Comparison of 3-D CME parameters derived from single and multi-spacecraft observations

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Abstract. Several geometrical models have been suggested to infer the 3-D parameters (e.g., radial velocity, angular width, and source location) of CMEs using multi-view observations (STEREO/SECCHI) and single-view observations (SOHO/LASCO). To prepare for when only single-view observation is available, we have made a test whether the 3-D parameters of CMEs from single-view observations are consistent with those from multi-view observations. For this test, we select 32 CMEs with the following conditions: broad CMEs (apparent angular width > 180 degrees) by SOHO/LASCO and limb CMEs by twin STEREO spacecraft. We use SOHO/LASCO and STEREO/SECCHI data during the period from 2010 December to 2011 June when they were in quadrature. These events have an advantage that we can directly determine their radial velocities and angular widths from twin STEREO spacecraft. In this study, we compare the 3-D parameters of these CMEs from four different methods: (1) a geometrical triangulation method for multi-view observations, which is provided by the Community Coordinated Modeling Center (CCMC) STEREO CME analysis tool (STEREO Cat), using STEREO/SECCHI and SOHO/LASCO data, (2) a Graduated Cylindrical Shell (GCS) flux rope model for multi-view observations using STEREO/SECCHI data, (3) an ice cream cone model for single-view observations using SOHO/LASCO data, and (4) the direct measurement from twin STEREO spacecraft. We find that the radial velocities of the CMEs from four methods are well consistent with one another with high correlations (CC > 0.89). We also find that the source locations of the CMEs from three geometrical methods are well consistent with the flaring locations with high correlations (CC > 0.9), implying that most of the CMEs are radially ejected. It is noted that the angular widths of the CMEs from the multi-view observations are consistent with the direct measurement from twin STEREO spacecraft, while the angular widths by the ice-cream cone model are underestimated for broad CMEs whose angular widths are larger than 100 degrees. The above results support that it is possible for us to reasonably estimate the radial velocities and the source locations of broad CMEs from single-view observations.

1. Introduction

Coronal mass ejections (CMEs) are the most spectacular eruptions in the solar corona. CMEs can produce geomagnetic storms and other space weather phenomena near the Earth. Especially, front-side halo CMEs (i.e., CMEs with an apparent angular width of 360 degrees in a coronagraph field of view) directed toward the Earth have been known to produce strong geomagnetic storms (Gosling et al. 1990; Srivastava and Venkatakrishnan, 2004). It is thus very important to determine 3-D CME parameters such as radial velocity, angular width, and source location for space weather forecast (Falkenberg et al. 2010; Taktakishvili, Macneice, and Odstrcil, 2010).

CMEs have been typically observed by single-view observations such as the Large Angle SpectrosCopic Observatory (LASCO: Brueckner et al. 1995) on board the SOlar and Heliospheric Observatory (SOHO). Single-view observations provide us with the projected images of CMEs on the plane of the sky. The projection effects on 3-D parameters of the CMEs can be estimated by making assumptions about the CME propagation and shape, but it is still difficult to reliably estimate 3-D CME parameters (Vrsnak et al. 2007). So far, several authors have estimated the 3-D CME parameters using different cone models: an elliptical-cone model (Xie, Ofman, and Lawrence, 2004); an ice-cream cone model (Xue et al. 2005); an asymmetric cone model (Michalek, 2006).

The Solar TErrestrial Relations Observatory (STEREO: Kaiser et al. 2008) was launched in 2006 October. 2006. The twin spacecraft were injected into two orbits around the Sun, with one ahead (A) and the other behind (B) the Earth. STEREO can observe the Sun–Earth space from multi-view. STEREO has the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) instrument package (Howard et al. 2008), comprising five different imaging telescopes, which together allow a view from the solar disk to 1 AU. Thus these instruments make us possible to derive 3-D CME parameters by using several stereoscopic methods (e.g., Harrison et al. 2008; Howard and Tappin 2008; Mierla et al. 2008; Liu et al. 2010; Temmer, Preiss, and Veronig, 2009; Thernisien, Vourlidas, and Howard. 2009; Maloney, Gallagher, and McAteer, 2009; Wood et al. 2009a, 2009b; Webb et al. 2009). In this study, we consider two different methods for multi-view observations: a geometrical triangulation method (e.g., Liewer et al. 2009a; Mierla et al. 2010; Liu et al. 2010a, 2010b) and a Graduated Cylindrical Shell (GCS) model (Thernisien, Howard and Vourlidas, 2006).

STEREO is scheduled to drift apart from Earth at a rate of approximately 22.5 degree per year in each direction. Around 2015, it becomes hard to apply the stereoscopic methods to data from multi-view observations, especially for earthward CMEs. At this time we have to rely on single-view observations again. Therefore, we want to check whether the methods to derive 3-D CME parameters from the single-view observations are consistent with the stereoscopic methods from the multi-view observations. In the present study, we consider three geometrical methods: the geometrical triangulation method and the GCS model for multi-view observations, and the ice-cream cone model for single-view observations. We apply these methods to 32 CME events observed from 2010 December to 2011 June, when SOHO and STEREO were in quadrature. Since these CMEs look like halo CMEs by SOHO/LASCO and like limb CMEs by twin STEREO spacecraft, it is possible to directly measure the radial velocities and angular widths of CMEs by twin STEREO spacecraft. The source locations of the CMEs are assumed to be the flaring locations from National Geophysical Data Center (NGDC) flare data and STEREO/EUVI brightening. We compare the 3-D parameters (e.g., the radial velocity, angular width, and source location) of the CMEs from four different methods: three geometrical ones and the direct measurement.

2. Method

2.1 Geometrical Triangulation Method

One simple and popular way to reconstruct the 3-D structure of CMEs from multi-view observations is based on triangulation. It consists in localizing the same feature in at least two different views of the same scene. Several different triangulation methods have been suggested (e.g., Liewer et al. 2009a; Mierla et al. 2008, 2009; Temmer, Preiss, and Veronig, 2009; Liu et al. 2010a, 2010b). In this study, we use a NASA/CCMC STEREO Cat based on the geometric triangulation method (Liu et al. 2010a, 2010b). This method assumes a fixed propagation angle of the feature relative to the Sun–spacecraft line. This tool can determine both propagation direction and radial velocity of a CME from multi-view observations. This tool has the following advantages over other methods: (1) it is applicable to two spacecraft data out of STEREO A, B and SOHO, while the other methods mostly use two STEREO data; (2) it provides us with a user-friendly interface via WEB for input and output data. Figure 1 shows a snapshot of the STEREO Cat on the WEB.

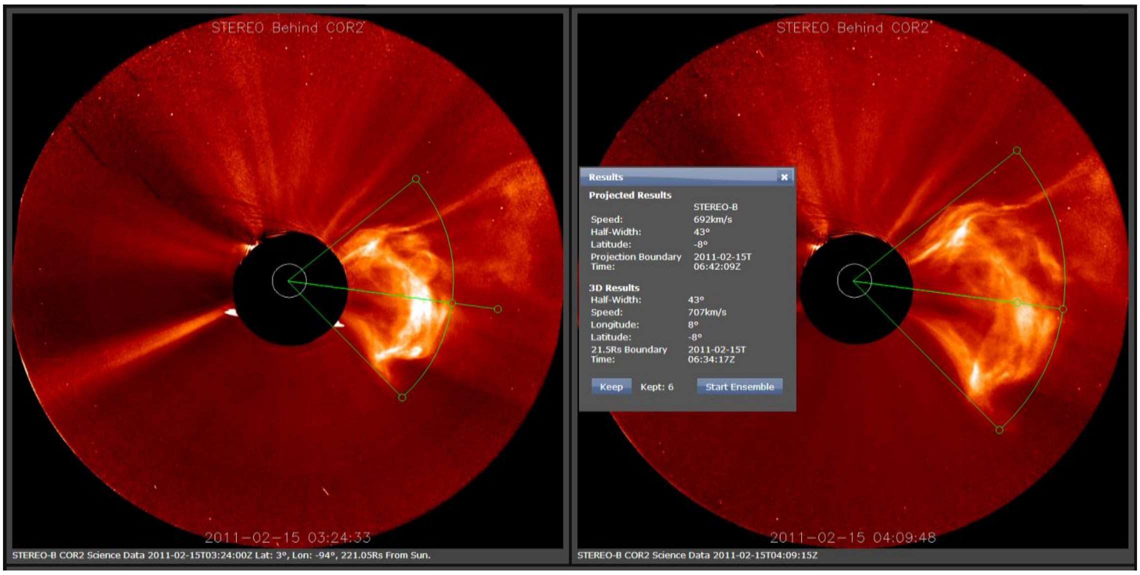

Figure 1. A snapshot of the STEREO Cat on 2011 February 15. These COR2 images are taken for two different times. The green handles specify the position of the CME in the images. The results of the calculation are automatically updated.

2.2 Graduated Cylindrical Shell (GCS) Model

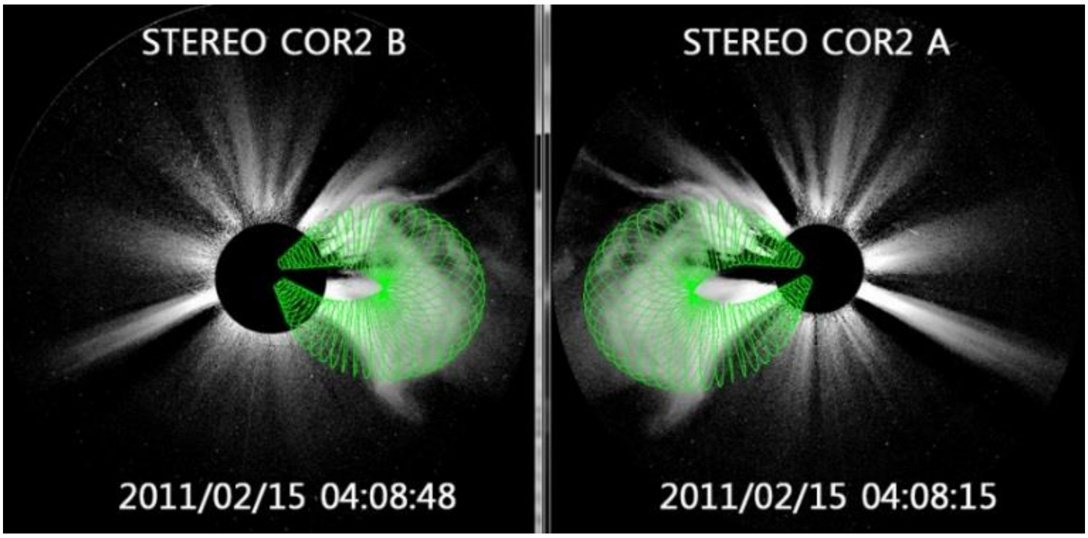

Figure 2. GCS (flux rope) model fittings (green wire lines) overlaid on the observed STEREO/SECCHI COR2 A and B images at 04:08 on 2011 February 15.

Flux rope models have been successfully applied to reproduce CME observations (Chen et al. 1997) and to analyze their properties (Vourlidas et al. 2000; Krall and St. Cyr, 2006). And it has been known that CMEs tend to expand in a self-similar expansion (Chen et al. 1997, 2000). Based on these facts, Thernisien et al. (2006, 2009) developed a GCS flux rope model which consists of a tubular section forming main body and stick two cones at the both ends of a main body. The GCS mean to reproduce the large-scale structure of flux rope like CMEs (Thernisien, Howard, and Vourlidas, 2006). The GCS model focuses on the geometric aspect of the flux rope, leaving the photometric aspect. The analysis is based on the comparison between a synchronized stereoscopic pair of SECCHI COR2 images and the wireframe projection of the model. The computation of the projected wireframe takes into account the spacecraft attitude at the time of the image acquisition and the projection type of the instrument (Calabretta and Greisen, 2002). Figure 2 shows the 3-D structure of the 2011 February 15 CME by the GCS model via SolarSoft *rtsccguicloud.pro* procedure.

2.3 Ice-cream Cone Model

The ice-cream cone model (Xue et al. 2005) for single-view observations, assumes that the shape of a CME is a symmetrical cone with a sphere like an ice-cream. The ice-cream cone structure is described in Figure 3a. To obtain the cone model parameters, we first measure the projection speeds of a CME by using the running-difference images of the SOHO/LASCO. For this, we estimate the front edges of the CME at different azimuthal angles (every 15 degrees, 24 points) for several different times (Figure 3b). Then the projection speeds are estimated from a linear fitting between time and height. Then we calculate the cone parameters using the least-square fitting method between measured and estimated projection speeds. The source location assumes to be the flaring location or an active region.

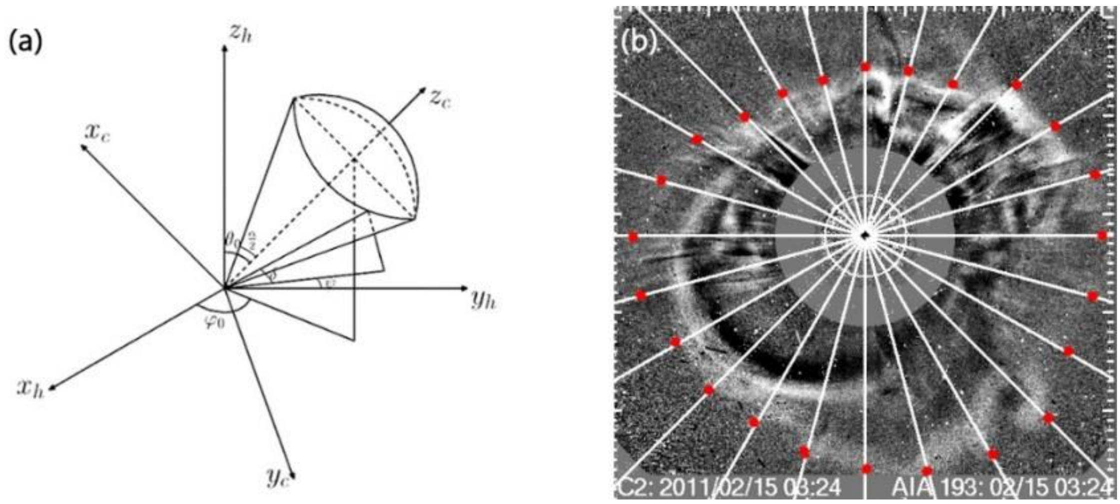

Figure 3. (a) A sketch map of the ice-cream-cone model structure and the relationship between the heliocentric coordinate system (x_h, y_h, z_h) and the cone coordinate system (x_c, y_c, z_c). (b) The running-difference images at 03:24 on 2011 February 15. White solid lines and red dots represent azimuthal angles (every 15 degrees) and the measured front edge of the CME, respectively.

3. Data

3.1. Data

In this study, we consider CMEs that occurred when SOHO and STEREO were in quadrature during 2010 December to 2011 June. During this period, we select very broad LASCO CMEs whose apparent angular widths are larger than 180 degrees, which also look like limb CMEs by twin STEREO spacecraft. We only choose CMEs whose front structures are clearly seen in both

SOHO/LASCO and STEREO/SECCHI/COR2. As a result, we select 32 well observed events. Figure 4 shows three images of one example. For the analysis, we use the CDAW LASCO CME catalog (http://cdaw.gsfc.nasa.gov/CME_list/), the STEREO Cat (http://ccmc.gsfc.nasa.gov/analysis/stereo/), and the SECCHI Flight images Query form (http://secchi.nrl.navy.mil/cgi-bin/swdbi/secchi_flight/images/form).

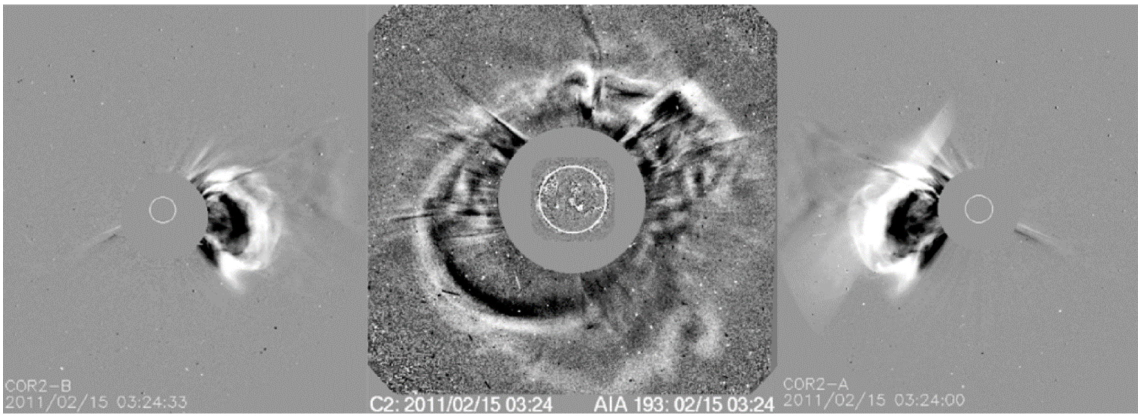

Figure 4. Running-difference images of the 2011 February 15 CME observed by STEREO/SECCHI and SOHO/LASCO. The images are taken from STEREO-B COR2 (left), LASCO/C2 (middle), and STEREO-A COR2 (right). The white circles on the occulting disks mark the size of the Sun.

3.2 Direct Measurement of 3-D CME parameters from observations

During the period of our observations, SOHO and STEREO were in quadrature. Since the CMEs appear to be like limb CMEs by twin STEREO spacecraft, we can directly measure their radial velocities and angular widths by minimizing projection effects. We estimate the radial velocities (V_{obs}) of CMEs using their height-time measurements from STEREO/SECHHI COR2 images. We determine the angular width (α_{obs}) of a CME by measuring the angle between two lines from the center of the Sun as seen in Figure 5a. For comparison, the average values of two radial velocities and angular widths from twin spacecraft are used.

The source locations (latitude θ, and longitude φ) are taken from the NGDC flare Catalog for front-side CMEs and by locating EUV brightening from STEREO/SECCHI EUVI for backside CMEs (Figure 5b). For comparison, we use a γ-value (γ_{flare}) that is the angle between the propagation direction and the plan of the sky [$\sin\gamma = \sin(90-\theta)\cos\varphi$]. The γ-value of 90 degrees indicates an earthward CME.

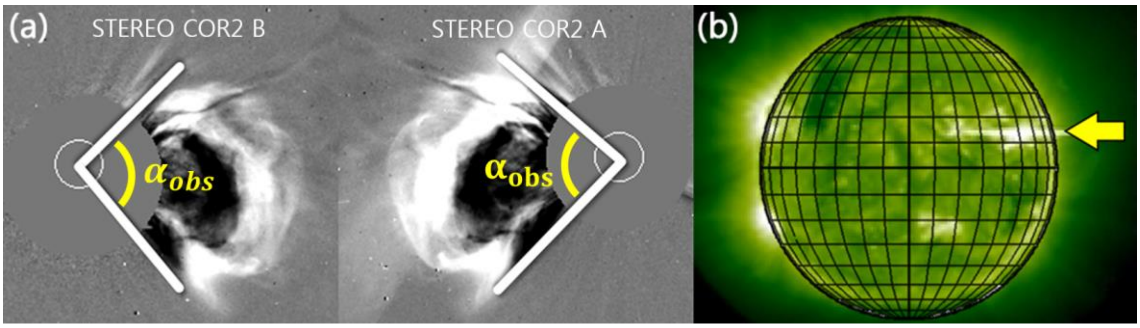

Figure 5. (a) The angular width of the 2011 February 15 CME from STEREO/SECCHI COR2 A and B. (b) EUV brightening from STEREO/SECCHI A 195Å EUVI on 2011 June 04.

4. Results and Discussion

We estimate the 3-D parameters of these CMEs using three geometrical methods and one direct measurement. Figure 6 shows a comparison of the radial velocities with the following pairs: (a) the triangulation method and the GCS model, (b) the triangulation method and the ice-cream cone model, (c) the GCS model and the ice-cream cone model, (d) the triangulation method and the direct measurement from twin STEREO spacecraft, (e) the GCS model and the measurement, and (f) the ice-cream cone model and the measurement.

The root mean square (RMS) errors of all pairs are smaller than 300 kms^{-1}. The radial velocities from the multi-view and single-view observations are consistent with the measurements with high correlations (CC > 0.89). However, the radial velocities from three geometrical methods are a little larger than the measurements, which might be explained by the project effects since these CMEs are not located at the exact limb position.

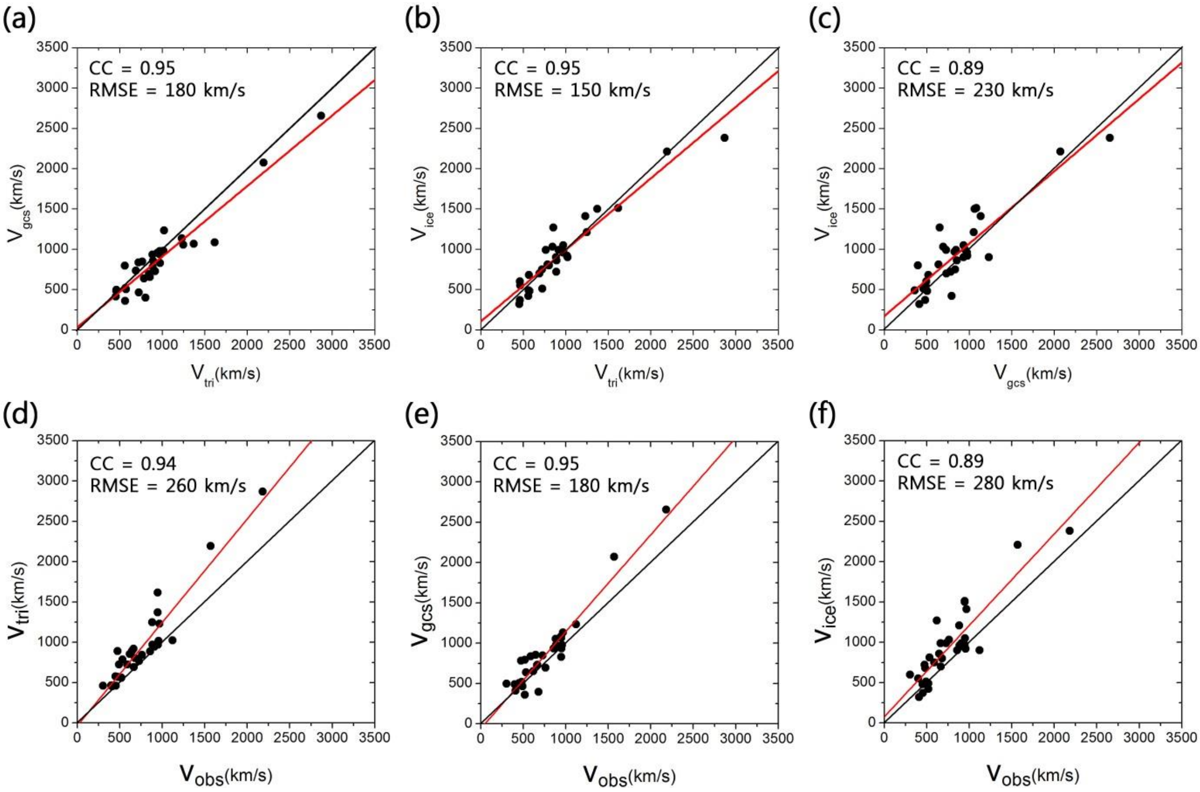

Figure 6. Comparison of the radial velocities of the CMEs from three geometrical methods and the direct measurement for the following pairs: (a) the triangulation method and the GCS model, (b) the triangulation method and the ice-cream cone model, (c) the GCS model and the ice-cream cone model, (d) the triangulation method and the direct measurement from twin STEREO spacecraft, (e) the GCS model and the measurement, and (f) the ice-cream cone model and the measurement. The red line is a linear fit to all data point and the solid line indicates that both quantities are perfectly consistent with each other.

Figure 7 shows a comparison of the angular widths of the CMEs for the six pairs described in Figure 6. The RMS errors of the angular widths of the CMEs are smaller than 30 degrees and the correlation coefficients range from 0.4 to 0.7. The correlation coefficient between the angular widths of the CMEs from the multi-view observations (pair a) is better than those from both single-view and multi-view observations (pairs b and c). It is also noted that the angular widths of the CMEs from multi-view observations are more consistent with those from observations than those from the single-view observations.

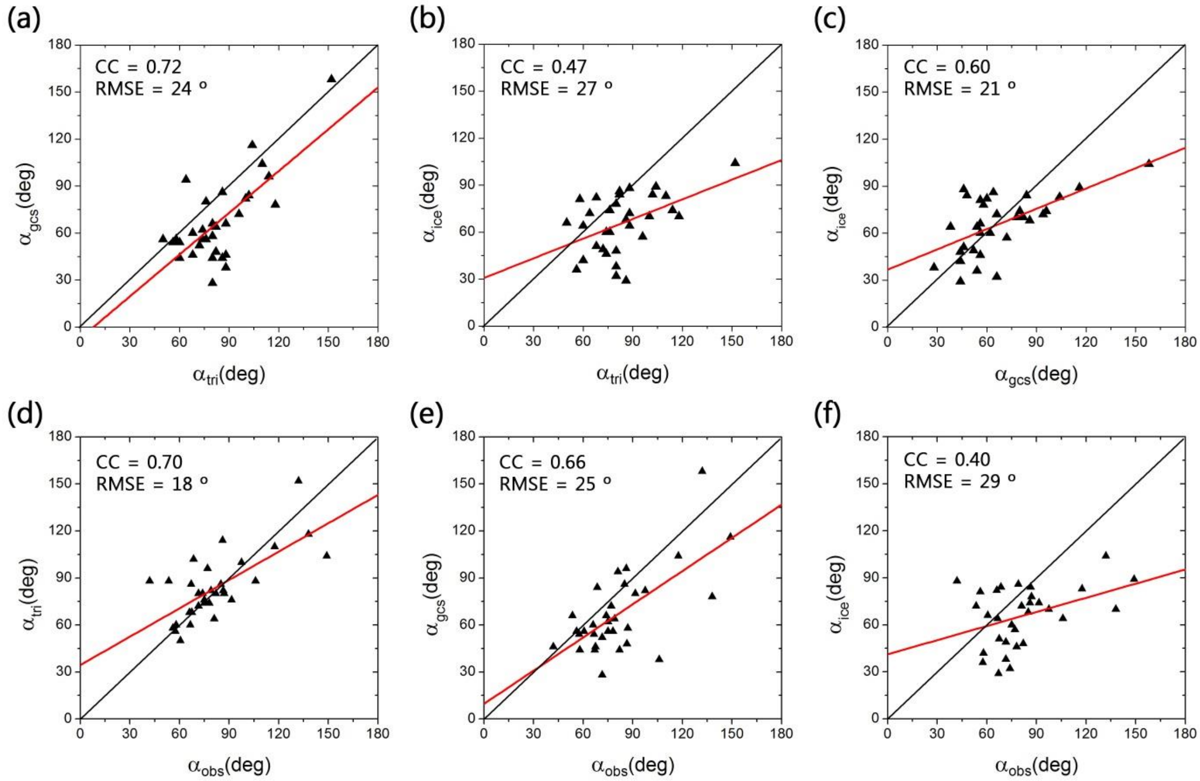

Figure 7. Comparison of the radial velocities of the CMEs from three geometrical methods and the direct measurement for the following pairs: (a) the triangulation method and the GCS model, (b) the triangulation method and the ice-cream cone model, (c) the GCS model and the ice-cream cone model, (d) the triangulation method and the direct measurement from twin STEREO spacecraft, (e) the GCS model and the measurement, and (f) the ice-cream cone model and the measurement. The red line is a linear fit to all data point and the solid line indicates that both quantities are perfectly consistent with each other.

Figure 8 shows a comparison of the source location (γ-value) of the CMEs for the same pairs in Figure 6. The correlation coefficients are larger than 0.9 for all pairs. It is noted that the RMS errors of the CME source locations (γ-value) between the multi-view observations (pair a) are smaller than those between the single-view observations and one multi-view observations (pairs b and c). It is also interesting that the source locations (γ-value) from the multi-view observations are quite consistent with those from the flaring locations with very high correlations and small RMS errors, implying that most of the CMEs are radially ejected near the flare locations.

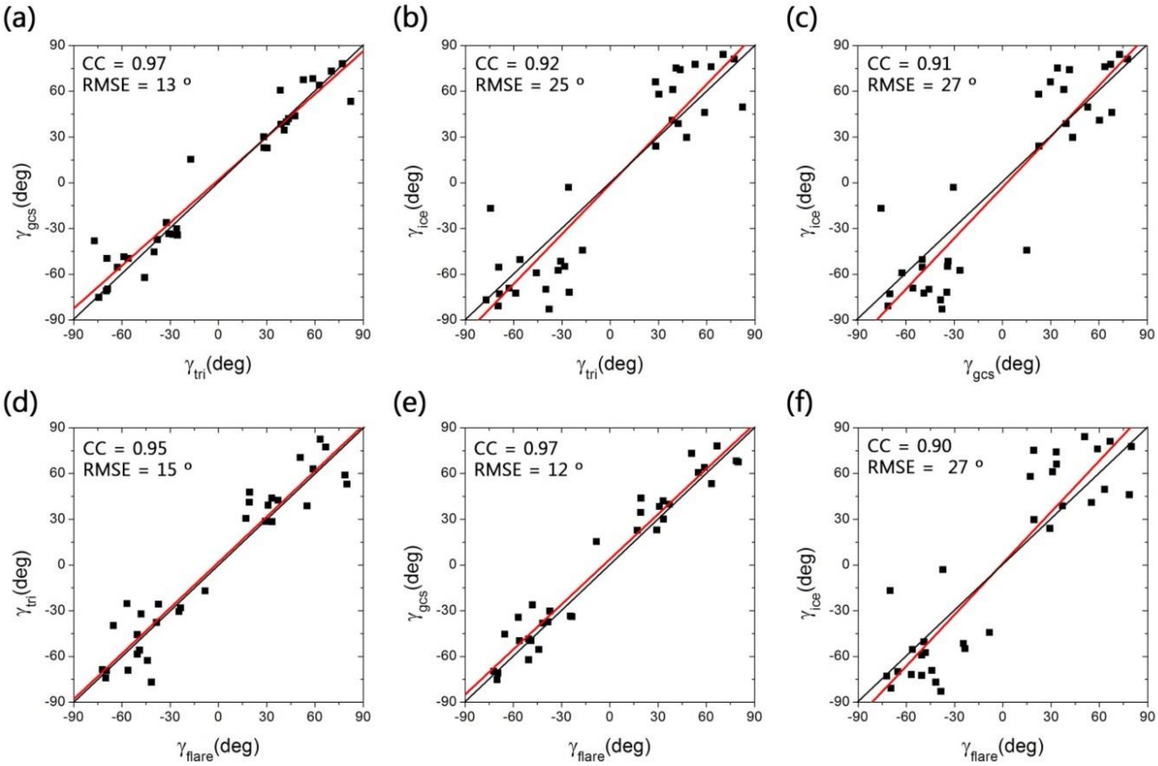

Figure 8. Comparison of the radial velocities of the CMEs from three geometrical methods and the direct measurement for the following pairs: (a) the triangulation method and the GCS model, (b) the triangulation method and the ice-cream cone model, (c) the GCS model and the ice-cream cone model, (d) the triangulation method and the direct measurement from twin STEREO spacecraft, (e) the GCS model and the measurement, and (f) the ice-cream cone model and the measurement. The red line is a linear fit to all data point and the solid line indicates that both quantities are perfectly consistent with each other.

5. Summary and Conclusion

In this study, we have made a test whether the 3-D parameters of CMEs from single-view observations (SOHO/LASCO) are consistent with those from multi-view observations (STEREO/SECCHI). For this we select 32 CMEs with the following conditions: broad CMEs by SOHO/LASCO and limb CMEs by twin STEREO spacecraft. We consider four different methods: (1) a triangulation method, (2) a Graduated Cylindrical Shell model for the multi-view observations, (3) an ice-cream cone model for the single-view observations, and (4) one direct measurement by twin STEREO spacecraft. We find that the radial velocities of the CMEs from four methods are well consistent with one another with high correlations (CC > 0.89). We also find that the source locations (γ-value) of the CMEs from three geometrical methods are well consistent with the flaring locations with high correlations (CC > 0.9), implying that most of the CMEs are radially ejected. It is noted that the angular widths of the CMEs from the multi-view observations are consistent with the direct measurements, while the angular widths of the CMEs by the ice-cream cone model are underestimated for broad CMEs whose angular widths are larger than 100 degrees. The above results support that it is possible for us to reasonably estimate the radial velocities and the source locations of CMEs from single-view observations. However, it is noted that the angular widths of CMEs from single-view observations are not so reliable, especially for broad CMEs.

6. References

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