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On 3D reconstruction of coronal mass ejections: II. Longitudinal and latitudinal width analysis of 31 August 2007 event

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In an earlier work, Mierla et al. (2009) applied four different reconstruction techniques to three coronal mass ejections (CMEs) at a given time. This study is a follow up of the above work in which we apply a local correlation tracking and tie-point reconstruction technique (LCT–TP) to the CME observed on 31 August 2007 by the COR1 and COR2 coronagraphs onboard the STEREO spacecraft at different times. The results show considerable scatter in the direction parallel to the line of sight, which is a direct indication of the CME depth. We derive the longitudinal and latitudinal sizes of the CME as a function of time. We find that a reasonable lower estimate of the longitudinal size is 18°–44° with an absolute largest extent of 78°–110°. We also find that a reasonable lower estimate for the latitudinal size of the CME is 18°–32° with an absolute largest extent of 44°–56°. In general, the latitudinal size is smaller than the longitudinal size, indicating an elliptical cone like structure or a flux rope like structure with very little tilt relative to the ecliptic. Self-similar expansion is observed above a height of $6.9R_{\odot}$. As our analysis is based on a statistical approach, large scatter is expected. In order for the method to be validated, more cases have to be studied.

1. Introduction

Coronal mass ejections (CMEs) are very energetic solar phenomena which can affect us directly by the geomagnetic disturbances produced when they interact with the Earth's magnetosphere (e.g. Srivastava and Venkatakrishnan, 2004; Gopalswamy et al., 2007). It is, therefore, important to be able to derive the kinematics and three-dimensional (3D) configuration of CMEs right from their initiation, in order to accurately predict their arrival time to the Earth and their possible impact on geospace.

Since the launch of the STEREO spacecraft in October 2006, several reconstruction techniques have been successfully used to derive the direction of propagation and true speed of CMEs at distances close to the Sun (see Mierla et al., 2010 for review of techniques within the coronagraph field of view) and in the interplanetary space (see Rouillard, this issue; Howard, this issue; Jackson et al., this issue for reviews of techniques within the HI and SMEI fields of view). However, inferring their full 3D geometry from only two vantage points is still a task difficult to achieve. One complication comes from the fact that the CME plasma is optically thin and its observed radiance results from the integration of the photospheric scattered light by the coronal electrons along the line of sight. In addition, the Thomson scattering introduces a weighting factor that maximizes the radiation scattered from the electrons located close to the plane of the sky (e.g. Billings, 1966; Vourlidas and Howard, 2006; Howard and Tappin, 2009). This introduces a bias for CME intensities that are detected by a coronagraph.

Reconstruction of the full 3D geometric shape have been attempted for several CMEs by using forward modeling (e.g. Thernisien et al., 2009), and by using the polarized ratio method based on Thomson scattering geometry (e.g. Moran and Davila, 2004; Dere et al., 2005; Moran et al., 2010). Different approaches to derive the 3D geometry are given in Antunes et al. (2009) and Wood et al. (2009). Antunes et al. (2009) used forward modeling in combination with inversion method in order to reconstruct the 3D mass distribution of a CME, while Wood et al. (2009) used an intuitive trial-and-error method, where synthetic SECCHI images were computed from an assumed 3D density distribution, and then the distribution was iteratively altered until the best visual agreement with the data were obtained. Each of these approaches

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have their limitations. In the forward modeling method, it is necessary to assume a CME shape function that depends on several parameters; in the polarized ratio method, only the weighted mean distance of the CME density from the plane of sky can be derived. The inverse modeling is constrained by the limits on the overlapping viewpoints and in general produces non-unique solutions if only a few view directions are provided.

In this paper, we make an attempt to reconstruct the 3D geometry of a CME observed on 31 August 2007 at the south-west limb of the Sun by SECCHI-COR1 and -COR2 coronagraphs onboard STEREO. We used the local correlation tracking plus tie-pointing method (LCT–TP). The method has an advantage as it does not suffer from the constraints of the methods mentioned above, but it has its own limitations as discussed in Section 4. This paper is a follow-up work of a previous research (Mierla et al., 2009) where four different reconstruction techniques were applied to the CME images at a given time. We extend the study by applying LCT–TP method to the CME at different times.

The paper is structured as follows: Section 2 deals with the data presentation and the general description of the CME on 31 August 2007. Section 3 presents the method and its application to the data. In Section 4 the results of the 3D reconstruction are presented. The main constraints in deriving the 3D reconstruction of the CME are also presented and discussed. The main results and conclusions are summarized in the last section.

2. Description of the CME on 31 August 2007

The CME on 31 August 2007 was observed as a "three-part" CME as defined by Illing and Hundhausen (1986), in white-light, by SECCHI-COR1 and -COR2 coronagraphs onboard STEREO. The separation angle between the STEREO spacecraft on that day was approximately 28°. The CME was associated with an eruptive prominence that was observed in ultraviolet (304 Å) by SECCHI-EUVI, at around 19:00 UT. The erupting plasma is seen as a filament in EUVI-A images, and as a limb prominence in EUVI-B images (A stands for the STEREO spacecraft moving ahead of the Earth and B for the spacecraft moving behind the Earth). The filament has a U-shape, oriented almost parallel to the solar limb. The prominence material is later seen as the core of a structured CME in COR1 field of view (around 20:50 UT—COR1-A and 20:55 UT—COR1-B) and COR2 FOV (around 21:52 UT—COR2-A, and 22:23 UT—COR2-B). The cadence of images is 5 min for COR1 and 30 min for COR2 polarization sequences. Only paired images were considered for the present analysis. In this study, the total brightness images of COR1 and COR2 were used. The images were derived from three sequential images taken with polarization angle of 0°, 120° and 240°, by means of SolarSoft routine secchi_prep. In order to remove the intensity contribution of coronal streamers and visualize the intensity contribution of the CME we subtract a minimum intensity image. This image is obtained by computing the minimum value in each pixel, from a set of images ranging over a period of several hours, centered on the CME time.

Fig. 1 shows the eruption in EUVI 304, COR1 and COR2 images at specific instants. Left panels represent the images recorded by STEREO-B and right panels the ones recorded by STEREO-A. COR1 and COR2 images were rotated to align them with the STEREO mission plane (SMP), where SMP is defined as the plane which contains the two spacecraft A and B and the center of the Sun. As a consequence, we roll the images such that the SMP north corresponds to the Y-axis in the image. The images from STEREO-B are brought to the same Sun center and the same resolution as the STEREO-A images. To reduce the calculation time, we exclude all parts of the images not covered by the CME by selecting a region of interest (ROI). We choose it manually by marking the points on the boundary of the ROI. All the calculations are done only for the pixels which lie within the ROI.

3. The LCT–TP method and its application to the data

We apply the LCT–TP (local correlation tracking plus tie-point reconstruction) method in order to reconstruct the 3D geometry of the CME. The method is described in Mierla et al. (2009). It consists in identifying the same feature appearing in the two A and B images with the help of LCT method, and then, by using triangulation, determine the position of the feature in 3D. The projections of a feature will lie along corresponding epipolar lines (Inhester, 2006) (also known as epipolar constraint), which reduces our search to a one-dimensional search. As part of the preprocessing steps, we rectified the images such that epipolar lines are orientated horizontally in the image, and as a consequence, the correlation between normalized intensities is calculated along horizontal lines. We choose a search window of 256×3 pixels, the correlation coefficient being calculated for each pixel of this window within a match window of 11×11 pixels, centered on the pixel; 11 pixels correspond to approximately $0.08R_\odot$ (56 000 km) for COR1 and $0.3R_\odot$ (209 000 km) for COR2. In order to find correlations, we keep the match window in a fixed position on a given epipolar line in one image and move it along the same epipolar line in the other image (or in the search window). When a maximum of the correlation occurs at a certain shift, the center position of the "window" is used for tie-pointing the 3D region which has produced this high correlation. The shift, known also as disparity, is directly proportional to the reconstructed depth. The depth is defined as the distance of a feature from the plane of the sky of a virtual observer half way between the two spacecraft. The size of our search window restricts the reconstruction of the CME to a depth range of $\pm2R_\odot$ for COR1 and $\pm8R_\odot$ for COR2. The values of the correlation coefficients range between -1 (anticorrelation) and 1 (maximum correlation). For the present study, we have ignored all the points where the correlation coefficients were smaller than 0.9.

Fig. 2 shows the reconstructed CME at around 21:30 UT (COR1—upper panels) and at around 01:52 UT (COR2—lower panels). The Sun is represented by the gray sphere. The radius of the outer gridded sphere is $1.5R_\odot$. The colors represent the distance along the X-axis (blue indicating maximum positive value). The coordinate system used here is Heliocentric Earth Equatorial (HEEQ) coordinate system. It has its origin at the center of the Sun, the Z-coordinate axis along the solar rotation axis and the X-axis so that Earth lies in the X–Z plane. The Y-axis is perpendicular to the X- and Z-axes and points towards the western limb of the Sun. Two viewpoints are chosen for presenting the reconstructions: head-on in the right panel (X and Z in the image plane, Z downwards and X towards right) and edge-on in the left panel (Y and Z in the image plane, Z upwards and Y towards right). The images show some scatter along the line of sight (approximately in X direction), best seen from the head-on perspective. Also, notice that the CME propagates roughly in the Y direction.

4. Analysis of the reconstructed CME

4.1. Results

We have applied the method described in Section 3 to the COR1 images taken in the time interval 21:05–22:10 UT, and to COR2 images recorded between 22:52 UT (31 August 2007) and 04:52 UT (1 September 2007).

Fig. 3 shows the histograms of points versus longitude (upper panels) and latitude (lower panels) for the CME observed at