

The inversion of the real kinematic properties of coronal mass ejections by forward modeling *

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Abstract Kinematic properties of coronal mass ejections (CMEs) suffer from projection effects, and it is expected that the real velocity should be larger and the real angular width should be smaller than the apparent values. Several attempts have been taken to correct the projection effects, which however led to an inflated average velocity probably due to the biased choice of CME events. In order to estimate the overall influence of the projection effects on the kinematic properties of the CMEs, we perform a forward modeling of real distributions of CME properties, such as the velocity, the angular width, and the latitude, by requiring their projected distributions to best match observations. Such a matching is conducted by Monte Carlo simulations. According to the derived real distributions, we found that (1) the average real velocity of all non-full-halo CMEs is about 514 km s^{-1} , and the average real angular width is about 33° , in contrast to the corresponding apparent values of 418 km s^{-1} and 42.7° in observations; (2) For the CMEs with the angular width in the range of $20^\circ - 120^\circ$, the average real velocity is 510 km s^{-1} and the average real angular width is 43.4° , in contrast to the corresponding apparent values of 392 km s^{-1} and 52° in observations.

Key words: Sun: coronal mass ejections (CMEs) — methods: statistical — methods: numerical

1 INTRODUCTION

Expulsions of dense clouds of plasma from the solar corona, which are termed coronal mass ejections (CMEs), have been explored during the past four decades. Most CMEs originate in the lower corona, and expel about $10^{14} - 10^{16} \text{ g}$ of plasma with kinetic energy of about 10^{30} to 10^{32} erg (Hudson et al. 2006), and have velocity ranging from tens to more than three thousand km s^{-1} (St. Cyr et al. 2000). The CME phenomenon has piqued great interest within the solar and solar-terrestrial physics communities since CMEs are often associated with other activities, such as flares, filament eruptions, radio bursts, and solar energetic particle events (e.g., Munro et al. 1979; Kahler 1992; Chen et al. 2006; Gopalswamy et al. 2008; Chen et al. 2009). Whether a CME can approach the Earth and

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induce a strong geomagnetic storm depends on various properties of the CME, e.g., the location of the source region, the angular width, mass, velocity, magnetic field intensity, and so on.

Since their first detection on 1971 December 14 by the seventh Orbiting Solar Observatory (OSO-7) coronagraph (Tousey et al. 1973), CMEs have been observed by several other space instruments (Yashiro et al. 2008). The Large Angle and Spectrometric Coronagraph (LASCO) onboard the Solar and Heliospheric Observatory (*SOHO*) mission has made a significant impact on the understanding of CMEs since its first light in 1996 January. The total number of CMEs that LASCO observed until the end of 2009 February is over 14 thousand.

The huge database, e.g., the CME catalog in NASA/CDAW¹, is very useful for investigating various properties of CMEs. For example, Yashiro et al. (2004) found that the average velocity of normal CMEs (with angular widths between $20^\circ - 120^\circ$) is about 428 km s^{-1} , and the corresponding average angular width is 56° for the CME events observed during 1996–2002. Although the statistical results might change more or less as more observations are made or different methods are applied in identifying the CME events, research on CME kinematic properties based on this catalog should have a high degree of reliability. However, the measurements of the CME's kinematic properties directly from coronagraph observations generally suffer from projection effects. For example, it would be expected that the real CME velocity could be higher and the real angular width could be lower than the apparent values (Vršnak et al. 2007).

One straightforward method to obtain the real kinematic properties of CMEs is to study the limb CME events, which are nearly free of projection effects. Burkepile et al. (2004) identify a sample of 111 “limb” events among 1351 CMEs observed by the Solar Maximum Mission (SMM) in 1980 and 1984–1989. The limb events have an average velocity of 519 km s^{-1} and an average angular width of 52.3° , in contrast to 349 km s^{-1} and 46° for all CMEs observed by SMM. It is understandable that the velocity of the limb events is larger than the apparent velocity of all events; however, the result of the angular width is not consistent with the projection effects, which might be due to the limb sample being biased toward the eruptive filament association and therefore is not necessarily representative (Burkepile et al. 2004). A similar survey with a larger sample is strongly needed. It is noted that, however, uncertainty may arise in identifying the limb events in this kind of survey. If EUV dimmings are used to identify the source region of the CMEs, many slow events without evident dimmings would be missed.

Several attempts have been made to correct the projection effects for individual events. For halo events, Michalek et al. (2003) presented a correction method and found that halo CMEs have an average real velocity of 1080 km s^{-1} and average real angular width of 120° , in contrast to 900 km s^{-1} and 360° before the correction. For non-halo CMEs, Leblanc et al. (2001) proposed a correction method, where the locus of the associated flare is used to determine the center of the source region of each CME. Yeh et al. (2005) slightly modified such a method and applied it to 619 CME/flare events where the loci of the flares are available in the Solar Geophysical Data Report. They found that the average velocity of the sampled CMEs is 792 km s^{-1} , and the average angular width is 59° , compared to 549 km s^{-1} and 77° before correction. It is noted that their surveys may be biased toward strong events (so that the loci of the flares were well documented), which results in a remarkably high average velocity.

One common requirement for the aforementioned inversion methods is that one needs to determine the central position of the CME source region, which is not easy to be determined for a large sample. In order to correct the projection effects without knowledge of the central position of the source region for each CME event, we propose a forward modeling technique in this paper, and apply it to derive the real velocity and angular width.

¹ http://cdaw.gsfc.nasa.gov/CME_list

This paper consists of four parts. The forward modeling method is described in Section 2, and the results are shown in Section 3, which is followed by discussions in Section 4.

2 METHOD

The directly measurable quantities of CMEs are the apparent velocity (v), the apparent angular width (AW), and the measurement position angle (MPA). With a large sample of events, we can statistically derive their distributions, which are fitted with respective formulae. Our forward modeling method can be described as follows: Assuming that the real velocity, real angular width, and the real latitude of sample CMEs follow the same functions as their apparent counterparts, but with different parameters, we project the sample CMEs into the plane of the sky to get the projected distributions of their kinematic quantities. The parameters are adjusted by trial and error until the projected distributions of v , AW, and MPA best fit the observed distributions.

In order to get the statistical results of the observations, we appeal to the NASA/CDAW CME catalog, which is based on *SOHO*/LASCO observations. There are 14 120 CMEs observed from 1996 January 11 to 2009 February 28 in this catalog. Among these events, there are 106 CMEs whose velocity cannot be detected, and 396 full halo CMEs which are excluded. From these, we obtain a sample of 13 618 CMEs. The distributions of their apparent velocity, apparent angular width, and MPA are shown in Figure 1, which can be fitted with lognormal, Gaussian, and double Gaussian functions, respectively, as given in Equations (1)–(3). The average apparent velocity of the whole sample is about 418 km s^{-1} , and the average apparent angular width is about 42.7° .

$$f(v) = \frac{1}{0.57\sqrt{2\pi}v} \exp\left[-\frac{(\ln v - 5.85)^2}{2 \times 0.57^2}\right], \quad (1)$$

$$f(\text{AW}) = \frac{1}{60.7\sqrt{2\pi}} \exp\left[-\frac{\text{AW}^2}{2 \times 60.7^2}\right], \quad (2)$$

$$f(\text{MPA}) = \frac{1}{30.5\sqrt{2\pi}} \exp\left[-\frac{(\text{MPA} - 90)^2}{2 \times 30.5^2}\right] + \frac{1}{30.5\sqrt{2\pi}} \exp\left[-\frac{(\text{MPA} - 270)^2}{2 \times 30.5^2}\right] + 0.003. \quad (3)$$

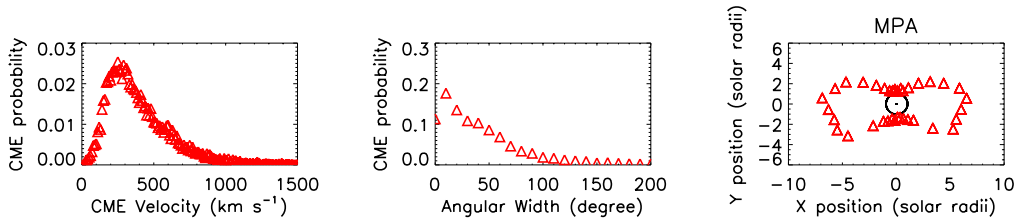


Fig. 1 Distributions of the apparent velocity (*left panel*), the apparent angular width (*middle panel*), and the MPA (*right panel*) of the sample CMEs. The velocity is binned in 10 km s^{-1} intervals, the angular width is in 10° intervals, and the MPA is in 10° intervals. In the right panel, the distance of each triangle from the solar disk center represents the fraction of CMEs in this direction, and the circle marks the solar limb.

Since most CMEs propagate radially with an almost fixed angular width, the so-called cone model is often applied to describe the geometry of CMEs (Howard et al. 1982; Fisher et al. 1984; Michalek et al. 2003; Burkepille et al. 2004; Schwenn et al. 2005; Vršnak et al. 2007; Gao et al. 2009). With the assumption of the cone model, the kinematic properties of a CME in 3-dimensional space are characterized roughly by four variables, i.e., the real velocity (v_{re}), the real angular width (AW_{re}), the latitude (θ) and the longitude (ϕ) of the source's center. It is reasonable to assume that CME sources are randomly distributed along longitude in the heliocentric coordinates. For the other three variables, we assume that the distributions of v_{re} , AW_{re} , and θ take the same functions as those of the apparent velocity, angular width, and MPA (Eqs. (1)–(3)), but with modified parameters, which are expressed as follows

$$F(v_{re}) = \frac{1}{v_{re}\sigma_1\sqrt{2\pi}} \exp\left[-\frac{(\ln v_{re} - \mu)^2}{2\sigma_1^2}\right], \quad (4)$$

$$F(AW_{re}) = \frac{1}{\sigma_2\sqrt{2\pi}} \exp\left(-\frac{AW_{re}^2}{2\sigma_2^2}\right), \quad (5)$$

$$F(\theta) = \frac{1}{\sigma_3\sqrt{2\pi}} \exp\left(-\frac{\theta^2}{2\sigma_3^2}\right), \quad (6)$$

where μ , σ_1 , σ_2 , and σ_3 are parameters to be determined.

In order to quantitatively calculate the projection effects on the CME velocity and angular width, we perform Monte Carlo simulations, which are described as follows: One million artificial CMEs are created, whose real velocity, angular width, and latitude of the central source region satisfy the distributions presented in Equations (4)–(6), and whose longitude values of the central source region are randomly distributed in the range of $0^\circ - 360^\circ$. Each of the artificial CMEs is then projected into the plane of the sky, through which the distributions of apparent velocity, apparent angular width, and the MPA can be derived. The four parameters (μ , σ_1 , σ_2 and σ_3) are adjusted until the projected distributions reproduce the observational counterparts (Eqs. (1)–(3)), where the similarity is examined with the Kolmogorov-Smirnov test.

It is noted that, when projecting the artificial CMEs into the plane of the sky, the relation between the apparent velocity and the real value depends on the particular choice of cone model (Schwenn et al. 2005; Vršnak et al. 2007; Gao et al. 2009). We assume that CMEs are symmetric, and propagate out radially through the corona, and their leading edge is part of a sphere connecting the cone tangentially like an ice-cream cone, i.e., Model C in Schwenn et al. (2005). Moreover, according to Zhang et al. (2010), some CMEs, especially those near the Sun-Earth line, would be too faint to be detected by coronagraphs due to Thomson scattering, which should be taken into account in our study. For that purpose, we calculate the white-light intensity of each CME's leading edge at $3R_\odot$ in the plane of the sky. Those CMEs whose white-light intensity falls below the 3σ value of the fluctuation level of the solar wind are considered undetected by coronagraphs (see Zhang et al. 2010, for details). The expression for calculating the Thomson-scattered intensity is given by Billings (1966). In our work, we neglect the limb darkening effect, so the expression can be simplified as follows,

$$I = \pi\sigma J_0 n_0 R_0 \frac{1}{81} \int_0^{\pi/2} (2C \cos^3 \theta - A \cos^5 \theta), \quad (7)$$

where σ represents the Thomson scattering cross section, J_0 the photosphere's radiative intensity at the solar surface, n_0 the electron density, R_0 the solar radius, θ the angle between the plane of the sky and the direction of CME propagation, $A = \frac{\cos^2 \theta \sqrt{9 - \cos^2 \theta}}{27}$, and $C = \frac{4}{3} - \frac{\sqrt{9 - \cos^2 \theta}}{3} - \frac{(9 - \cos^2 \theta)^{3/2}}{81}$.

3 RESULTS

The derived real distributions of the CME velocity, the angular width, and the latitude are expressed as follows:

$$F(v_{\text{re}}) = \frac{1}{0.53\sqrt{2\pi}v} \exp\left[-\frac{(\ln v_{\text{re}} - 6.09)^2}{2 \times 0.53^2}\right], \quad (8)$$

$$F(AW_{\text{re}}) = \frac{1}{37.2\sqrt{2\pi}} \exp\left(-\frac{AW_{\text{re}}^2}{2 \times 37.2^2}\right), \quad (9)$$

$$F(\theta) = \frac{1}{26.0\sqrt{2\pi}} \exp\left(-\frac{\theta^2}{2 \times 26.0^2}\right). \quad (10)$$

Their profiles are depicted in the left column of Figure 2. As these quantities are projected into the plane of the sky, the resulting distributions of the apparent velocity, the angular width, and the MPA are shown in the right column of Figure 2 (crosses), where they are compared to the LASCO observations (triangles). It is seen that the simulated apparent distributions of the CME velocity, the angular width, and the MPA match the observations very well, which implies that the derived distributions in Equations (8)–(10) might well represent the real situation.

According to the derived real distributions of the CME velocity and the angular width (AW_{re}) for all non-full-halo CMEs, the average CME velocity is 514 km s^{-1} , which is $\sim 23\%$ larger than the apparent value, and the average angular width is 33° , which is $\sim 23\%$ smaller than the apparent value. In particular, for those CMEs whose angular widths are between 20° and 120° (the so-called normal CMEs in Yashiro et al. 2004), the corrected average CME velocity is 510 km s^{-1} , which is $\sim 30\%$ larger than the apparent value (392 km s^{-1}), and the corrected average angular width is 43.4° , which is $\sim 17\%$ smaller than the apparent value (52°).

It is noticed that the real angular width distribution is peaked near 0° , however, its apparent angular width is peaked around 10° , which is consistent with the observations. Our simulations reveal that the significant drop of the number of narrow CMEs (with an angular width less than 10°) is due to the fact that some of them are too weak to be detected when they propagate near the Sun-Earth line.

4 DISCUSSION

The accumulating observations of CMEs enable calculation of the statistics describing their properties, such as their angular size and their kinematics. However, the measurements of the CME geometry and kinematics suffer from projection effects, and it is expected that the real angular width should be smaller, whereas the real velocity should be larger. In this paper, with a forward modeling by Monte Carlo simulations, we corrected the distributions of the CME velocity and the angular width for the projection effects, as revealed by Equations (8)–(10). It is found that (1) for all non-full-halo CMEs, the real velocity has an average of 514 km s^{-1} , and the real angular width has an average of 33° , in contrast to 418 km s^{-1} and 42.7° before correction; (2) for CMEs with an apparent angular width between $20^\circ - 120^\circ$, the real velocity has an average of 510 km s^{-1} , and the real angular width has an average of 43.4° , in contrast to 392 km s^{-1} and 52° before correction. The average real velocity of CMEs derived in this paper is similar to that of the limb events, which are free of the projection effects (Burkepile et al. 2004).

It should be noted that in our forward modeling, it was assumed for simplicity that the three prescribed variables (i.e., the CME velocity, the angular width, and the latitude of the central source region) are completely independent. With a large sample, Yeh et al. (2005) did find that there is little correlation between the CME velocity and the angular width. However, Yashiro et al. (2004) and Vršnak et al. (2007) claimed that wider CMEs tend to be faster. In order to clarify the discrepancy,

we collect the 13 618 non-full-halo CME events observed by *SOHO/LASCO* during the period 1996 January – 2009 February and display the scatter plot of the relation between the observed CME angular width and the velocity in the left panel of Figure 3. It is found that the two quantities present a very weak positive correlation, with the correlation coefficient only being 0.23. We also divide the sample into a subsample with CMEs observed near solar maximum and the other subsample with CMEs near solar minimum. It is also revealed that the CME velocity and the angular width present little correlation. For comparison, the right panel of Figure 3 displays the scatter plot of the CME velocities and the angular widths of the artificial CMEs in our Monte Carlo simulations. It can be seen that the distributions of the scatter points in the two panels of Figure 3 are quite similar. The linear Pearson correlation test indicates that the similarity between the two panels is as high as 0.95. It is noted that the sparse data points with $v > 1000 \text{ km s}^{-1}$ or $\text{AW} > 120^\circ$ are not shown in Figure 3 in order to make the figure clear, though they are included in our study.

In Figure 4 we compare the correlations between the CME velocity and the MPA in both observations and simulations. The left panel displays the scatter plot of the observations, where we can see that the correlation coefficient between the CME velocity and the MPA is almost zero. The right panel shows the corresponding scatter plot in our Monte Carlo simulations. The linear Pearson correlation test indicates that the similarity between the distributions in the two panels is as high as

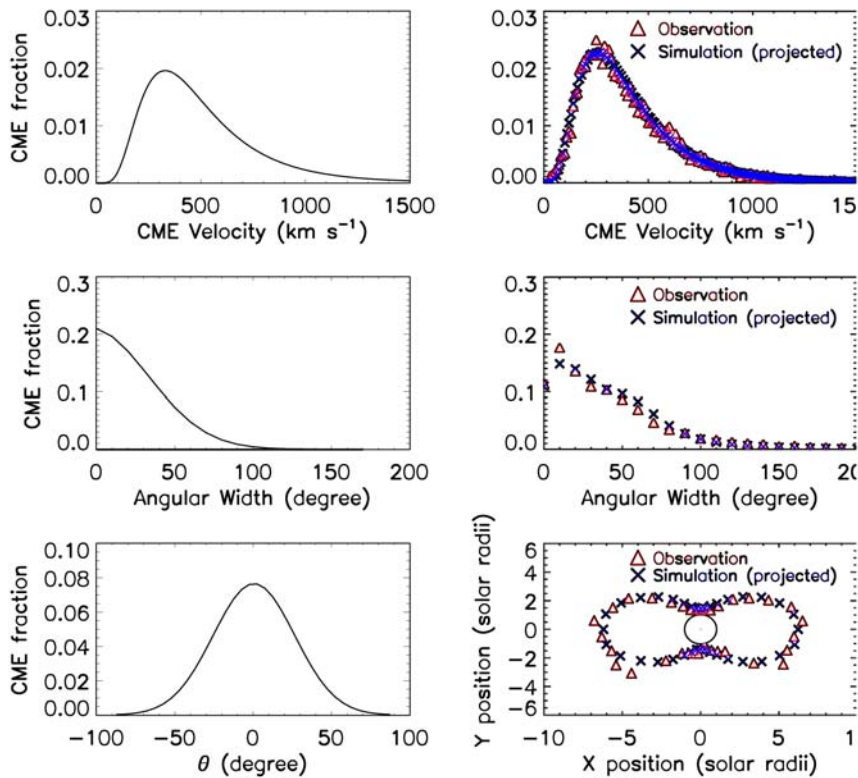


Fig. 2 *left column:* The derived real distributions of the CME velocity (*top*), the angular width (*middle*), and the latitude θ (*bottom*); *Right column:* The apparent distributions of the CME velocity (*top*), the angular width (*middle*), and the MPA (*bottom*), where the triangles correspond to the *SOHO/LASCO* observations, and the crosses to the projection of the real distributions.

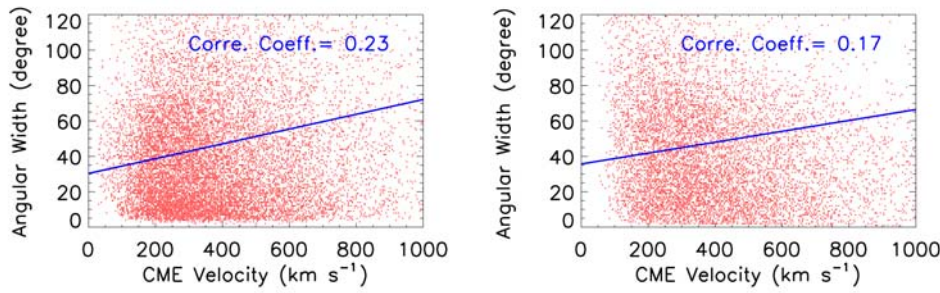


Fig. 3 Scatter plots of the relation between the CME velocity and the angular width in observations (*left*) and simulations (*right*). The solid lines represent the linearly fitted lines.

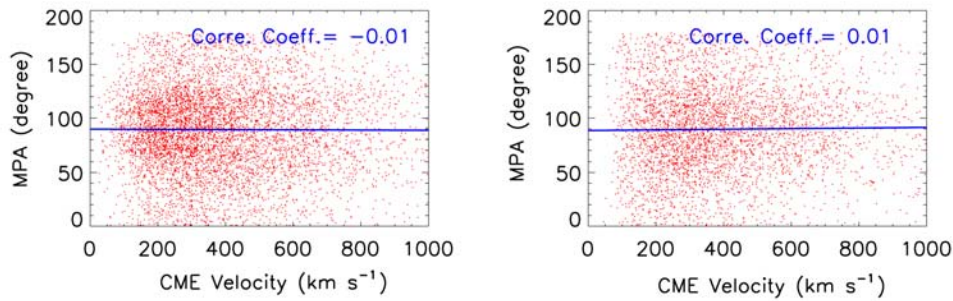


Fig. 4 Scatter plots of the relation between the CME velocity and the MPA in observations (*left*) and simulations (*right*). The solid lines represent the linearly fitted lines.

0.91. Similar to Figure 3, the sparse data points with $v > 1000 \text{ km s}^{-1}$ or $\text{MPA} > 200^\circ$ are not shown in Figure 4, though they are included in our study.

It is noted in passing that the CME angular width and the MPA also show little correlation. Therefore, with the largest-ever sample that includes almost all the CMEs observed by the *SOHO/LASCO* coronagraph, we found that the CME velocity, the CME angular width, and the latitude of the central source region are all mutually uncorrelated. Such a lack of correlation validates our assumptions used in our forward modeling in deriving the real CME velocity and angular width distributions.

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