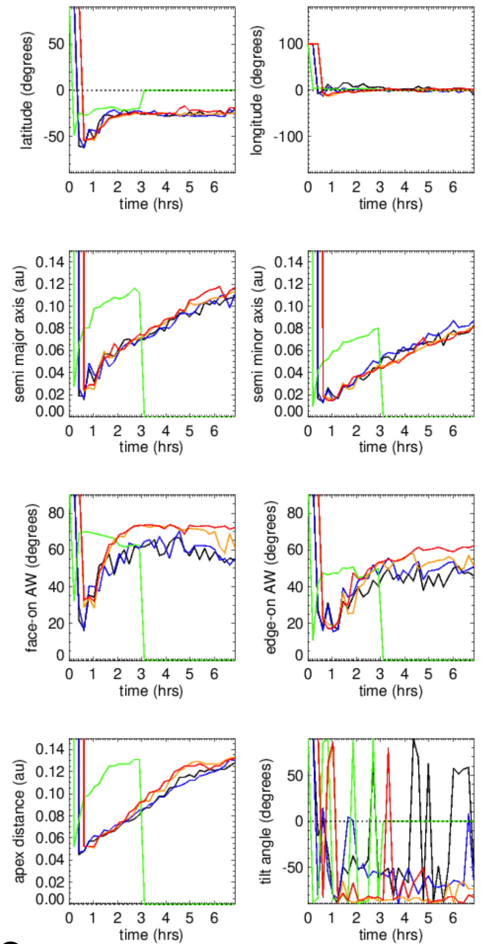




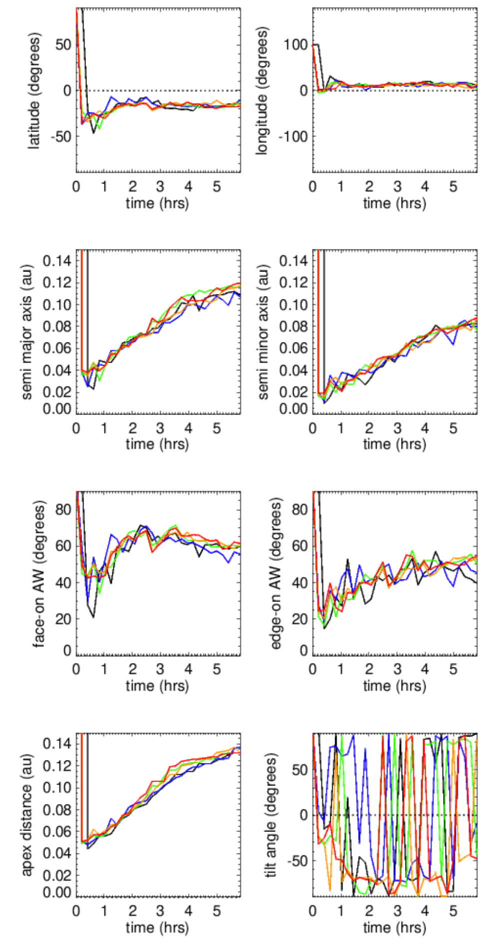
Results: CME parameters



CME1



CME2



CME3

Summary

- We use state-of-the-art MHD simulations to model three coronal mass ejections
- The simulated density is used to create realistic white-light coronagraph images fro a fleet of observing spacecraft

- Different combinations of these spacecraft are used in order to test the discrete tomography method as a means of reconstructing three-dimensional CME structure from two-dimensional images

- We find that a greater number of observing spacecraft improves to fidelity of the reconstruction

- The extra information afforded by polarised brightness measurements means that we are better able to constrain CME density structure

- The advantage of using pb images diminished with increasing number of spacecraft

- CME parameters, e.g. latitude, longitude, width, can be well constrained using just a small number of spacecraft