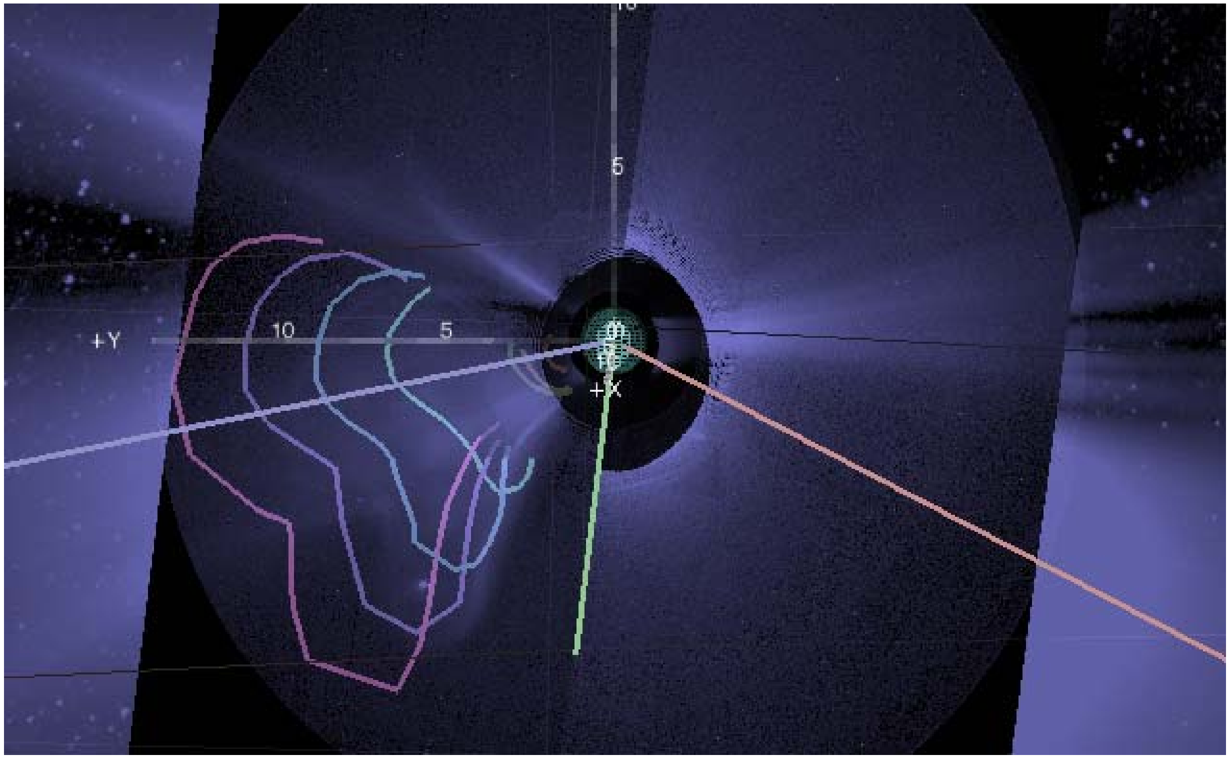
Determination of CME 3D Trajectories using COR Stereoscopy + Analysis of HI1 CME Tracks



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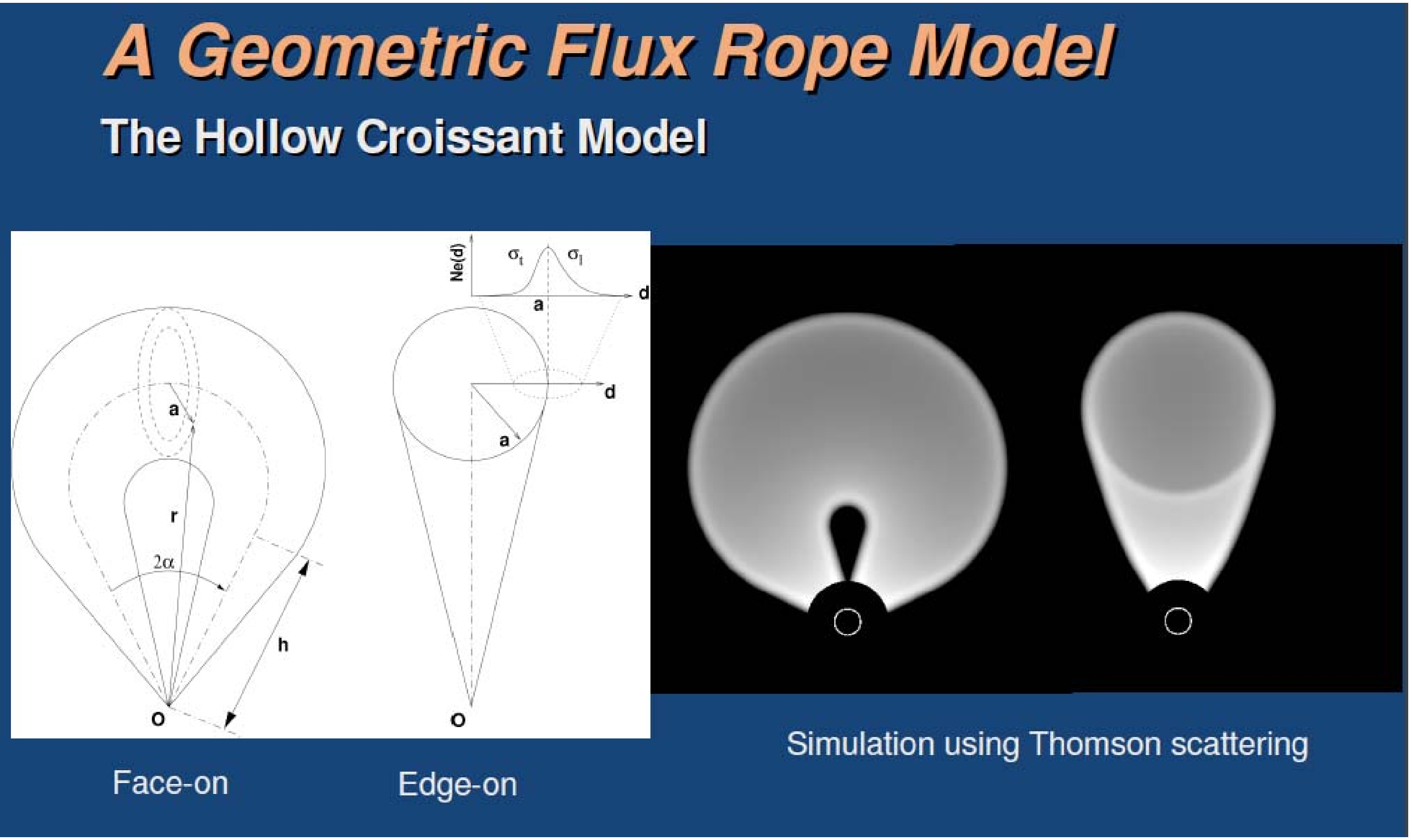
W. Thompson, GSFC and the SECCHI Team

STEREO SWG, Pasadena, February 2009

Outline

- CME trajectory can be determined from STEREO/SECCHI data using various techniques
- Here, we look at 3 CME events and compare trajectories from 3 techniques:
- Two techniques work near the Sun using data from CORs on SC A+B
  - Stereoscopy compared to forward modeling (Thernisien)
- Third technique – "Jplot" analysis uses COR + HI data from one SC (either A or B)
- Goal: Use Jplots of HI FOVs together with 3D trajectory determinations from CORs A+B to study CME propagation to 1 AU & interactions with the solar wind

Forward Modeling by Thernisien et al



Fit observed CME sequence to hollow croissant model (Thernisien et al ApJ 2006)

Assume radial motion at constant radial velocity

Fit determines velocity and propagation angle

Routines available in Solar soft

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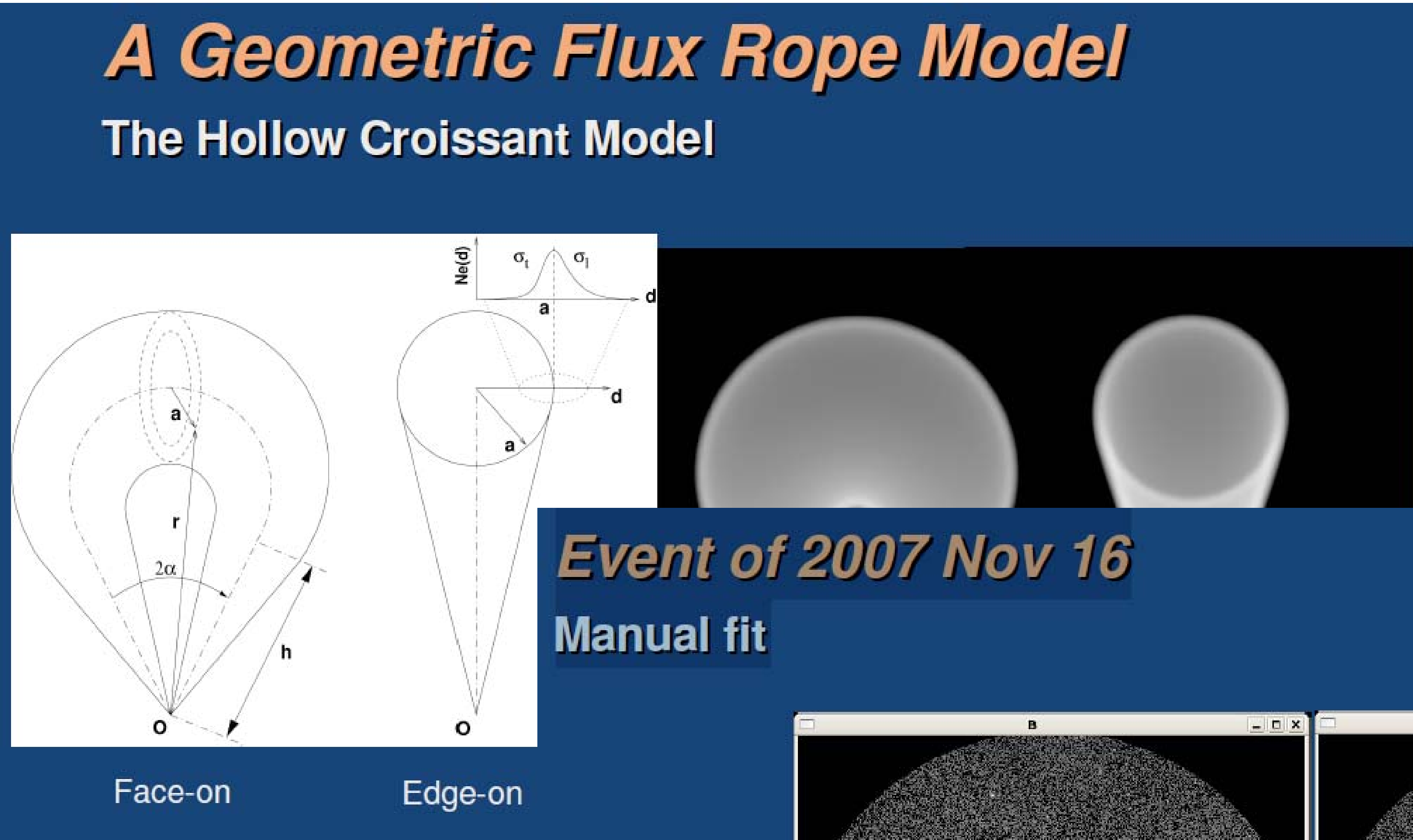

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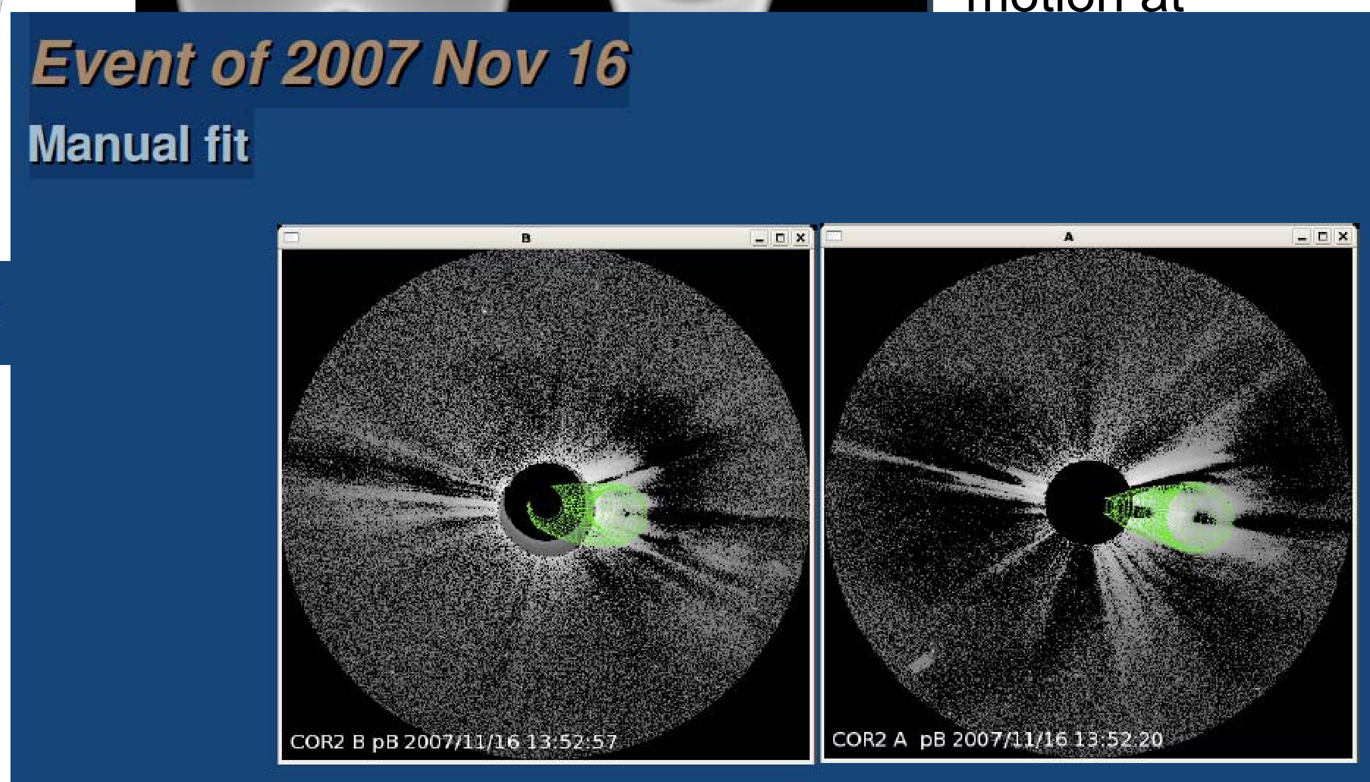
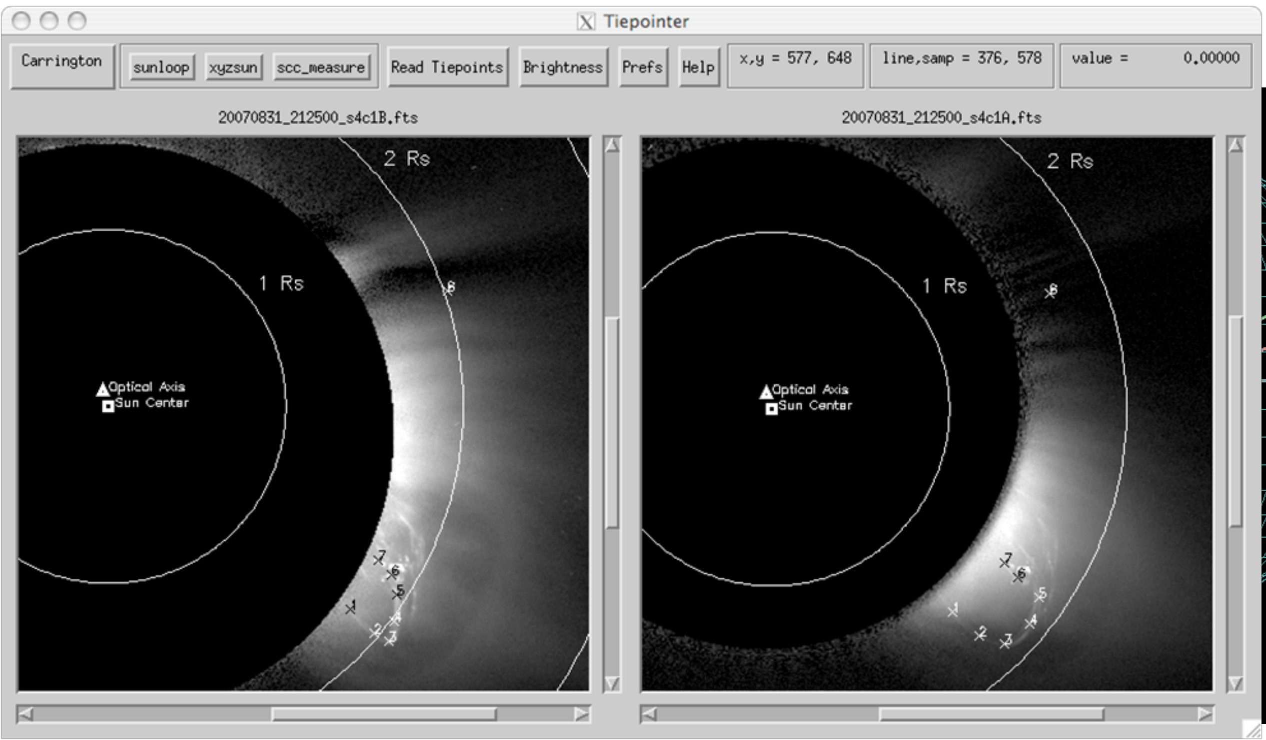
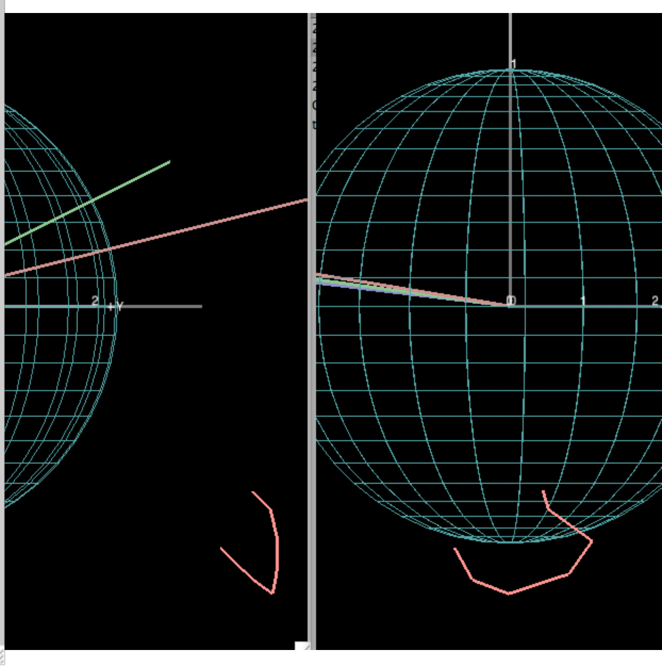


Stereoscopy & CMEs

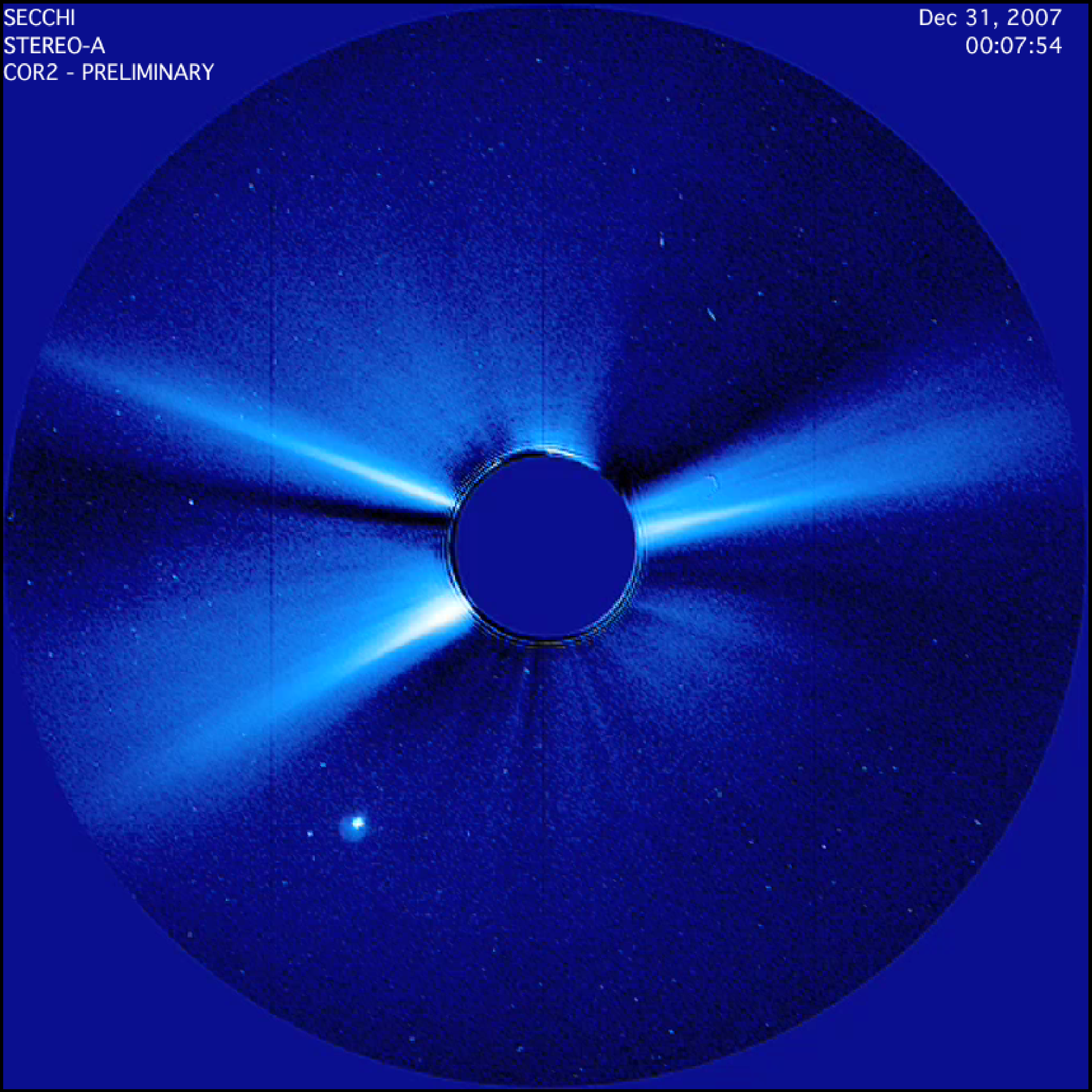
- STEREO's two views allows use of tiepointing and triangulation for 3D reconstruction of bright, localized features
- Below, tiepointing and reconstruction of bright filament seen in COR1 A&B 8/31/2007
- We use same technique to track LOS features such as CME bright leading edge
  - Comparisons with Thernisien forward modeling for 6 CMEs has shown that stereoscopy gives a good approximation of true location



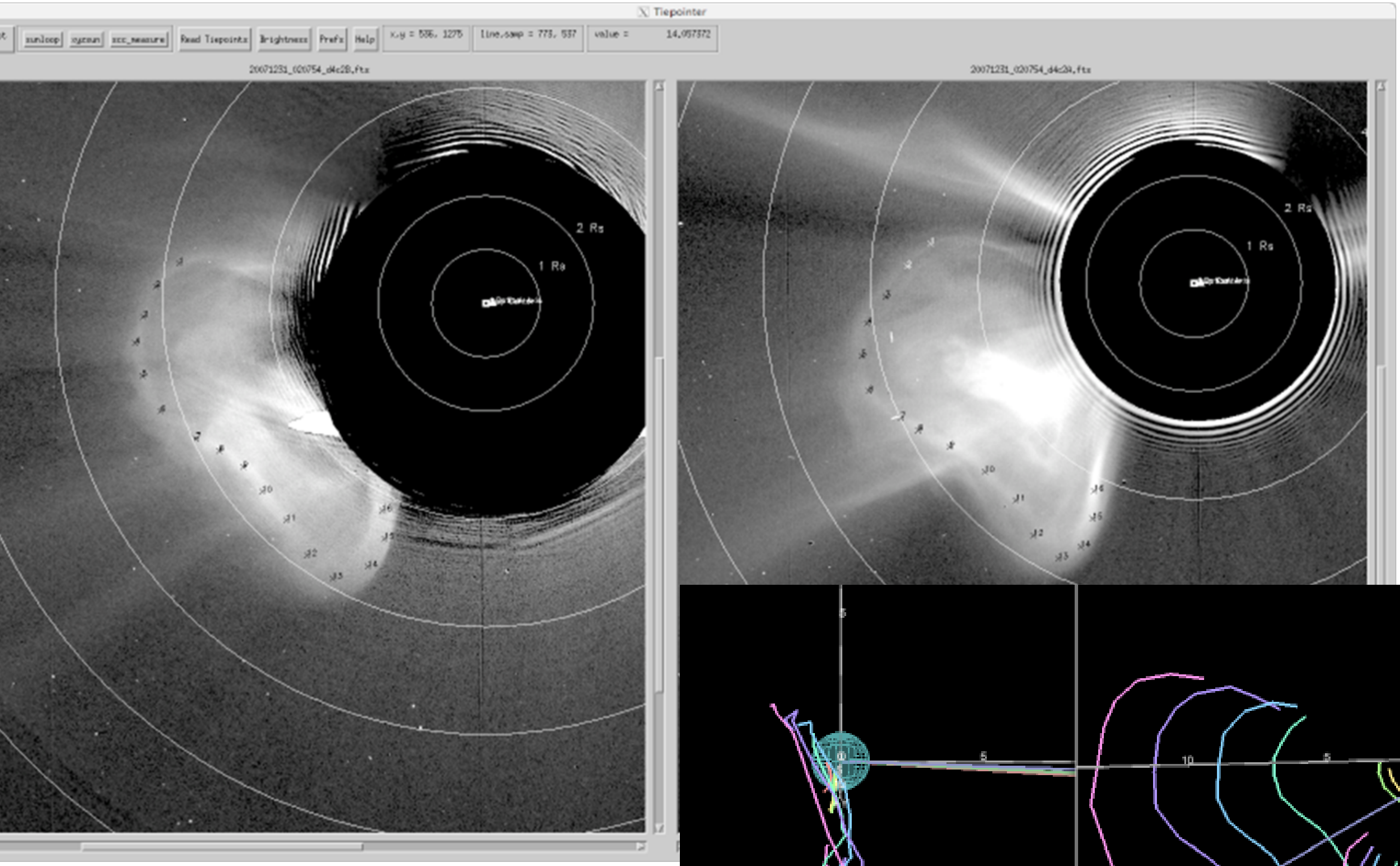
3D reconstruction from 2 views



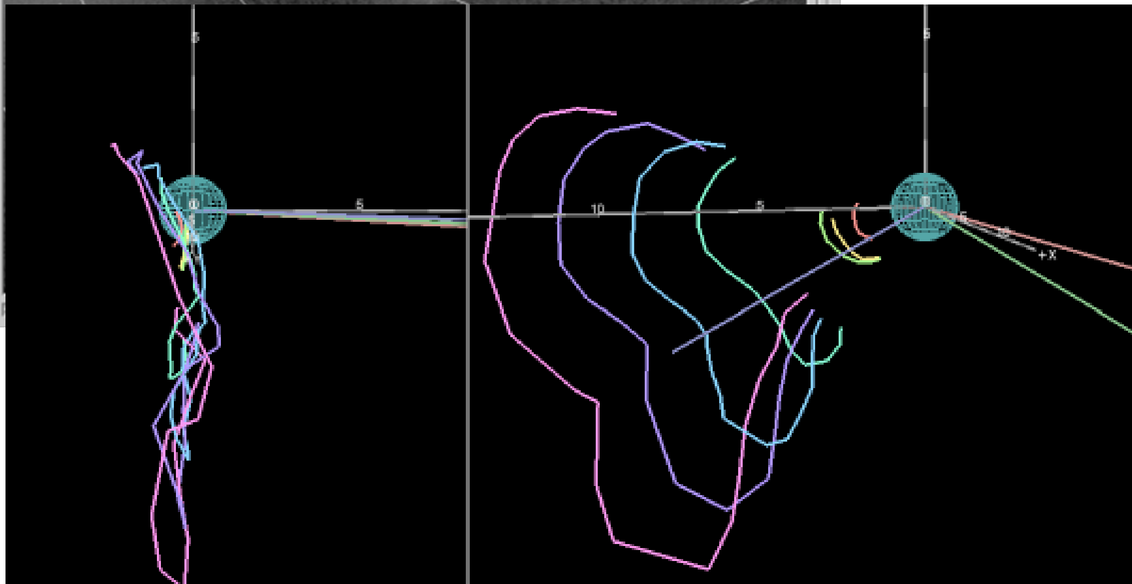
12/31/2007
CME
COR2A



December 31, 2007 CME - Trajectory Determination via Stereoscopy

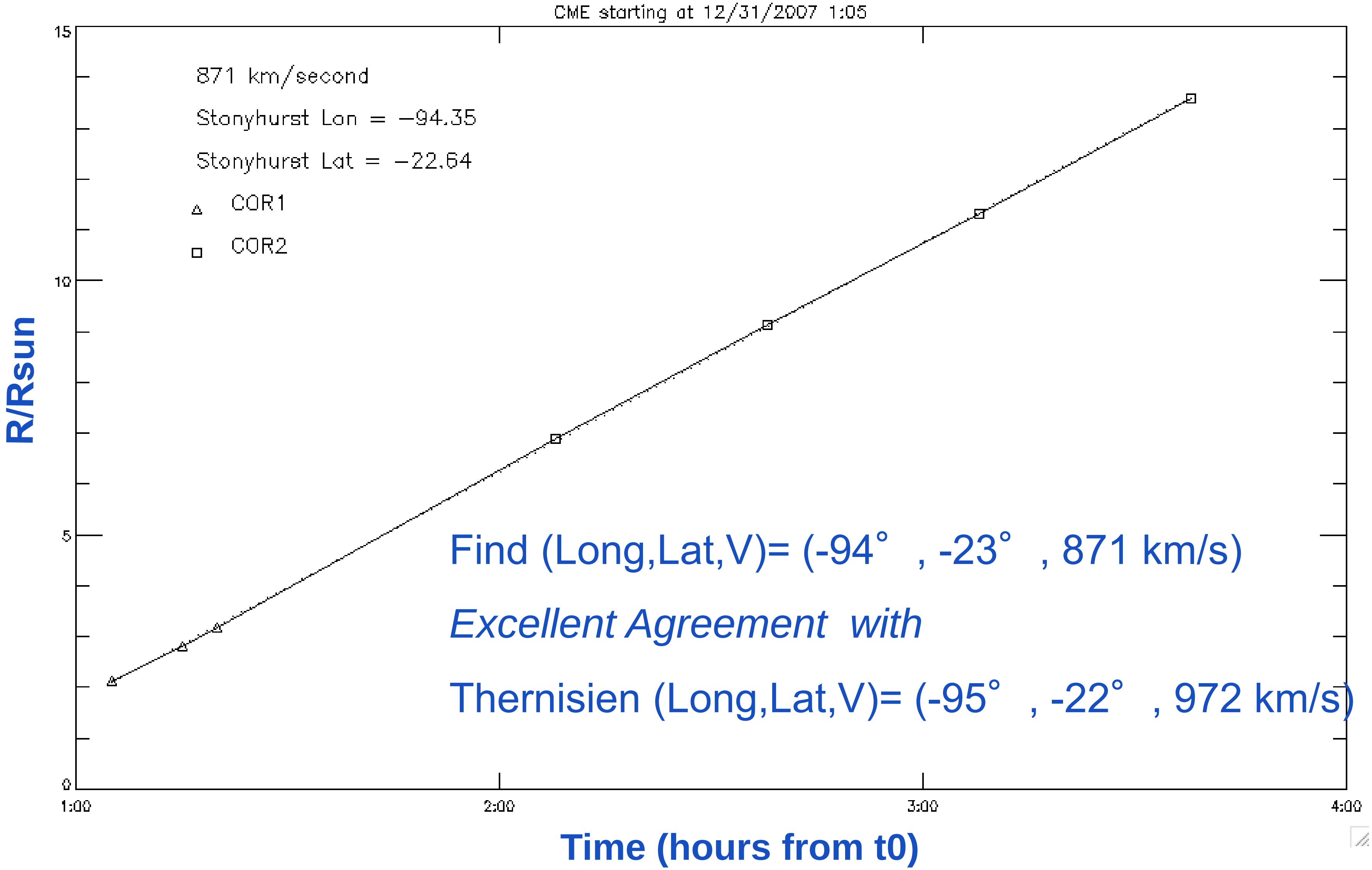


COR2 B&A Tiepoints @ 02:07:54



3D Reconstructions from Sterescopy at 7 times *COR1& COR2*

Dec 31, 2007: Determination of 3D Trajectory from Time Series of 3D Reconstructions



Find (Long,Lat,V)= (-94° , -23° , 871 km/s)

Excellent Agreement with

Thernisien (Long,Lat,V)= (-95° , -22° , 972 km/s)

How can we use CME Track in HI1&2?

- We have good determinations of CME trajectories in COR FOVs near the Sun
- Difficult to use stereoscopy on CME in HI FOVs
  – Often only visible in A or B, but not both
  – Very faint; Thompson scattering effects large
- Can we use HI tracks from single (A or B) to verify 3D trajectories from stereoscopic analysis?
  - Can we track different parts of a CME? Separate CMEs and CIRs?
- Can we use HI tracks to study interaction of CME with solar wind?

HI1A
12/31/07
CME

Tracks in HI FOVS – Elongation* vs. Time

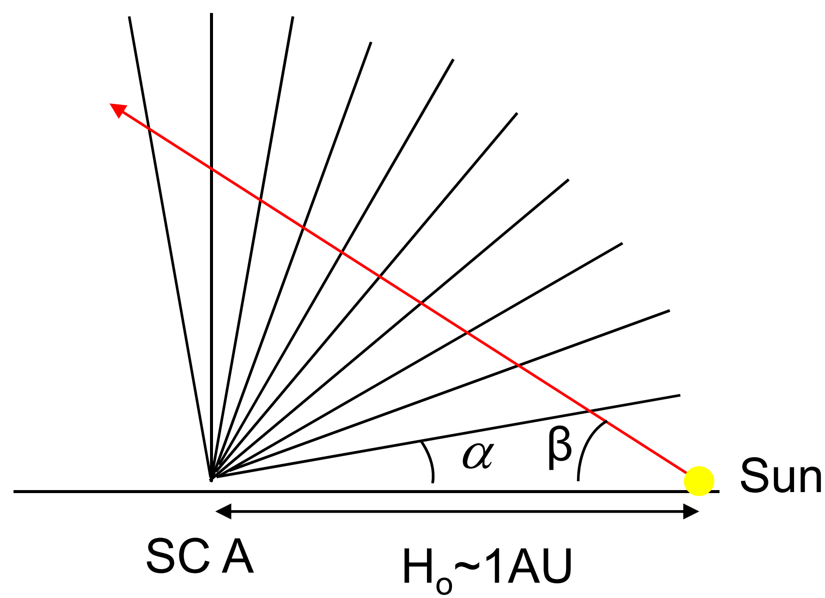
For large elongation angles α - as in HI FOVs -- CME tracks are NOT straight lines in plots of elongation α(t) vs time even if speed is constant *(See Sheeley et al., JGR 1999; Rouillard et al GRL, 2008)*

For CME propagating out radially at a constant speed v

$$\alpha(t) = \arctan\left[\frac{vt\sin(\beta)}{H_o - vt\cos(\beta)}\right]$$

Where H_o is distance to SC A or B

See Sheeley et al., JGR,1999
for derviation of the above formula



Cartoons from Rouillard et al
Polar view

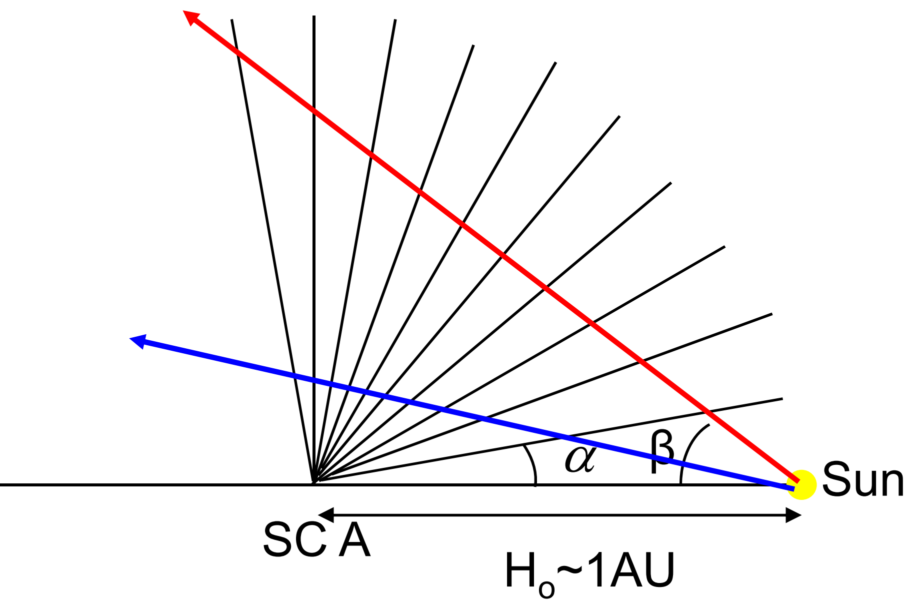
For a given value of speed *v* and angle β, there is a unique profile of elongation angle α(t) vs t

*** Elongation = angle from Sun**

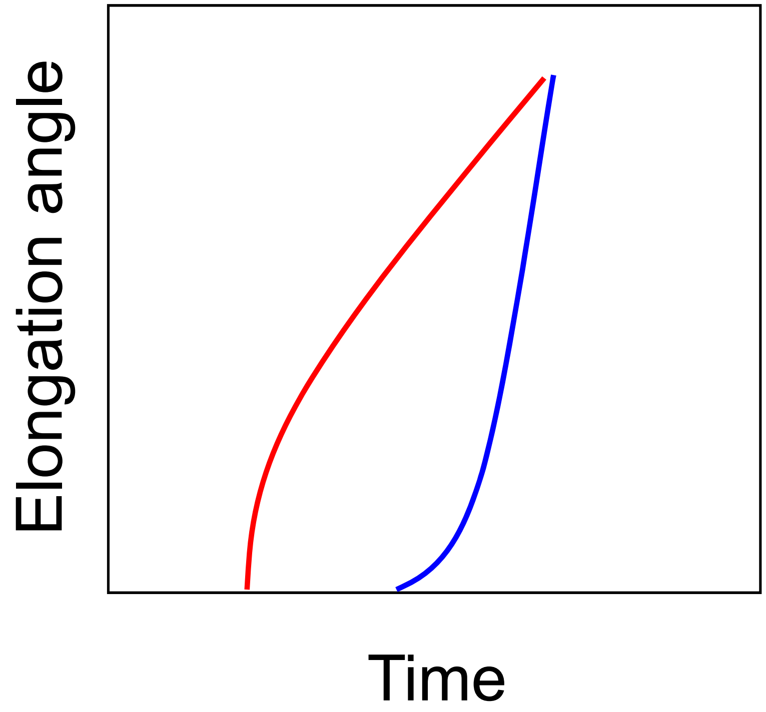
Elongation Profiles α(t) vs t

Assuming radial propagation, for a given value of speed *v* and angle β, there is a unique profile of α(t) vs t for the large elongations of HI FOVs

We want to use this to verify our stereoscopic determinations of *v* & β



Cartoons from Rouillard et al
Polar view point

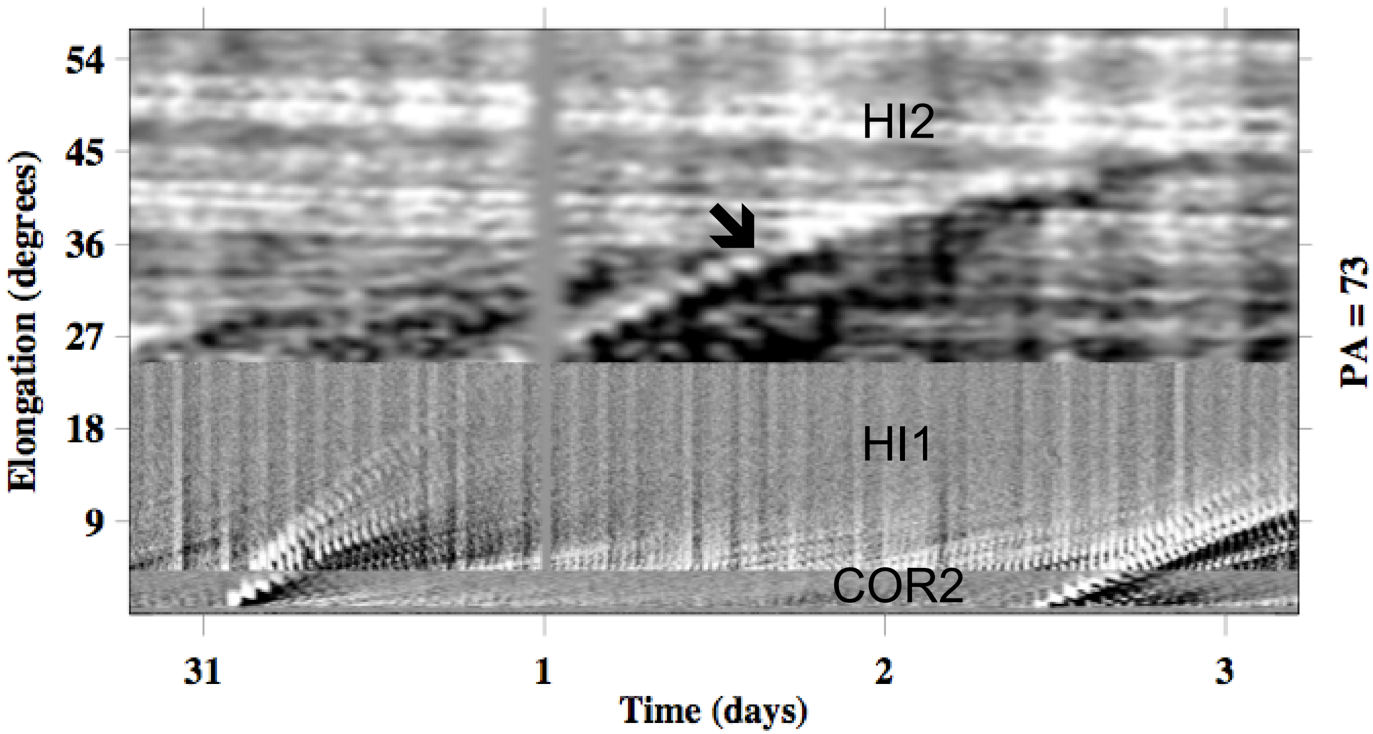


$$\alpha(t) = \arctan\left[\frac{vt\sin(\beta)}{H_o - vt\cos(\beta)}\right]$$

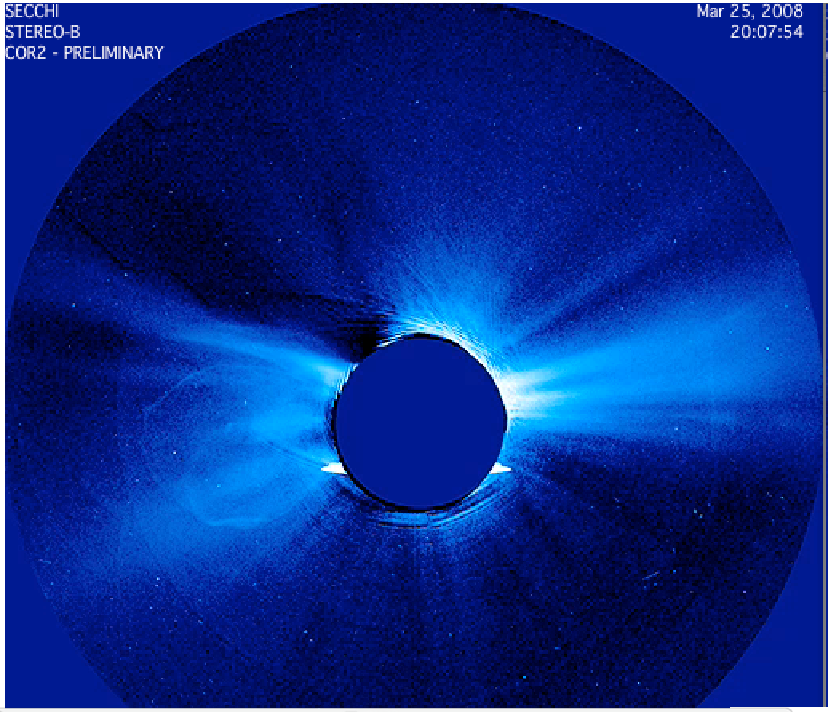
Third Technique: "Jplot" Analysis of Sheeley

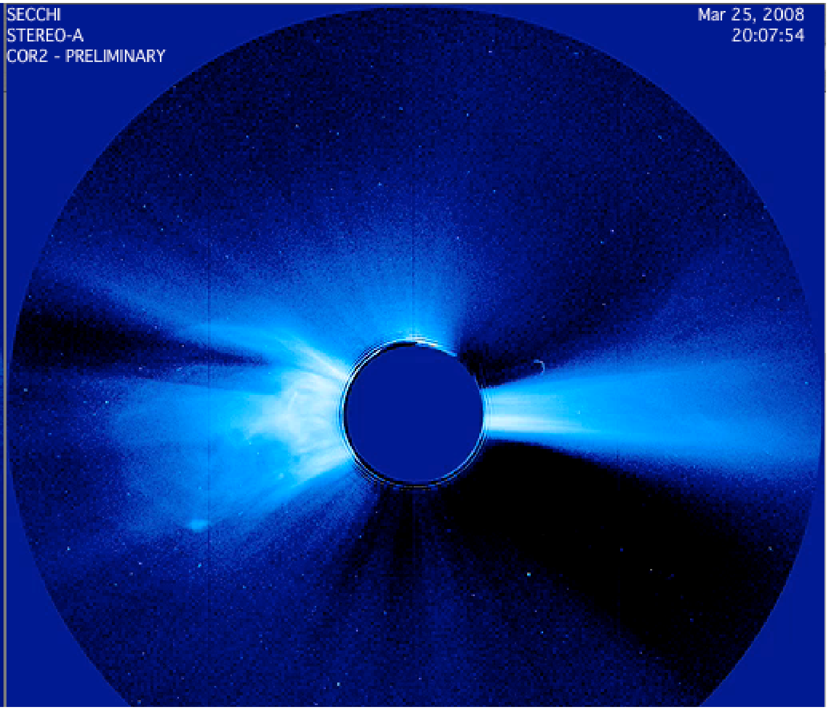
- Sophisticated image processing: difference images and star removal
- Plot elongation vs time for a fixed position angle PA (ccw from solar north)
- CME and other features (CIRs) show up as curved lines
  - Trajectory from stereoscopy used to identify appropriate feature
- Fit lines to analytic expression $\alpha(t) = \arctan\left[\frac{vt\sin(\beta)}{H_o - vt\cos(\beta)}\right]$ to determine propagation angle and speed
- Gives longitude = -93° in good agreement with stereoscopy *(but speeds differ)*

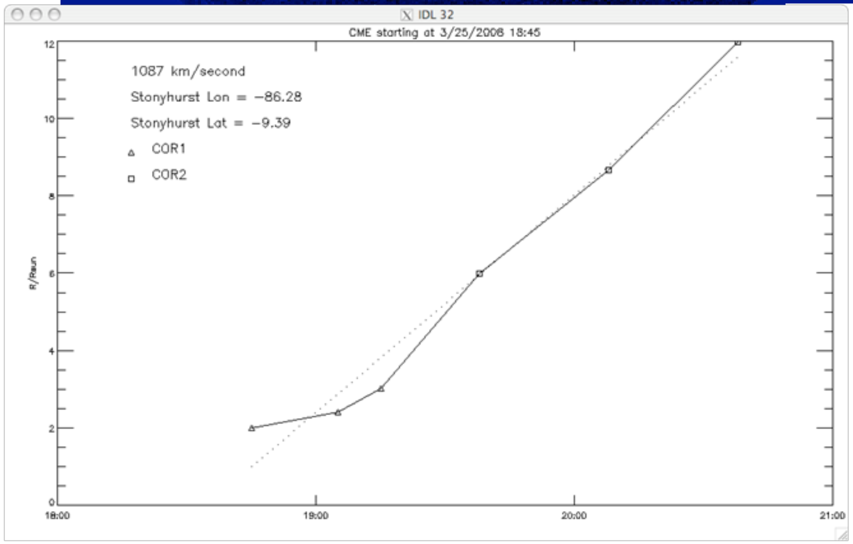
JPLOT for Dec 31, 2007 – Jan 3, 2008



Case 2: March 25, 2008 CME







Left: 3D Height time plot of R_{max}

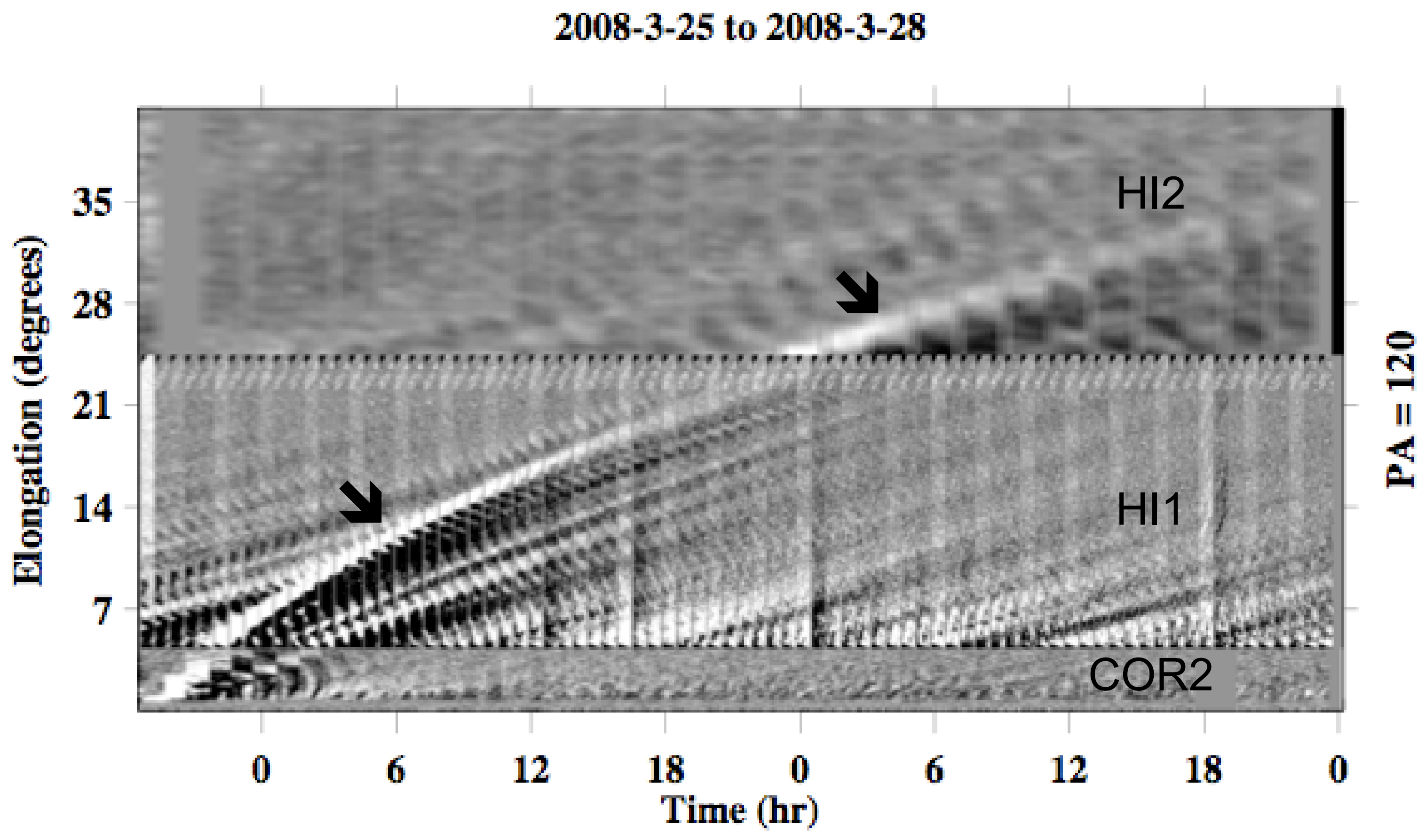
Find SH Longitude = -86°

Thernisien Longitude = -83°

"Jplot" Analysis by Sheeley

Case 2: March 25, 2008

- Plot elongation vs time for fixed position angle from 3D trajectory latitude
- CME is the bright curved line
- Fit lines to $\alpha(t) = \arctan\left[\frac{vt\sin(\beta)}{H_o - vt\cos(\beta)}\right]$ to determine propagation angle and speed



Comparison of Techniques

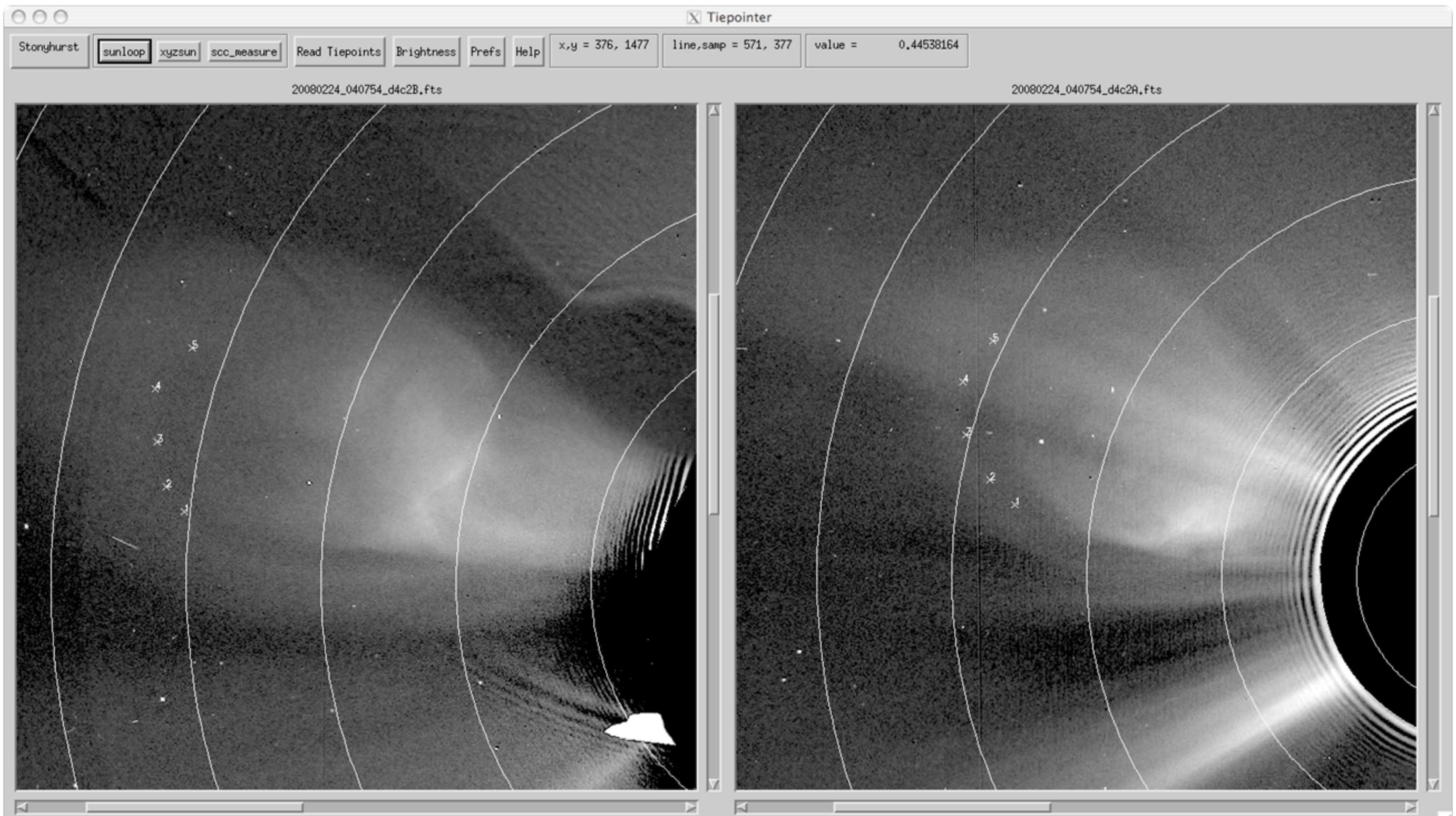
CME date	V (linear) km/s	V Thernisien	Latitude (degrees)	Lat Thernisien	Longitude from Earth	Longitude Thernisien	Longitude Sheeley
12/31/2007	871	972	-23°	-22°	-94°	-95°	-93°
2/23/2008	232	NA	18°	18°	-106°	-129°	-70°
3/25/2008	1087	1127	-9°	-14°	-86°	-82°	-82°

- Good Agreement on longitude for CMEs of 12/31/2007 and 3/25/2008
  - These CMEs were fast and well defined – makes tiepointing and model - fitting unambiguous

- For CME of 2/23/2008, techniques all differ by >30° in longitude – 70°, 106° and 129° degrees longitude.
  - What happened here?
  - CME was much slower….

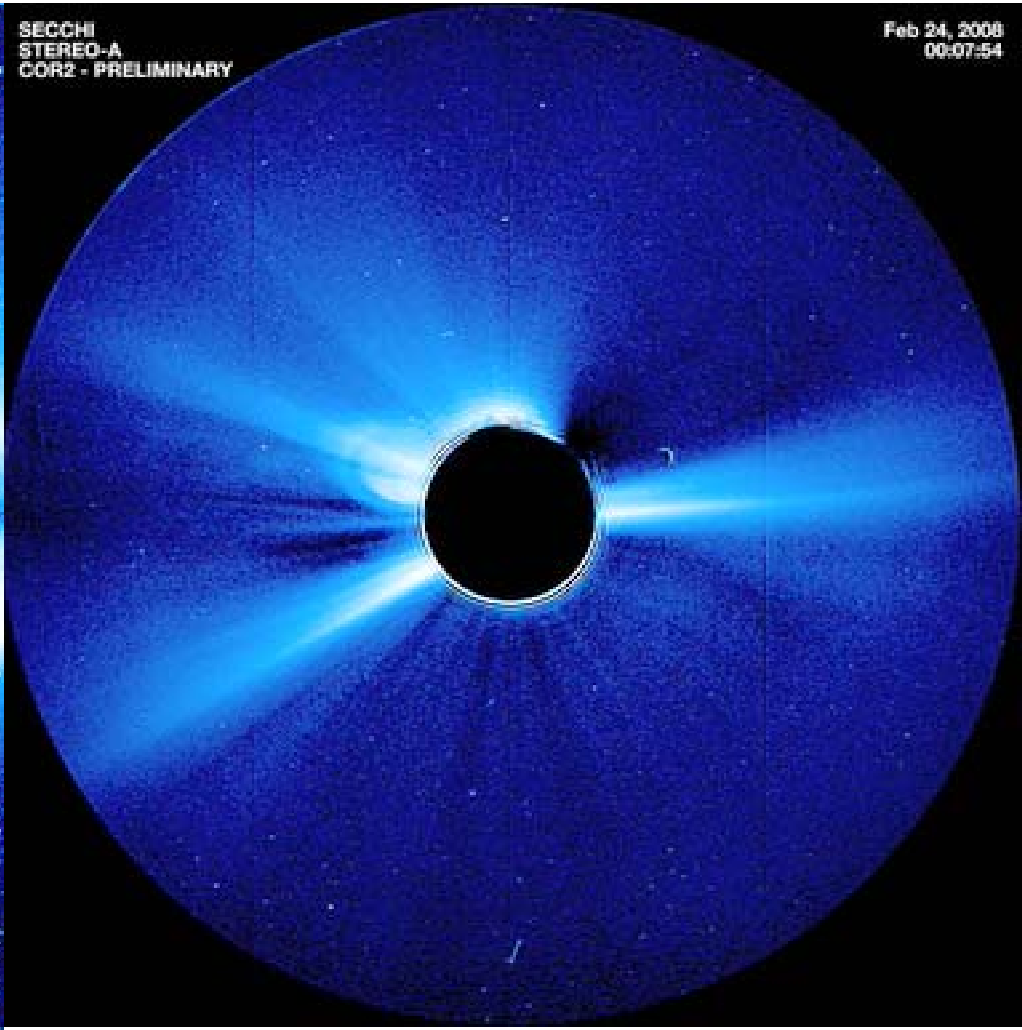
Case 3: CME of Feb 23, 2008

- Slow (<300 km/s) CME with ill-defined leading edge
- Discrepancy in stereoscopy and forward-modeling probably due to ambiguity in both techniques



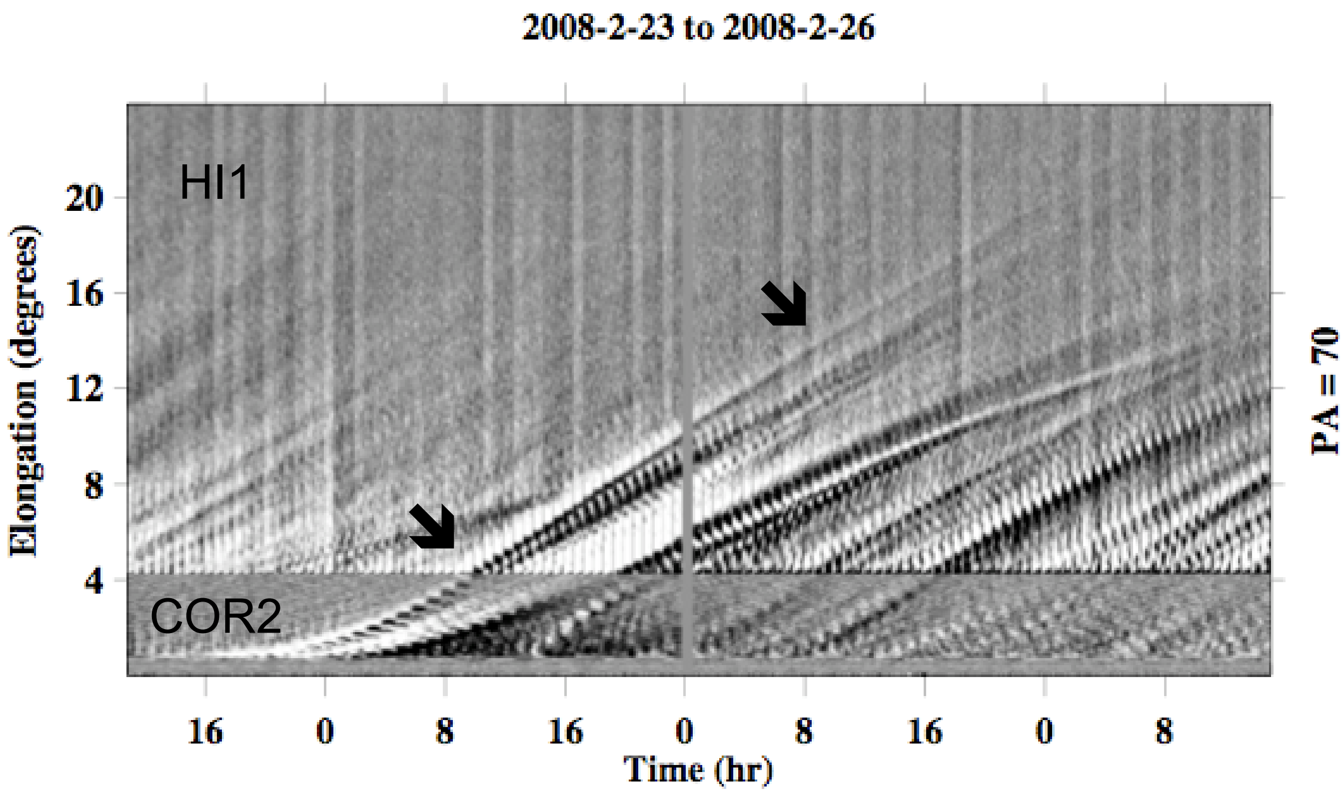
Case 3: CME of Feb 23, 2008

- SECCHI shows another faster feature coming up behind CME
- Do they interact?



Jplot for Feb 23, 2008 by Sheeley

- Plot shows evidence of CME interaction with other features
- Fit Non-constant velocity in HI FOV – invalidates constant velocity assumption used to get trajectory via fit



Conclusions

- Demonstrated that stereoscopy can be used to track CME propagation in 3D near the Sun (COR1&2 AB pairs
  - Validated approach by comparison with trajectories determinations by A. Thernisien using forward modeling fit to COR AB observations
  - Excellent agreement for fast, well defined CMEs
- First comparisons with trajectories obtained from Sheeley's Jplot analysis ("fit') of 2D tracks in HI1&2 FOVs
  - Use 3D trajectory to select CME "feature" in Jplots
  - Some agreement on 2 fast CMEs, but not on slow CME
  - Further analysis of differences should teach us more about CME propagation

Goal: Compare observed CME tracks in HI Jplots to extrapolated predictions from constant velocity propagation to understand CME propagation & interaction with solar wind

Conclusions

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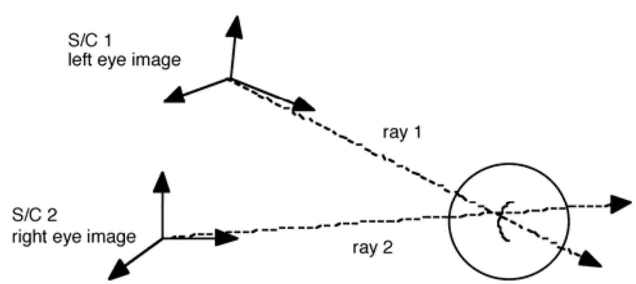
  - Excellent agreement for fast, well defined CMEs
- First comparisons with trajectories obtained from Sheeley's Jplot analysis ("fit') of 2D tracks in HI1&2 FOVs
  - Use 3D trajectory to select CME "feature" in Jplots
- Jplot trajectory agreed with 3D trajectory for 2 fast CMEs
- Techniques disagreed on longitude by >30° for slow CME

Goal: Compare observed CME tracks in HI Jplots to predictions from constant velocity propagation to understand CME propagation & interaction with solar wind

Stereoscopy and STEREO/SECCHI

- SECCHI uses World Coordinate System (WCS) solar soft routines to relate image plane coordinates to heliocentric coordinate systems *(see W. Thompson, A & A, 2005, MS 4262thom)*
  - Need location of spacecraft A&B (from emphemeris), pixel size (arcsec), and pixel location of Sun-center (x_{SUN} , y_{SUN}).
- Each pixel defines a unique ray
  - In a single 2D image, feature can be anywhere along ray
  - In 3D, if perfect tiepointing, rays intersect at feature
- Triangulation program locates feature at point of closet approach of the two rays



Summary

3D Trajectories and Comparison with Thernisien Forward Modeling Determinations

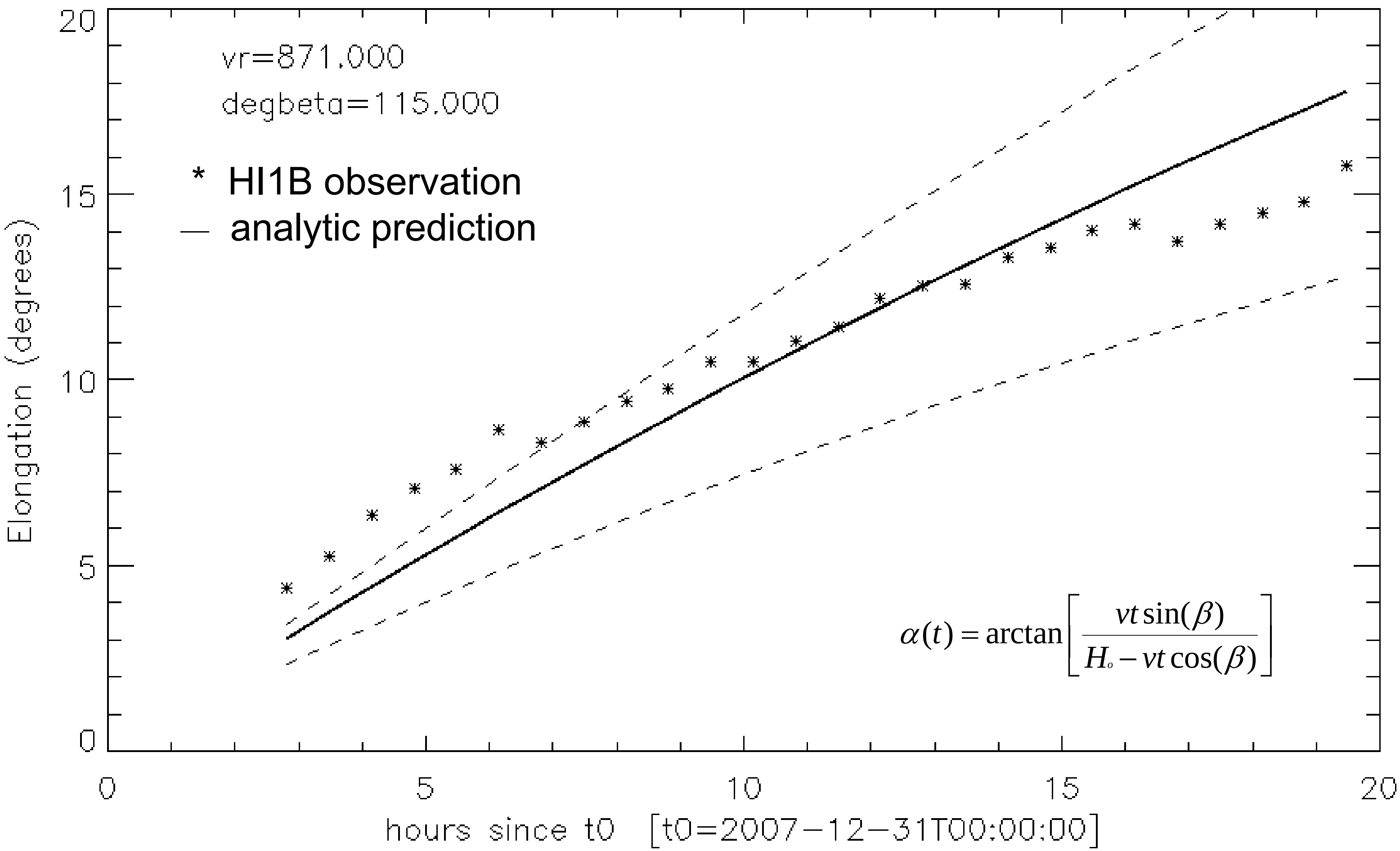
CME date	FOVs tracked	V (linear) km/s	V Thernisien	Latitude (degrees)	Lat Thernisien	Longitude from Earth	Longitude Thernisien
8/31-9/01/2007	EUVI-COR1-COR2	313	NA	-23	NA	64°	NA
11/16/2007	COR2	383	345	-13°	-15°	159°	132°
12/31/2007	COR1-COR2	871	972	-23°	-22°	-94°	-95°
1/02/2008	EUVI-COR1-COR2	614	731	-4°	-9°	-65°	-56°
2/23/2008	COR2	232	NA	18°	18°	-106°	-129°
3/25/2008	EUVI-COR1-COR2	1087	1127	-9°	-14°	-86°	-82°

- ***Remarkably good agreement on 3D trajectory - longitude, latitude and speed!***

Comparison of Observed and Predicted Tracks

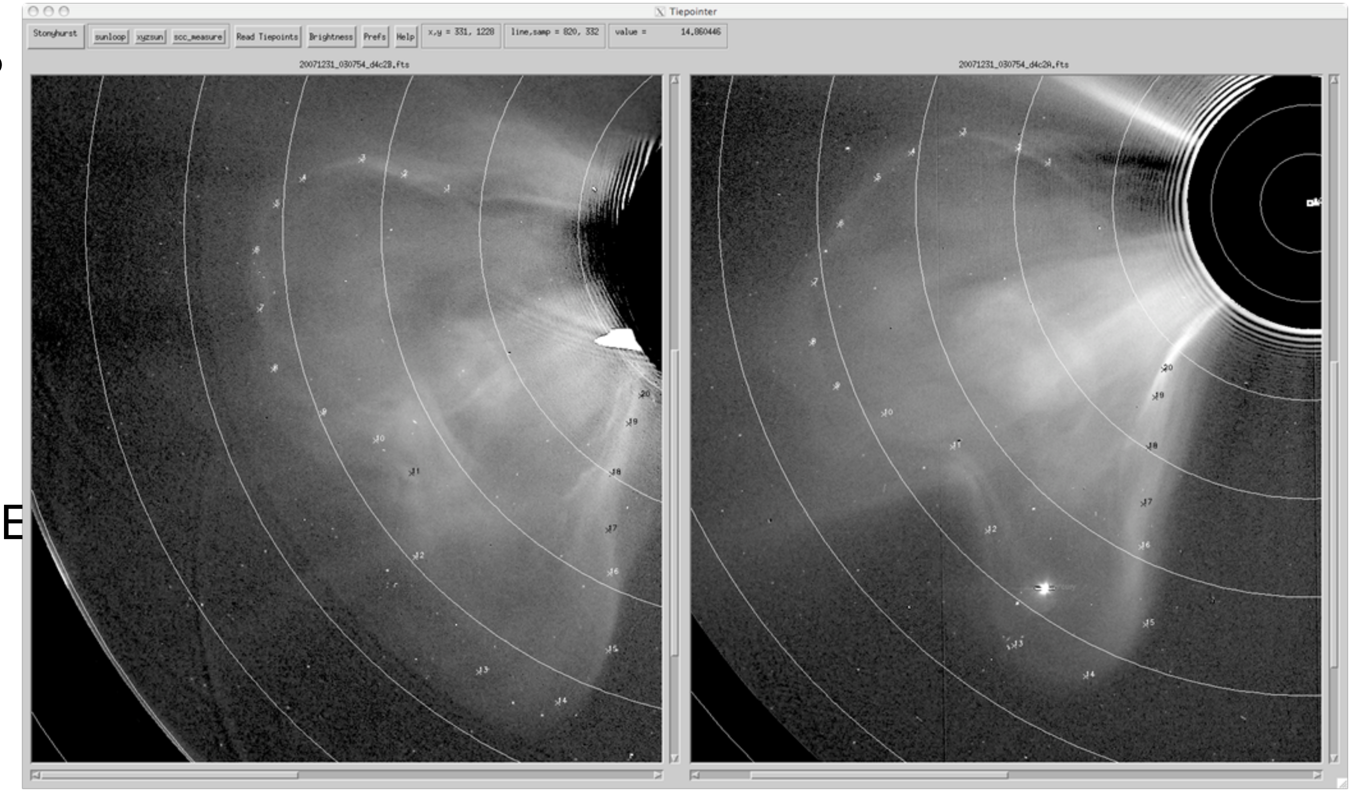
December 31, 2007

- Use analytic expression for α(t) vs t using velocity *v* and propagation angle β determined stereoscopically
- Compare with α(t) vs t determined from HI1B using scc_wrunmoviewm.pro



$$\alpha(t) = \arctan\left[\frac{vt\sin(\beta)}{H_{\circ} - vt\cos(\beta)}\right]$$

12/31/2007 & 3/25/2008 had well defined CME fronts



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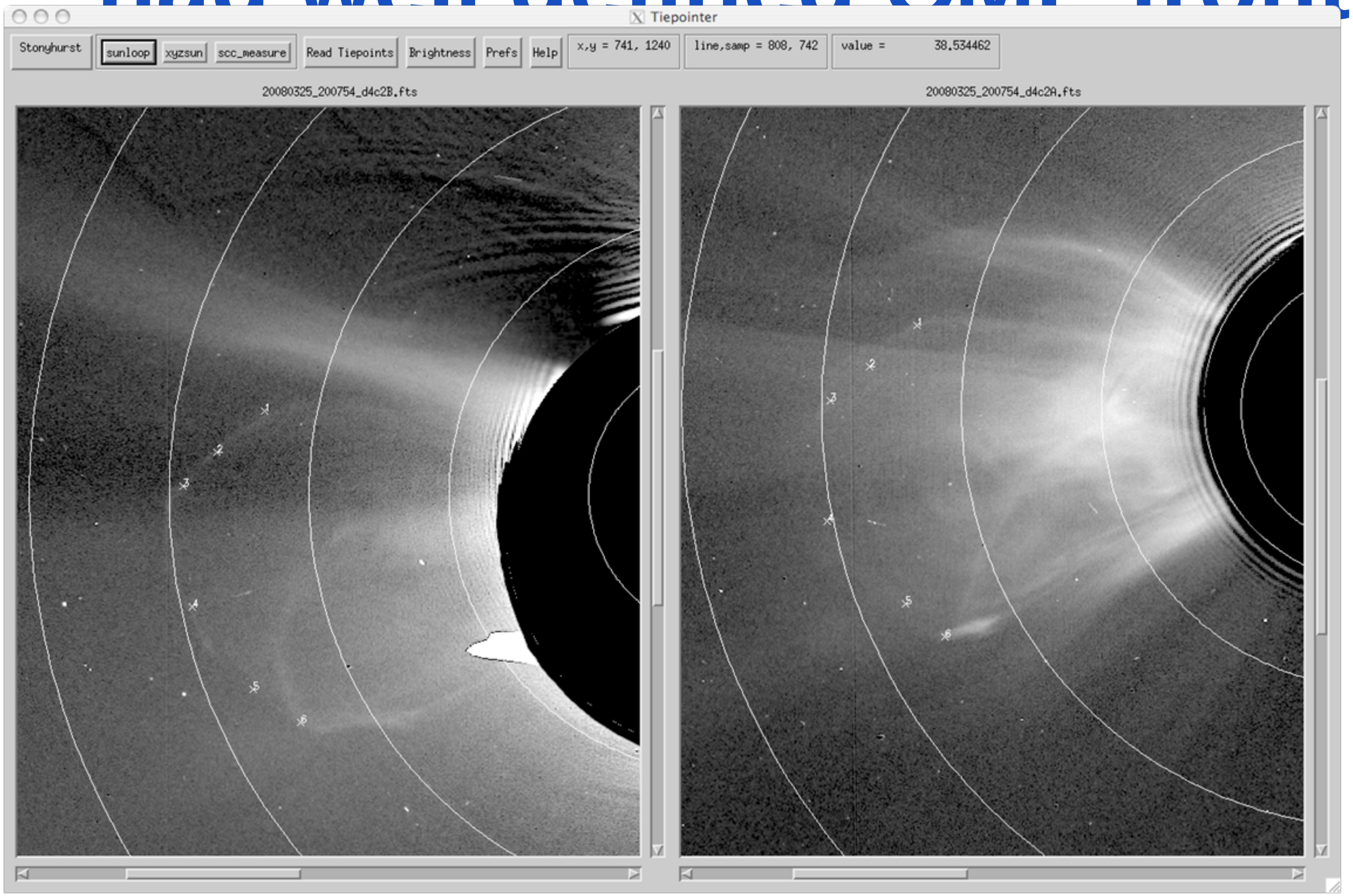

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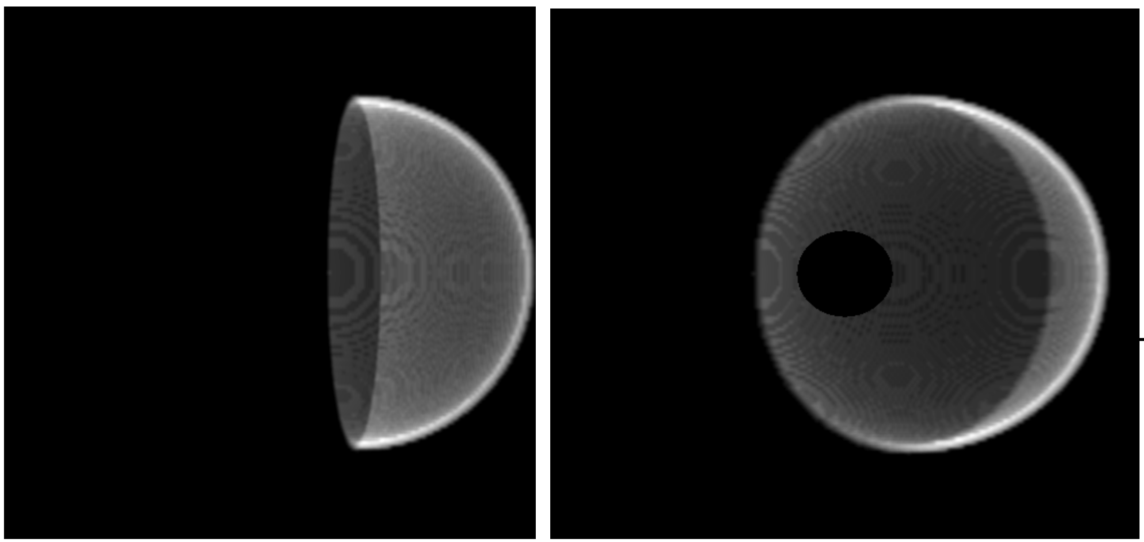
Stereoscopy of CMEs vs Localized Structures

- Because CMEs are so diffuse, stereoscopy on line-of-sight (LOS) coronagraph images gives approximate 3D location of CME "edges"

COR2 - SC A at -20° **COR2 - SC B at +20°**



Synthetic image pair from hemisphere shell CME model