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
  - \(\alpha_A = 40.4^\circ\) \(\alpha_B = 39.7^\circ\)
  - Plugging in beta_Earth = -4.5\(^\circ\)
  - But \(r_A = 135 \text{ Rs} \neq r_B = 145 \text{ Rs}\)

Correct formula:

- Beta_Earth = 13\(^\circ\)

Here dB/dA = 1.07

- \((dB/dA)_{\text{max}} = 1.13\)
- \((dB/dA)_{\text{min}} = 1.04\)

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

\[
P = \frac{d_B \sin \alpha_B}{d_A \sin \alpha_A}
\]
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 5° 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:

\[
\mathbf{r}_{F \phi} = \frac{d \sin \epsilon}{\sin (\epsilon + \phi)}
\]

\[
\mathbf{r}_{PP} = d \sin \epsilon
\]

\[
r = 2d \sin \epsilon / (1 + \sin (\epsilon + \phi))
\]

\[
1/r = .5 (1/r_{PP} + 1/r_{F \phi})
\]
Geometrical Model

\[ \phi = \arcsin \left( \frac{P - 1}{Q} \right) + \beta, \]

with

\[ P = \frac{d_B \sin \alpha_B}{d_A \sin \alpha_A}, \]

\[ Q = \sqrt{P^2 + 2P \cos(\gamma_B + \gamma_A + \alpha_B + \alpha_A) + 1}, \]

and

\[ \tan \beta = \frac{P \sin(\gamma_A + \alpha_A) - \sin(\gamma_B + \alpha_B)}{P \cos(\gamma_A + \alpha_A) + \cos(\gamma_B + \alpha_B)}. \]

- 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: $V = 366 \text{ km/s, } \beta = -24^\circ \pm 5.5^\circ$
  - ST-B: $V = 298 \text{ km/s, } \beta = 21^\circ \pm 11.5^\circ$

- **Triangulation:**
  - $V = 342 \text{ km/s, } \beta = -4^\circ$

- **Tangent:**
  - $V = 374 \text{ km/s, } \beta = -17^\circ$

- **Thernisien et al. (2009):**
  - $V = 260 \text{ km/s, } \beta = -37^\circ$

- **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:** $25.4^\circ$
RAL:
- ST-A: $V = 333 \text{ km/s}, \beta = 10^\circ \pm 6^\circ$
- ST-B: $V = 305 \text{ km/s}, \beta = 8^\circ \pm 11.5^\circ$

Triangulation:
- $V = 327 \text{ km/s}, \beta = 12^\circ$

Tangent
- $V = 337 \text{ km/s}, \beta = 33^\circ \text{ to } 18^\circ$

- Nothing in ST-A and ST-B
- Possibly (?) something in ACE
Jan. 9, 2009 CME

RAL:
- ST-A: $V = 352 \text{ km/s}, \beta = -33^\circ \pm 17^\circ$
- ST-B: $V = 321 \text{ km/s}, \beta = -14^\circ \pm 7.5^\circ$

Triangulation (up to 0.55 AU):
- $V = 318 \text{ km/s}, \beta = -6^\circ$

Tangent (up to 0.55 AU):
- $V = 325 \text{ km/s}, \beta = -11.5^\circ$

Separation Earth-B: 46.5°

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 $\beta < -25^\circ$
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
STEREO Best vs. Triangulation: method of Liu et al. (2010)

- Triangulation systematically under-estimate the absolute value of the direction
STEREO Best vs. Tangent: method of Lugaz et al. (2010)
Not such issue
Comparisons

**Tangent vs. Triangulation:**

- **Correlation:** $\text{correl} = 0.98$
- **Tangent:** correl $= 0.62$
- **Triangulation:** correl $= 0.73$

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 $\alpha_B = 2 \alpha_A$ (33 % for example $\alpha_B = 24^\circ$, $\alpha = 16^\circ$).
Tangent Absence of Limitation

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