Stereoscopic Observations of CMEs in HI fields-of-view Comparing different methods

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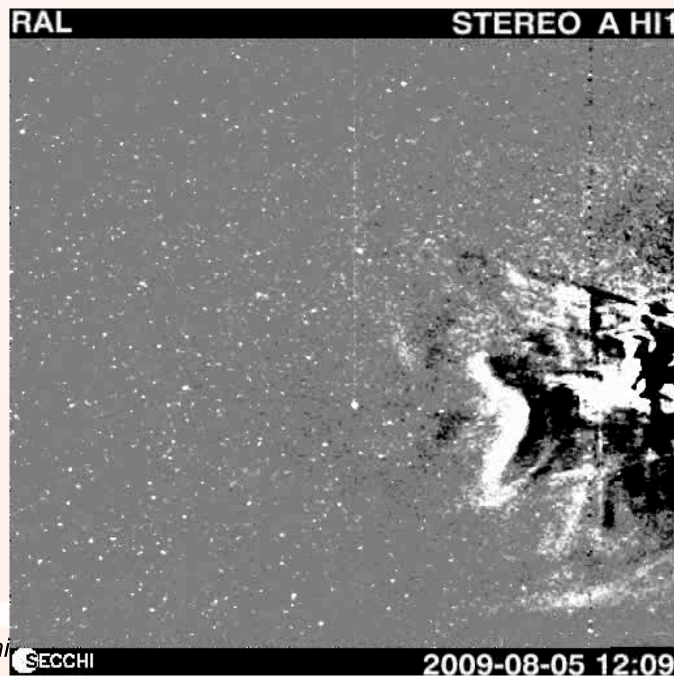
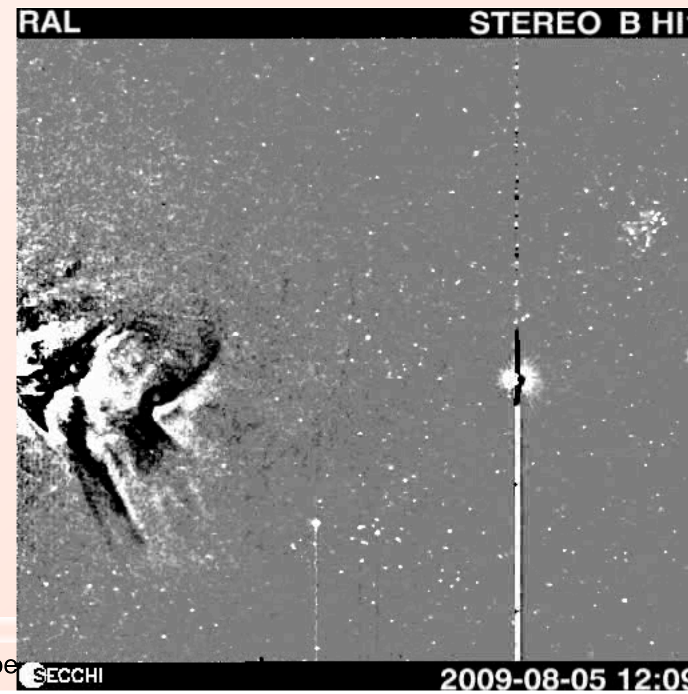
How many CMEs?

- Stereoscopic observations are very common in EUV and CORs, what about HIs?
- None in 2007.
- About 5 CMEs observed in 2008:
  - April 26 , *June 2*, August 30, November 3, December 12.
- About 10 observed in 2009 (excluding December):
  - January 9, 10 & 22, May 9 & 13, **August 25**, September 4, October 18, *November 1* & 21.





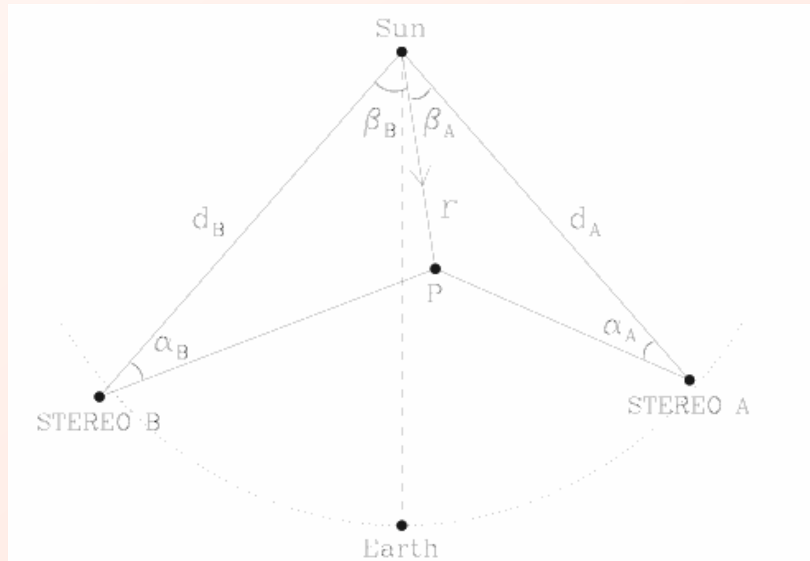
Existing Methods (by late 2009)

- Assume no deflection and use values from COR data. Many methods (Mierla et al., McAteer et al., Thernisien et al.) can provide "initial" direction. Problems:
  - Not enough to study heliospheric properties (deflection, etc…)
  - Not fully using HI data.
- One can fit constant (V,alpha) and it has proven successful (RAL). Problems:
  - Fast CMEs do not have a constant speed,
  - Different direction for ST-A and ST-B data,
  - How much better are these procedures compared to LASCO?
- Geometrical reconstruction (Wood et al.) has also proven successful (NRL).
  - Can provide size and orientation on top of direction,
  - Problems:
    - Usually used with self-similar and constant acceleration approximations.
    - More quantitative methods are needed

Direct triangulation (Liu et al., 2010)

- **One has to use the correct distances for the STEREO spacecraft**
- Liu et al.'s formula

$$\tan \beta_A = \frac{\sin \alpha_A \sin(\alpha_B + \gamma) - \sin \alpha_A \sin \alpha_B}{\sin \alpha_A \cos(\alpha_B + \gamma) + \cos \alpha_A \sin \alpha_B},$$

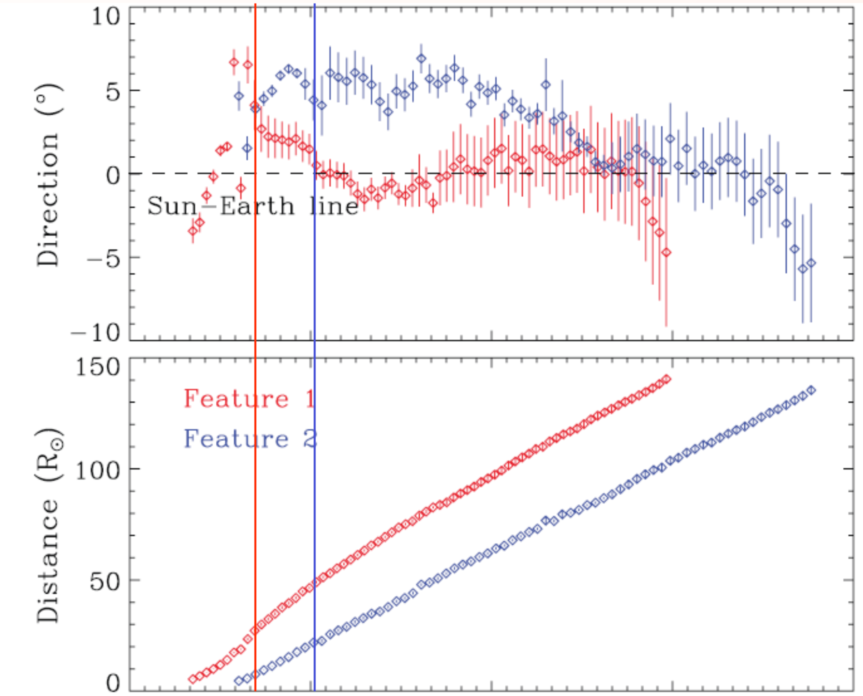


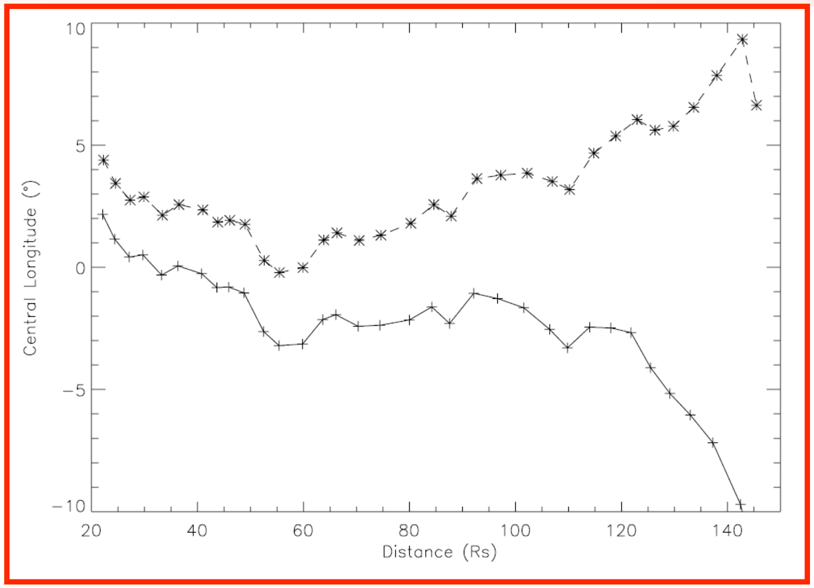
- 12/12/2008 CME front 2
  - dA = 0.967 AU , dB = 1.039 AU
  - 12/15 @ 20:40UT
    - alphaA = 40.4° alphaB = 39.7°
    - Plugging in beta_Earth = -4.5°
    - But rA = 135 Rs ≠ rB = 145 Rs
  - Correct formula:
    - Beta_Earth = 13°
  - Here dB/dA = 1.07
    - $(dB/dA)_{max}$ = 1.13
    - $(dB/dA)_{min}$ = 1.04

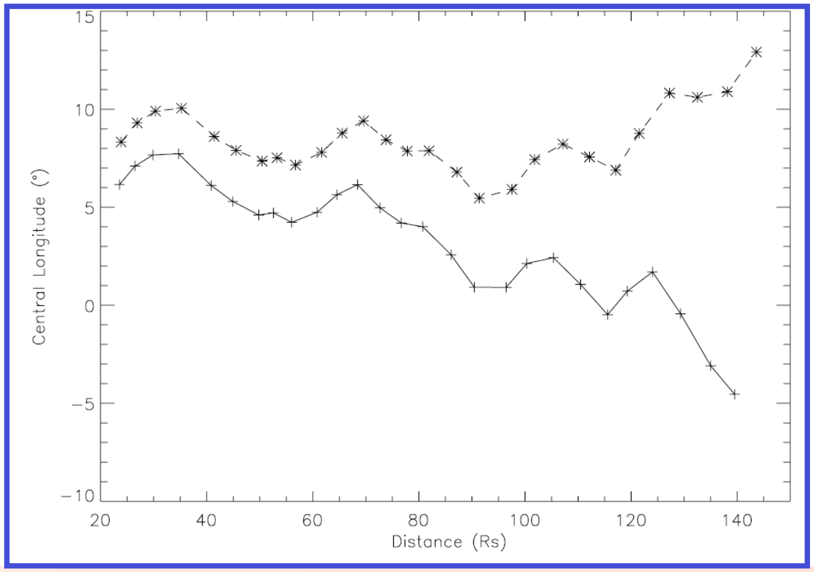
$$\tan \beta = \frac{P \sin(\alpha_A + \gamma_A) - \sin(\alpha_B + \gamma_B)}{P \cos(\alpha_A + \gamma_A) + \cos(\alpha_B + \beta_B)}$$

$$P = \frac{d_B \sin \alpha_B}{d_A \sin \alpha_A}$$

Analysis of the December 12 CME with corrected formula



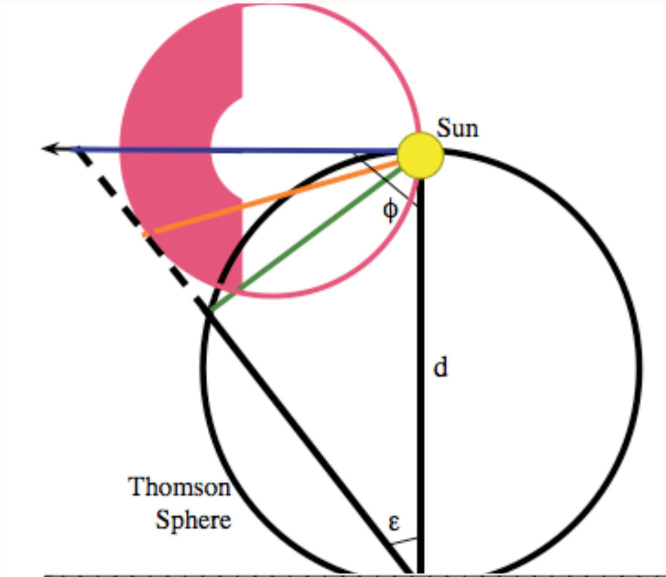




- Decrease in longitude at late time in Liu et al. (2010) is absent using the corrected formula.
- CME appears to move radially outward. Second feature is about 5º west of the first feature.

New geometrical method to derive CME position from elongation angle

(Lugaz et al., Ann. Geo., 2009)



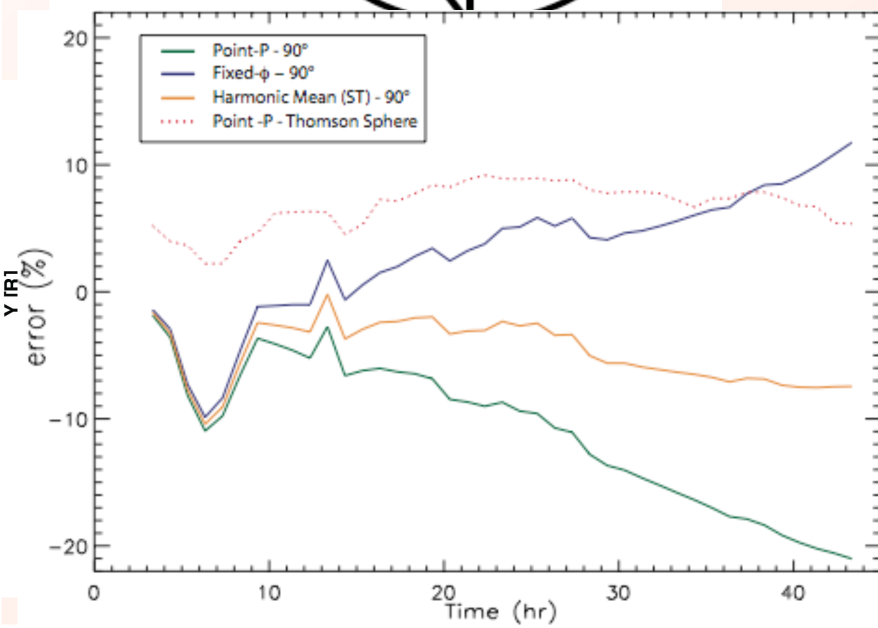
- Instead of using single-point approximation or assuming a spherically symmetric front we use a sphere attached to the Sun.
- New assumption is good for wide CMEs (better than Point-P).
- It can be shown that:

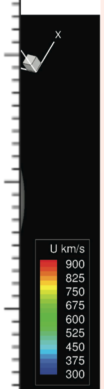
$$r_{F\phi} = d \sin \varepsilon / \sin(\varepsilon + \phi)$$

$$r_{PP} = d \sin \varepsilon$$

$$r = 2d \sin \varepsilon / (1 + \sin(\varepsilon + \phi))$$

$$1/r = .5\,(1/r_{PP} + 1/r_{F\phi})$$



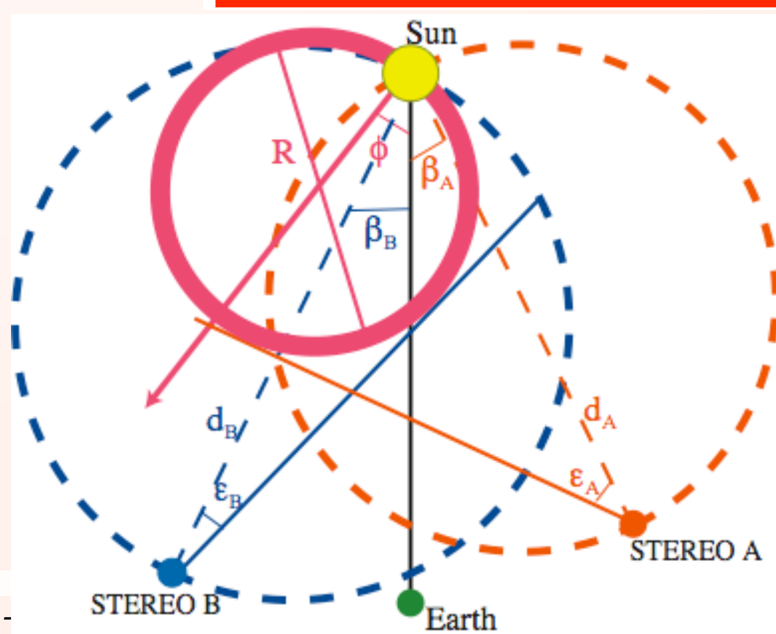


Geometrical Model

Fixed size

Varying direction

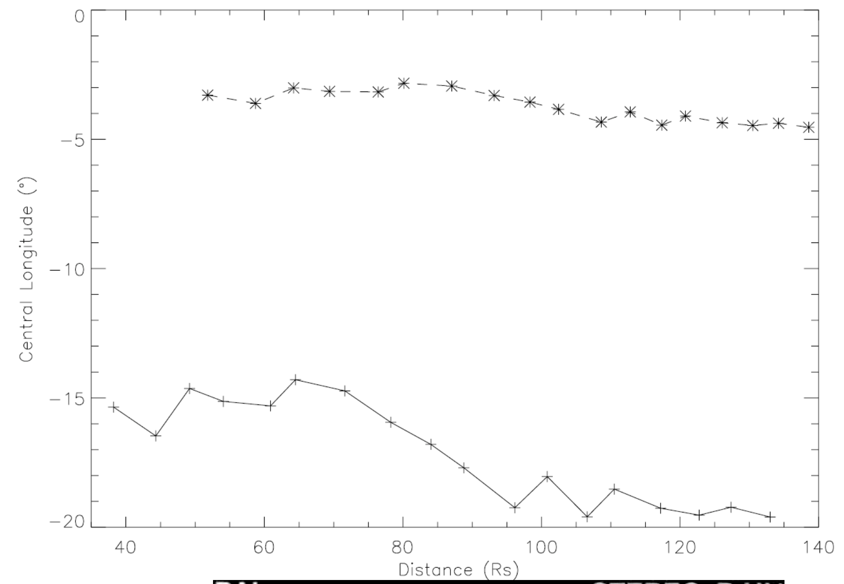
$$
\begin{aligned}
\phi &= \boxed{\arcsin\left(\frac{P-1}{Q}\right)} + \boxed{\beta}, \quad \text{with} \\
P &= \frac{d_B \sin\alpha_B}{d_A \sin\alpha_A}, \\
Q &= \sqrt{P^2 + 2P\cos(\gamma_B+\gamma_A+\alpha_B+\alpha_A)+1}, \quad \text{and} \\
\tan\beta &= \frac{P\sin(\gamma_A+\alpha_A)-\sin(\gamma_B+\alpha_B)}{P\cos(\gamma_A+\alpha_A)+\cos(\gamma_B+\alpha_B)}.
\end{aligned}
$$

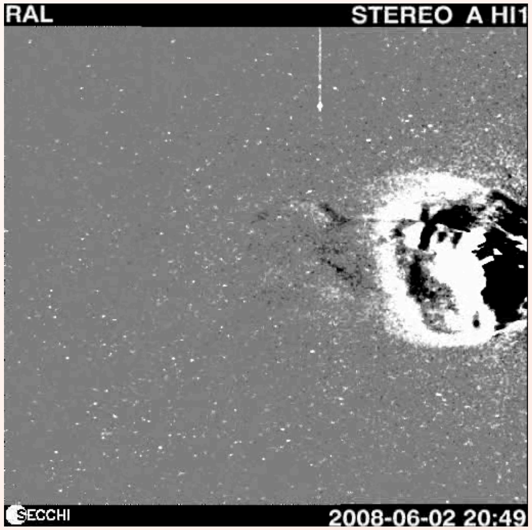


- Same as previous model but with 2 spacecraft.
- **Both satellites do not observe the same plasma element.**
  - Red box: same as direct triangulation
  - Blue box: new term
- Can track CMEs which are not propagating between the spacecraft.

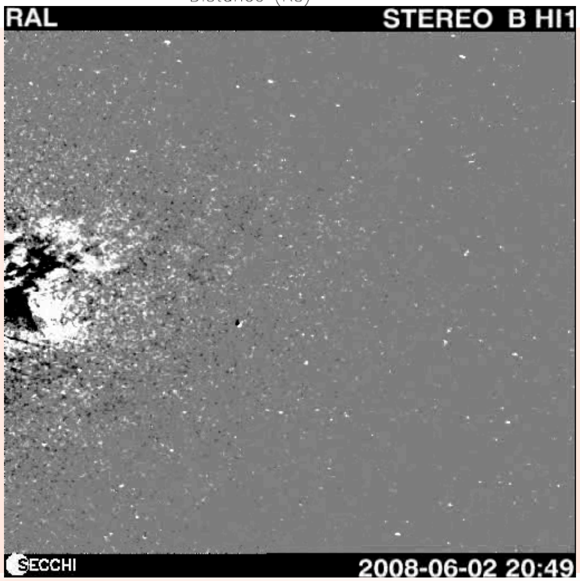
June 2, 2008 CME

- RAL:
  - ST-A: V = 366 km/s, beta = -24º ± 5.5º
  - ST-B: V = 298 km/s, beta = 21º ± 11.5º
- Triangulation:
  - V = 342 km/s, beta = -4º
- Tangent:
  - V = 374 km/s, beta = -17º
- Thernisien et al. (2009):
  - V = 260 km/s, beta = -37º



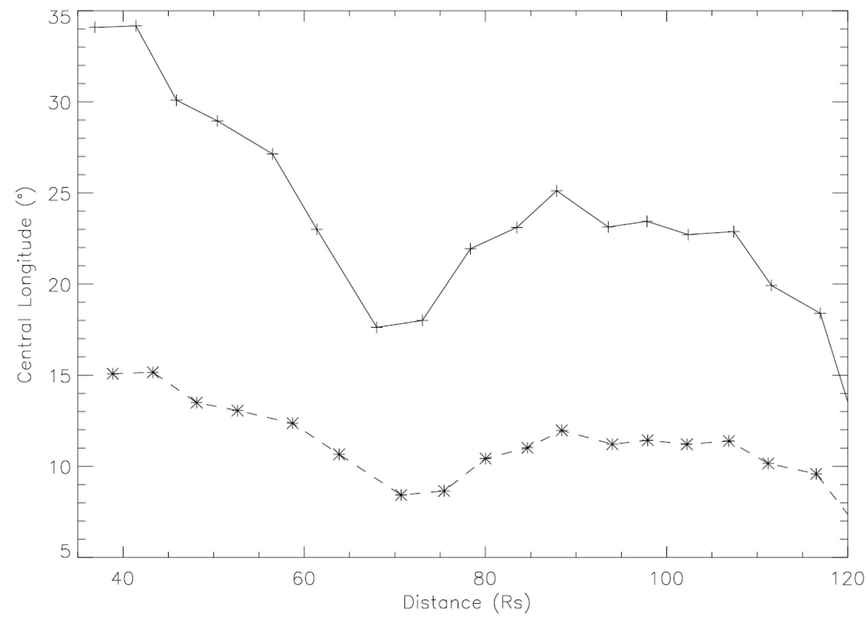


- IMPACT level 3 data
  - MC at ST-B
    - Starts 06/06 at 22UT
    - Finish 06/07 at 12:30UT
  - Nothing at ST-A and at **ACE**
- Separation between B and Earth: 25.4º

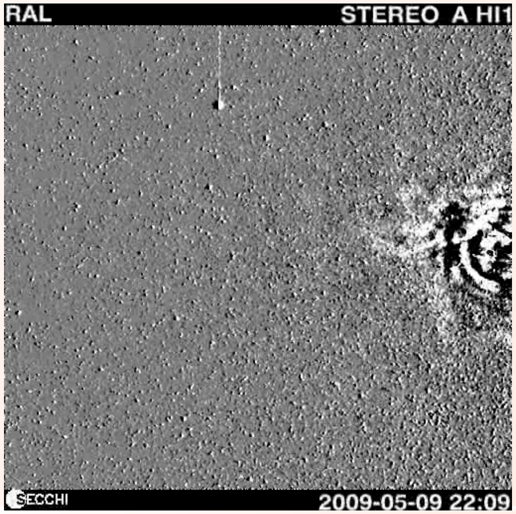


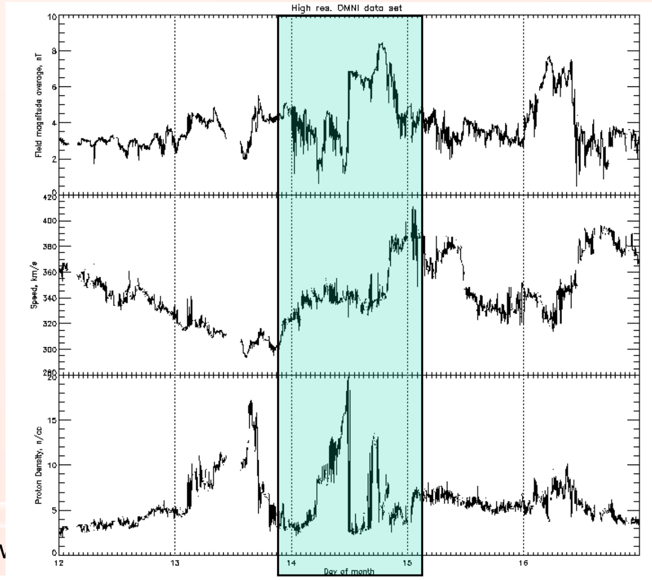
May 9, 2009 CME

- RAL:
  - ST-A: V = 333 km/s, beta = $10^o \pm 6^o$
  - ST-B: V = 305 km/s, beta = $8^o \pm 11.5^o$
- Triangulation:
  - V = 327 km/s, beta = 12^o
- Tangent
  - V = 337 km/s, beta = 33^o to 18^o



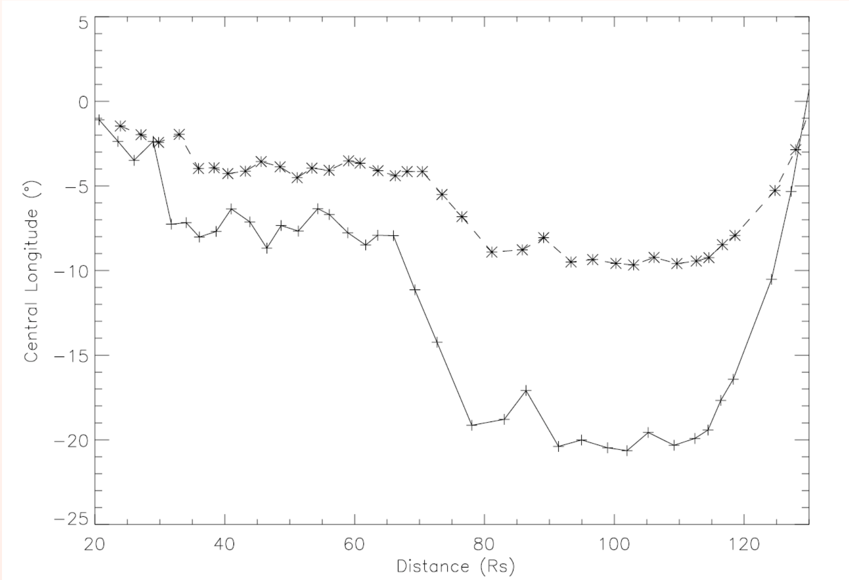
- Nothing in ST-A and ST-B
- Possibly (?) something in ACE

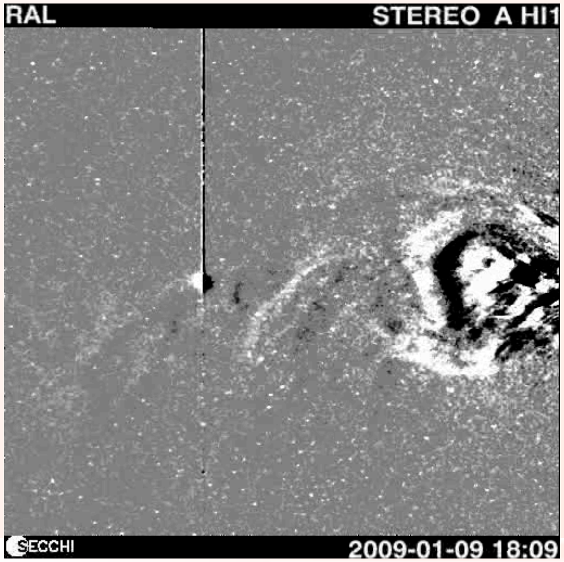




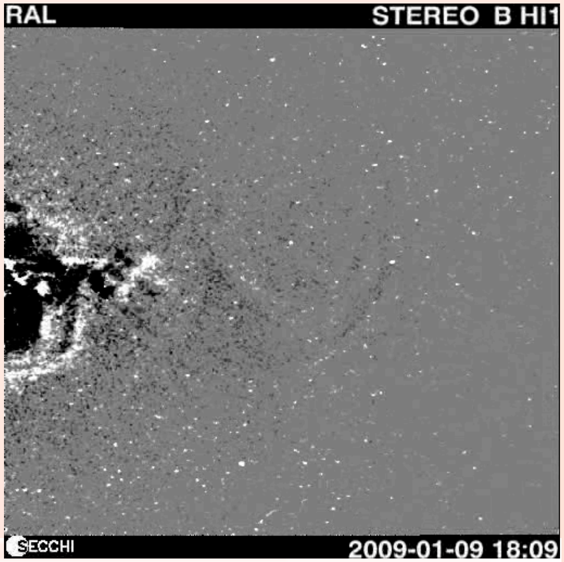
Jan. 9, 2009 CME

- RAL:
  - ST-A: V = 352 km/s, beta = -33º ± 17º
  - ST-B: V = 321 km/s, beta = -14º ± 7.5º
- Triangulation (up to 0.55 AU):
  - V = 318 km/s, beta = -6º
- Tangent (up to 0.55 AU):
  - V = 325 km/s, beta = -11.5º
- Separation Earth-B : 46.5º



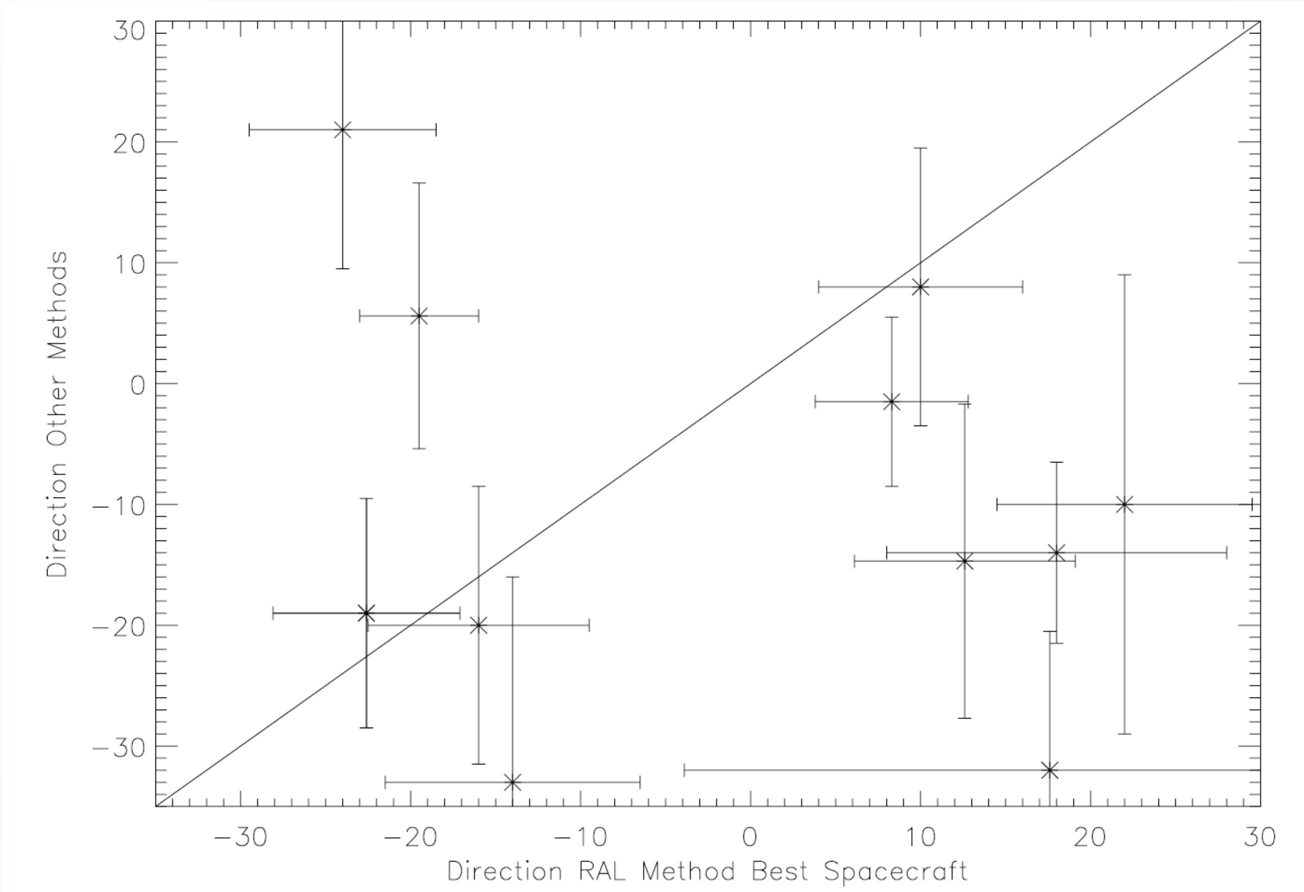


- IMPACT level 3 data
  - MC at ST-B
    - Starts 01/13 UT at 05UT
    - Finish 01/13 at 22UT
  - Nothing at ST-A and ACE
- Good candidate (not a nicer CME within 2 days)
- Indication of beta < -25º



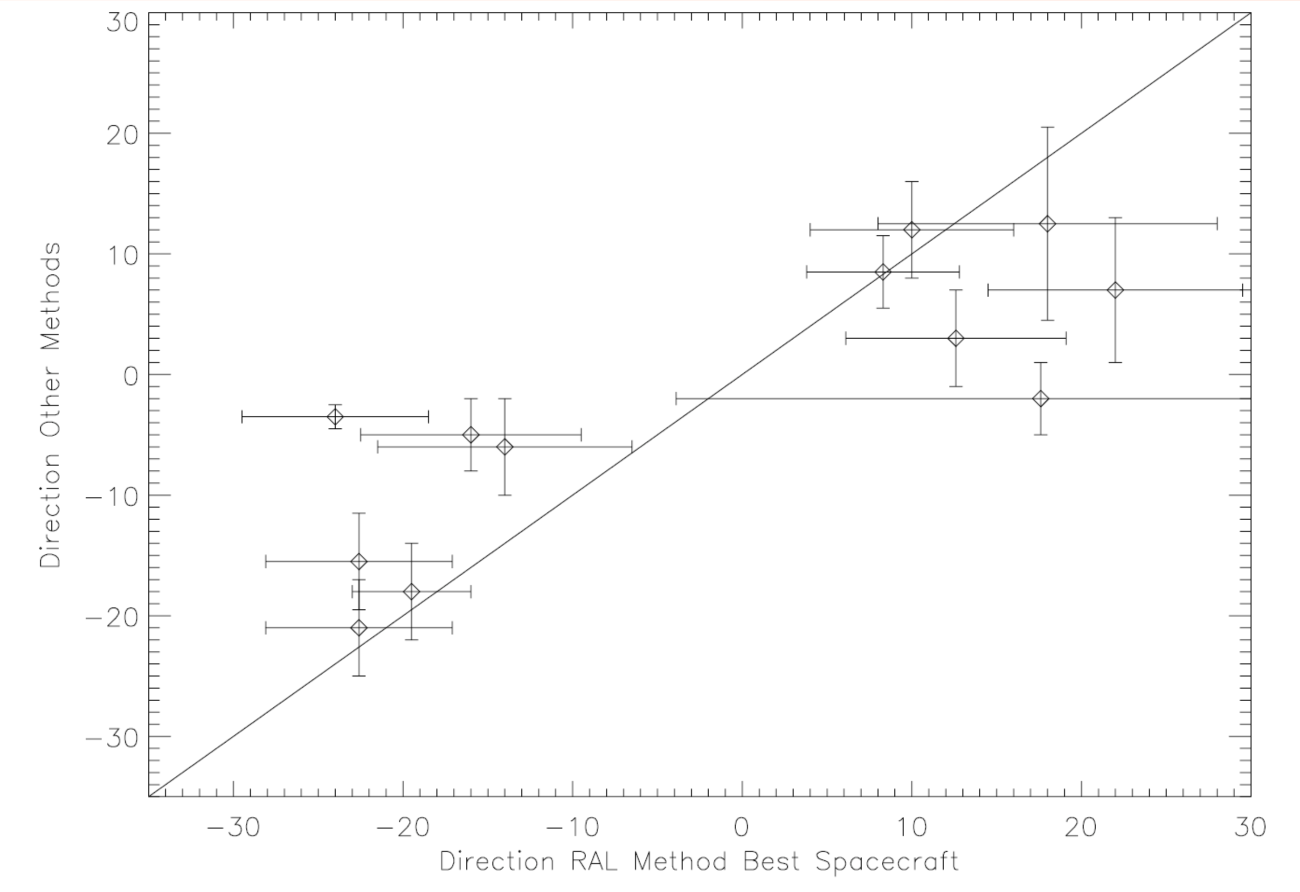
Comparisons

- STEREO Best vs. other STEREO: method of Rouillard et al.
  - More or less random (correl = -0.135)



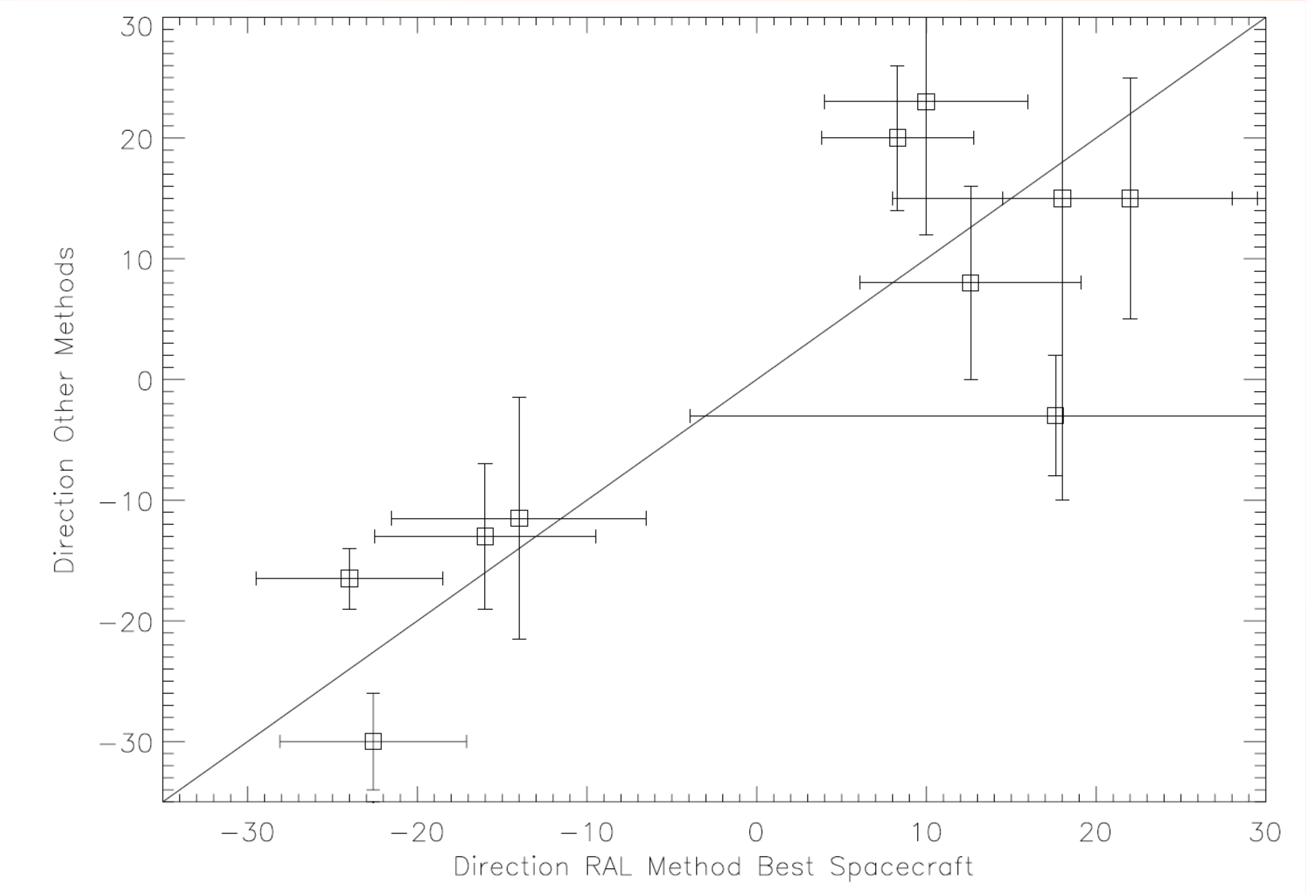
Comparisons

- STEREO Best vs. Triangulation: method of Liu et al. (2010)
  - Relatively good agreement (correl. 0.82)



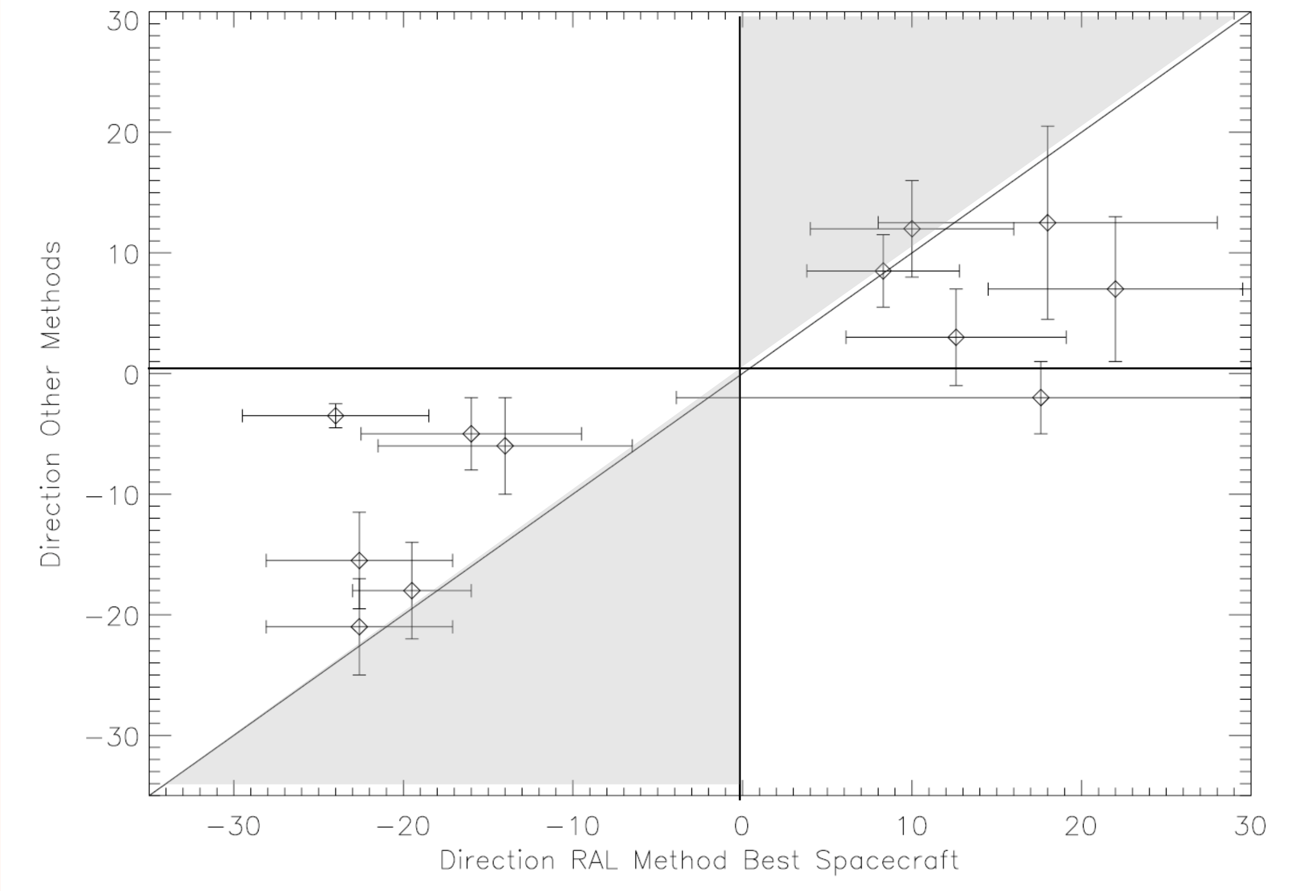
Comparisons

- STEREO Best vs. Tangent: method of Lugaz et al. (2010)
  - Good agreement (correl 0.85), method is noisier, some points are off



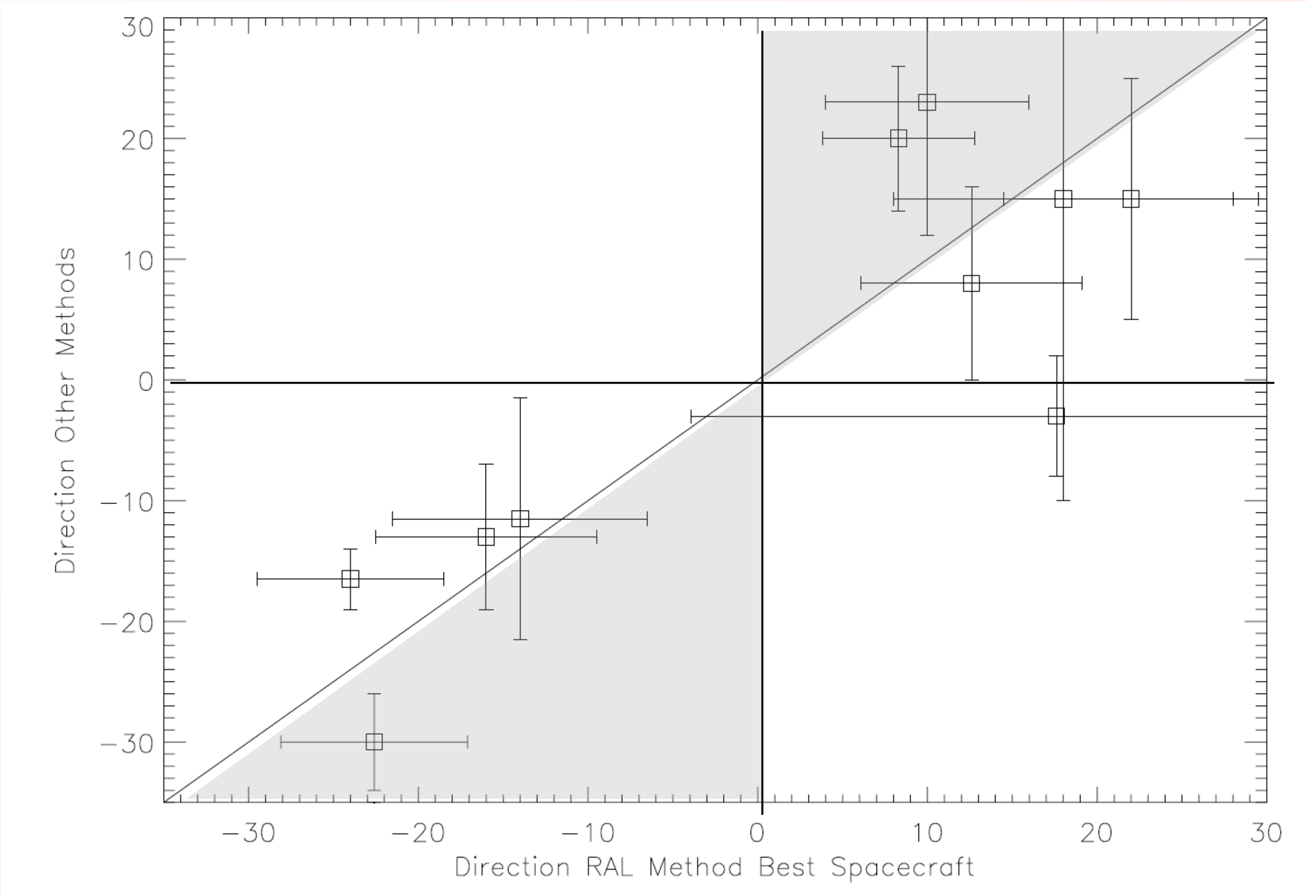
Comparisons

- STEREO Best vs. Triangulation: method of Liu et al. (2010)
  - Triangulation systematically under-estimate the absolute value of the direction



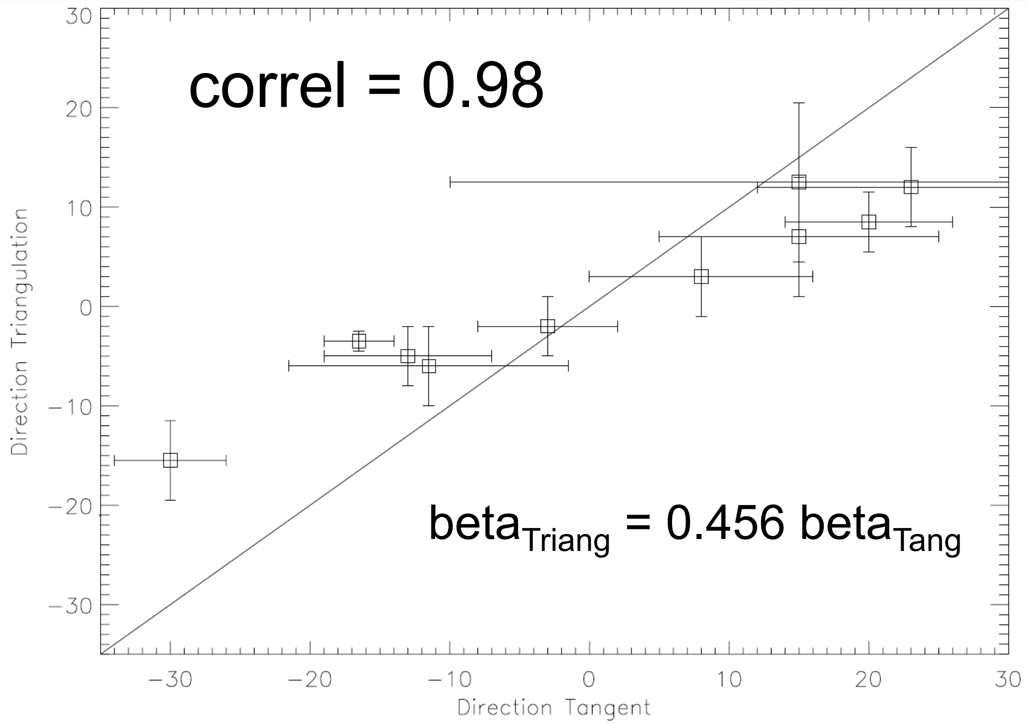
Comparisons

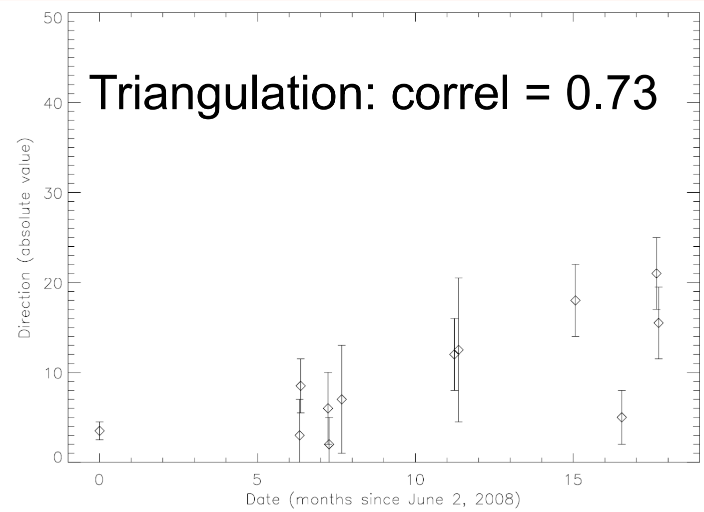
- STEREO Best vs. Tangent: method of Lugaz et al. (2010)
  - Not such issue

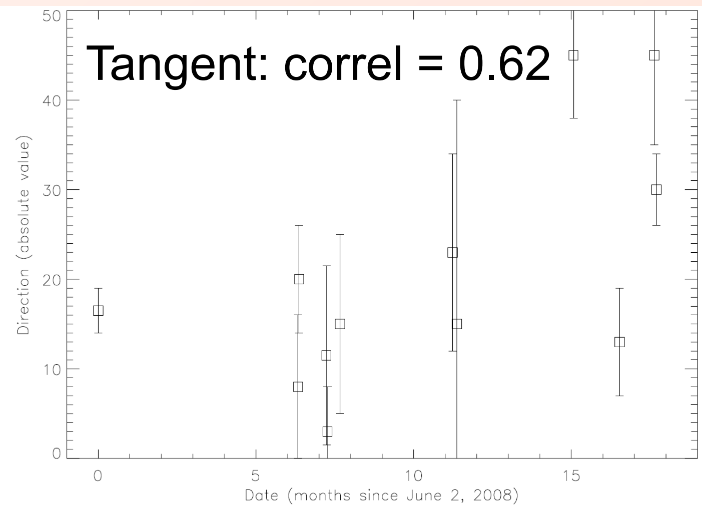


Comparisons

- Tangent vs. Triangulation:



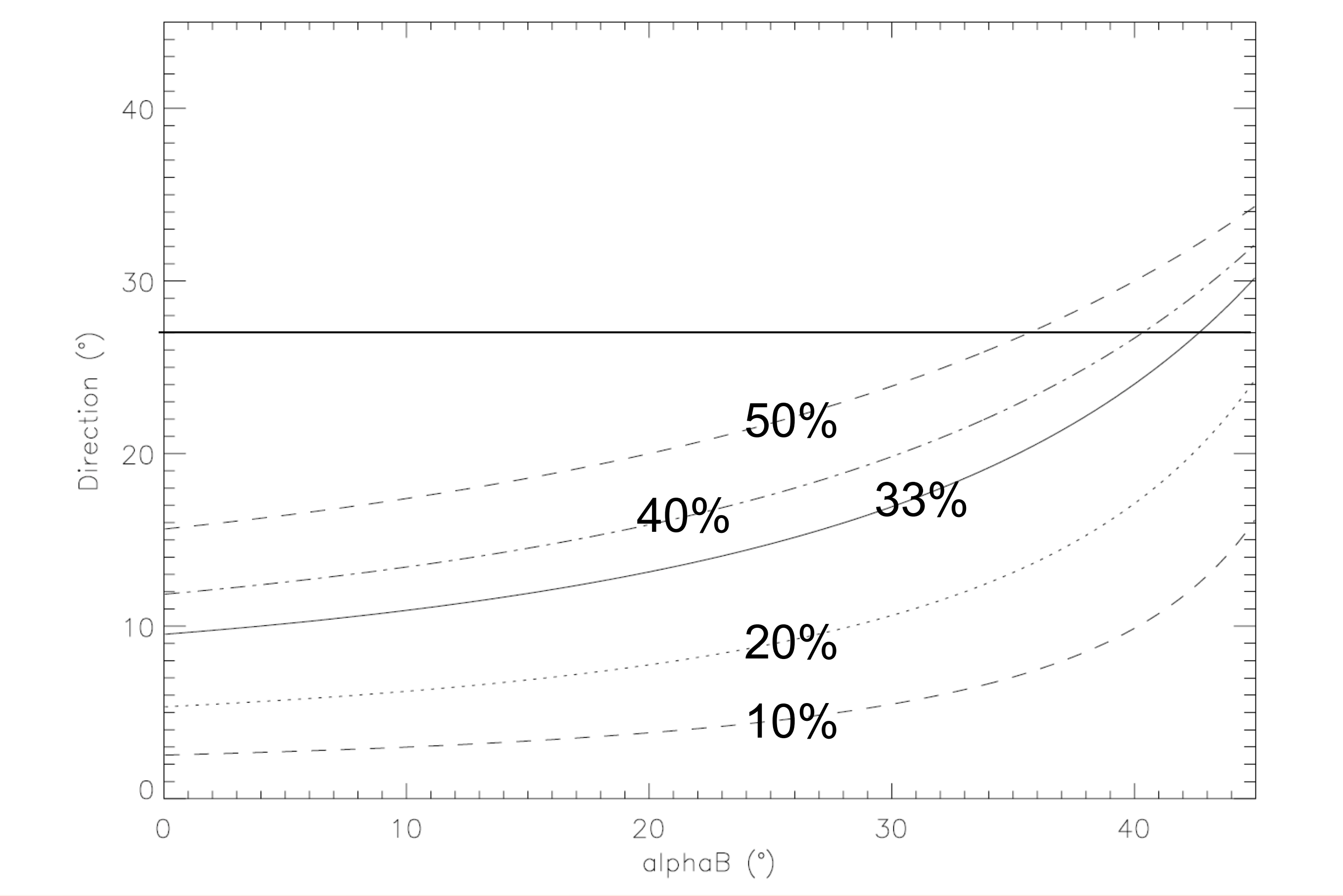




Correlation between ST-A and time = 0.18

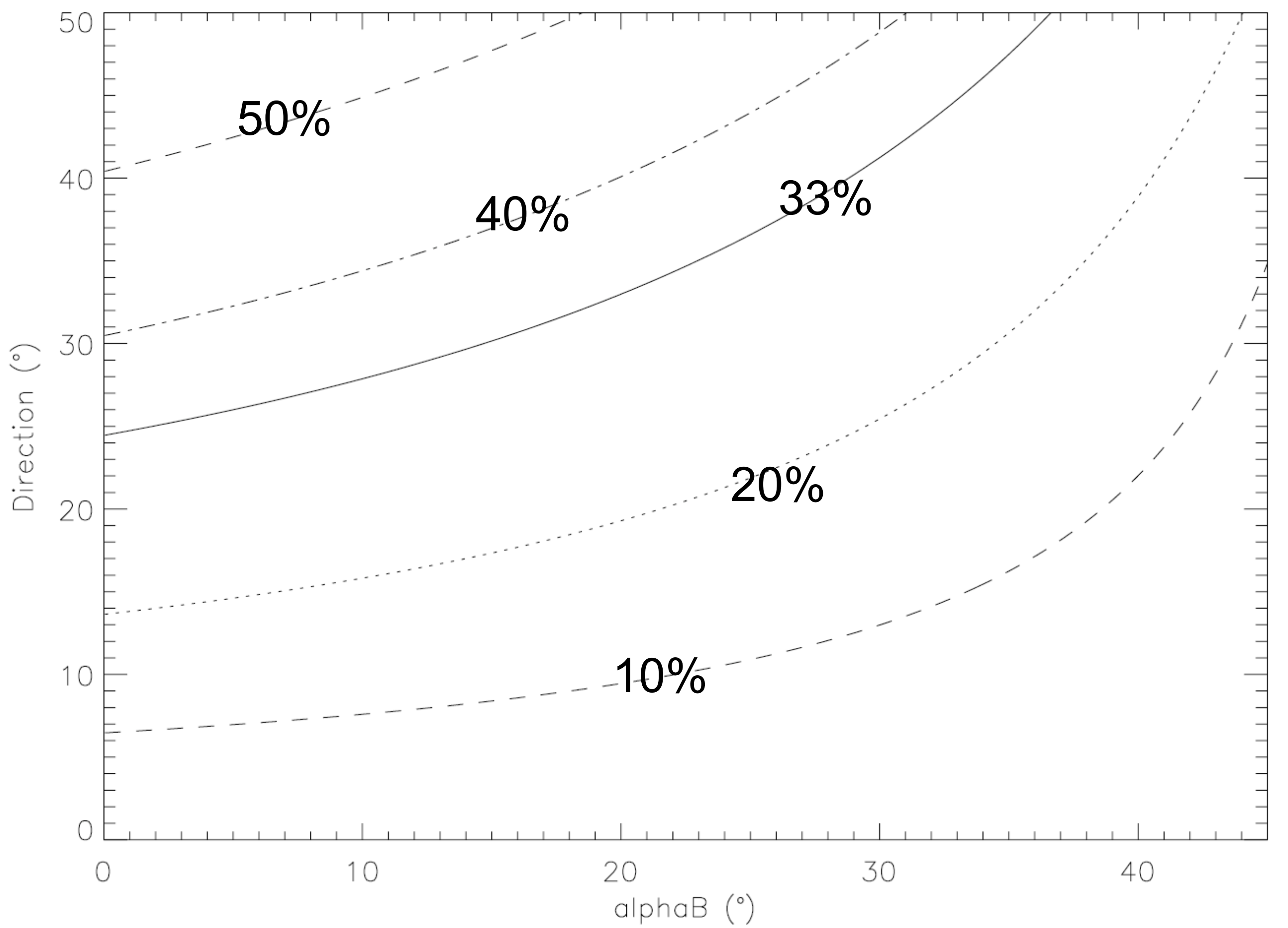
Triangulation Limitations

- Direction of propagation vs. angle and angular asymmetry for separation between A and B of 80° (corresponds to late Oct. 2008).
- 50% means alphaB = 2 alphaA (33 % for example alphaB = 24°, alpha = 16°).



Tangent Absence of Limitation

- Direction of propagation vs. angle and angular asymmetry for separation between A and B of 80^o (corresponds to late Oct. 2008).
- 50% means alphaB = 2 alphaA (33 % for example alphaB = 24^o, alpha = 16^o).



Conclusions

- **Methods to evaluate CME direction**:
  - Direction from the procedure of Rouillard et al. gives good results, as long as one chooses the best-observing spacecraft.
  - Triangulation also works well, **but** limited to CMEs propagating close to the Sun-Earth line (will never give results greater than 1/3 of spacecraft separation).
  - New method based on tangent does not have this limitation but appears more noisy.
  - I believe tests of methods from real data is limited because no wide and fast CMEs have yet been imaged (except 01/25/2007, only CME > 1000 km/s in HI FOV)
    - Constant speed cannot be assumed for fast CMEs.
    - Fixed-Phi approximation and triangulation shall fail for wide CMEs.
- **CME properties**:
  - There seems to be no deflection of CMEs in the heliosphere.
  - More CMEs are needed to really test this.
  - Methods must be validated, probably with simulated data.
  - Most of the deflection happens in the corona (first 10 solar radii).