Automated Detection of Accelerating Solar Eruptions Using Parabolic Hough Transform

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Abstract  Solar eruptions such as coronal mass ejections (CMEs) observed in the inner solar corona (up to 4 R⊙) show acceleration profiles that appear as parabolic ridges in height–time plots. Inspired by the white-light automated detection algorithms Computer Aided CME Tracking System (CACTus) and Solar Eruptive Events Detection System (SEEDS), we employ the parabolic Hough transform for the first time to automatically detect off-disk solar eruptions from height–time plots. Due to the limited availability of white-light observations...

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in the inner corona, we use extreme ultraviolet (EUV) images of the Sun. In this article we present a new algorithm, CME Identification in Inner Solar Corona (CIISCO), that is based on Fourier motion filtering and the parabolic Hough transform, and we demonstrate its implementation using EUV observations taken by the Atmospheric Imaging Assembly (AIA) onboard the Solar Dynamics Observatory (SDO), Extreme Ultra Violet Imager (EUVI) onboard the STEREO-A and -B spacecraft, and Sun Watcher using Active Pixel System detector and Image Processing (SW AP) onboard the PROject for On-Board Autonomy-2 (PROBA2) spacecraft. We show that CIISCO is able to identify off-disk, outward-moving features in EUV images. The use of automated detection algorithms, such as CIISCO, can potentially be used to provide early warnings of CMEs if an EUV telescope is located at ±90° from the Sun–Earth line, providing CME characteristics and kinematics close to the Sun. This article also presents the limitations of this algorithm and the prospects for future improvement.

Keywords Corona · Coronal mass ejections · Automated detection

1. Introduction

Coronal mass ejections (CMEs) are large-scale eruptions of plasma and magnetic field from the solar atmosphere into interplanetary space, and they are most commonly observed with white-light coronagraphs. These eruptions are known to have a three-phase kinematics profile starting with a gradual rise phase, followed by an impulsive acceleration phase below 2 R⊙, and a final phase of constant average speed (Zhang et al., 2001, 2004; Bein et al., 2011; Majumdar et al., 2020). It is now well established that CMEs play an important role in driving space weather (Gosling, 1993), and therefore it is necessary to understand their origin and early development through the inner (up to 4 R⊙) and outer corona (above 4 R⊙).

For the last two decades, space-based white-light observations of the corona have been made by the Large Angle Spectroscopic COronagraph (LASCO), which was originally a coronagraph system comprising of three units C1, C2, and C3 capable of observing the Sun from 1.1 to 30 R⊙ (Brueckner et al., 1995), with the inner coronagraph [C1] having a FOV from 1.1 to 3 R⊙. More recently, observations have also been made with the Solar TErrestrial RElations Observatory (STEREO) COR1 coronagraph, which has a FOV extending from 1.4 to 4 R⊙ (Howard et al., 2002). However, LASCO-C1 stopped observing after 1998 and STEREO/COR1 images suffer from heavy compression, noise, and artefacts. Even with the inner edge of our space-based coronagraphs extending down to 1.4 R⊙, these imagers struggle to capture the kinematics of eruptions during their acceleration phase. Such observations are important for understanding the over-arching propagation of an eruption. Models such as Empirical CME Arrival (ECA: Gopalswamy et al., 2000, 2001) use the initial kinematics of CMEs as an input to predict their arrival times at Earth. A better understanding of their initial properties can help to improve such empirical models. It should be noted that some ground-based coronagraphs, such as K-Cor (de Wijn et al., 2012), at the Mauna Loa Solar Observatory (MLSO), image the lower solar corona (1.05 – 3 R⊙). However, ground-based imaging has its own set of issues, such as being limited by atmospheric conditions and daytime observations.

Full-disk images of the EUV emission corona have been regularly taken over the past two solar cycles, starting from the Extreme ultra-violet Imaging Telescope (EIT: Delaboudinière et al., 1995) onboard the Solar and Heliospheric Observatory (SOHO), followed by the Extreme UltraViolet Imager (EUVI: Howard et al., 2002) onboard the Solar TErrestrial
RELations Observatory (STEREO), the Atmospheric Imaging Assembly (AIA: Lemen et al., 2012) onboard the Solar Dynamics Observatory (SDO), the Sun Watcher using Active Pixel System detector and Image Processing (SWAP: Seaton et al., 2013; Halain et al., 2013) onboard the PROject for Onboard Autonomy 2 (PROBA2) mission, and the recent Solar Ultra Violet Imager (SUVI: Seaton and Darnel, 2018) onboard the Geostationary Operational Environmental Satellite (GOES-R). It has long been known that the coronal emission observed in EUV pass-bands is generated by atomic transitions of different ions present in the solar atmosphere, whereas the white-light corona is photospheric light bouncing off free electrons due to Thomson scattering. As a consequence, the coronal features observed by the two types of imager are not always the same. A study of the kinematics of CMEs made by Bein et al. (2011) (and the references therein), combining EUVI data from the emission corona with white-light observations from COR-1 and COR-2, suggests that the early phases of CMEs can have accelerations as high as 1000 m s$^{-2}$. With large-FOV EUV imagers such as SWAP and EUVI, the eruptive profiles recorded from EUV and white-light observations can be combined to create a more complete picture of the initial kinematics of a CME. Although an EUV eruption front may not have a one-to-one correspondence with the leading edge of a white-light CME, it can give us an idea about the over-arching kinematics of propagating eruptions in the inner corona.

The manual detection and tracking of solar eruptions in large datasets is time consuming and subjective. In order to overcome these limitations, algorithms to automatically detect CMEs in coronagraph imagery were developed, starting with CACTus, which uses the linear Hough transform to detect CMEs as white ridges in height–time plots of LASCO images (Robbrecht and Berghmans, 2004; Robbrecht, Berghmans, and Van der Linden, 2009). CACTus was later extended to STEREO/COR2 data. It was recently adapted as CACTus-CAT (see sidc.be/cactus/h/) to be used with STEREO-HI1 images (Pant et al., 2016). Another algorithm, SEEDS, transforms images from the LASCO and the STEREO coronagraphs to polar coordinates in which the intensity is integrated in the radial direction at each position angle (PA) and reduced to one-dimensional (1D) arrays. CMEs are identified in such arrays and processed to track the leading edge as the outermost boundary of the moving feature in the intensity threshold running-difference images. A similar approach was also used to automatically detect CMEs in K-Cor images by Thompson et al. (2017). In another algorithm, Automatic Recognition of Transient Events and Marseille Inventory from Synoptic maps (ARTEMIS), adaptive filtering and segmentation techniques are used to identify CMEs as bright streaks in synoptic maps of LASCO images (Boursier et al., 2009). The Coronal Image Processing (CORIMP) algorithm separates quiescent and dynamic coronal structures observed in coronagraph images using deconvolution and detects CMEs structure using a multi-scale edge-detection method (Morgan, Byrne, and Habbal, 2012; Byrne et al., 2012) taking into account CME kinematics and morphology changes. In a recent work, Qiang et al. (2019) developed an algorithm based on adaptive-background learning to detect CMEs in LASCO-C2 images considering CMEs to be dynamic foreground features in running-difference images.

Recently, algorithms based on machine learning have also been developed for automated CME detection (Qu et al., 2006; Zhang et al., 2016; Zhang et al., 2017; Wang et al., 2019). Onboard algorithms based on an intensity threshold, using running-difference polarized-brightness coronagraph images, have been developed for Multi Element Telescope for Imaging and Spectroscopy (METIS: Bemporad et al., 2014) onboard Solar Orbiter. The Visible Emission Line Coronagraph (VELC: Prasad et al., 2017), onboard Aditya-L1 (Seetha and Megala, 2017), has a simple onboard algorithm for CME detection based on intensity and area threshold (Banerjee, Patel, and Pant, 2017; Patel et al., 2018a,b).
The aforementioned algorithms focus on the white-light data. However, not much work has been done to automatically identify the EUV counterparts of white-light CMEs. Recently, an algorithm was developed to automatically detect and catalog prominence eruptions in SDO/AIA 304 Å (see cdaw.gsfc.nasa.gov/CME_list/autope/) observations (Yashiro et al., 2020). Among the existing automated CME detection methods, CACTus is limited by the use of the linear Hough transform. Since CMEs in the inner corona accelerate, they may appear as parabolic or higher-order (> two) polynomial ridges in height–time (r–t) plots. CACTus has been designed to detect straight lines in r–t plots, the slope of which gives the speed of CMEs, and therefore may miss eruptions or parts of eruptions that are represented as parabolic ridges in the r–t plots of inner corona. A consequence of this will be that the algorithm misses important information about the CME acceleration. It should be noted that SEEDS and CORIMP are not successfully implemented on the images taken by STEREO-COR1, which observes the inner corona.

As discussed above, although there is not an exact correspondence between EUV and white-light observations, the structures observed in emission will go some way to providing an approximation of the early characteristics of CMEs observed further out in white-light observations. In this article we present a novel automated method, CMEs Identification in Inner Solar Corona (CIISCO) that identifies the off-disk solar eruptions as intensity enhancements and tracks them as parabolic ridges in height–time plots of EUV images using the parabolic Hough transform. By applying automated-detection algorithms to EUV observations of the inner corona we can identify and track the eruptions in their early stages of development. Similarly to CACTus, if CIISCO is applied to a large dataset it can provide a large statistical sample of solar eruption properties in the inner corona. This article is organized as follows: We describe the different datasets used for analysis in Section 2 along with the algorithm. In Section 3, we present the results of the application of the algorithm on several EUV images from different instruments, in particular the large-FOV EUV imager SWAP. We conclude with a summary and discussion in Section 4.

2. Observations and Method of Detection

The erupting plasma can be distinctly seen in both 171/174 Å and 304 Å EUV pass-bands. The 171/174 Å pass-band EUV imagers observe hotter coronal plasmas, whereas the 304 Å pass-band observes chromospheric temperatures, and hence cooler, denser structures such as filaments. Therefore, we have used full-disk EUV images from AIA, EUVI, and SWAP. The FOV of these instruments are up to 1.3 $R_\odot$, 1.7 $R_\odot$, and 1.7 $R_\odot$ respectively. The high-cadence (12 seconds), but smaller-FOV, observations from the AIA at 171 and 304 Å were used and processed to Level 1.5 using aia_prep.pro to correct for solar north, plate-scale, and alignment adjustment. Level 1 SWAP images were prepared using p2sw_prep.pro with corrections for dark, flat-field, point spread function (PSF) deconvolution, and despiking, and the images were corrected for alignment. SWAP observes coronal emission at the ≈ 174 Å pass-band, with a larger FOV than AIA and at a cadence of ≈ two minutes. STEREO/EUVI images in the 304 Å pass-band at a cadence of ten minutes. Due to the relatively lower cadence of two hours, the EUVI 171 Å images were not used for our analysis unlike AIA. The data were processed to Level 1 using the secchi_prep.pro routine, which corrects for flat-field and bias, calibrates to physical units, and normalizes the filter response to the clear filter. AIA and EUVI images were rebinned to 1024×1024 pixels for the generalization of the algorithm and to save processing time.
We used the aforementioned pass-bands to observe several periods in the near-maximum phase of Solar Cycle 24 when off-limb solar eruptions could be clearly identified visually. More specifically we used observations on 8 April 2012, 27 June 2012, and 31 August 2012 in the 171 Å pass-band of AIA, and on 8 April 2012 and 8 July 2014 in the AIA 304 Å channel. EUVI-A and EUVI-B observations taken at 304 Å pass-bands on 13 May 2013 and 31 August 2012 respectively and SWAP 174 Å observations on 24 December 2011, 16 April 2012, 1 May 2013, 21 June 2013, and 24 August 2014 were used.

The SOHO/LASCO, STEREO/COR-2, and STEREO/HI-1 instruments image the outer corona where solar eruptions attain relatively constant velocities or have relatively moderate acceleration/deceleration profiles dictated by their interaction with the ambient solar wind, and they are therefore ideally suited for detection by algorithms such as CACTus, which uses a linear Hough transform (Gopalswamy et al., 2000; Temmer et al., 2011). As discussed in the introduction, the early evolution of solar eruptions shows gradual and impulsive accelerations that are not seen when they reach the outer corona (Bein et al., 2011). Solar eruptions in outer corona appear as straight lines in height–time (r–t) plots that are detected by CACTus using the linear Hough transform. On the other hand, solar eruptions propagating in the inner corona appear as parabolic or higher-order (>two) polynomial ridges in r–t plots. Assuming that solar eruptions accelerate uniformly in the inner corona, we used a parabolic Hough transform aided with Fourier motion filtering to detect and track solar eruptions in solar EUV images. This assumption is meant for simplicity in the automated detection.

Automated detection of the second-order polynomial (parabola) is a first step towards the detection of higher-order polynomials (>two), which will be done in future studies. The steps involved in CIISCO for detecting solar eruptions are outlined in the flowchart of Figure 1.

The method of detection employed by CIISCO is illustrated using SWAP Level 1 images taken on 24 December 2011, and the steps are explained in the next few subsections.

### 2.1. Intensity Enhancement

As density, and consequently intensity, in the corona decreases radially with distance from the solar limb, coronal features appear fainter at larger distances. In order to enhance the coronal intensity in off-limb corona, a radial filter was applied (Morgan, Habbal, and Woo, 2006). First we create a background image taking an average of the lowest 3% intensities at each pixel of all images of the dataset, following DeForest, Howard, and McComas (2014). A radial intensity profile of this image is generated taking a radial cut at the polar region with a fixed width of three pixels and then averaging their intensities. To avoid the errors created by bad-pixel intensities, this array of radial intensity profile is further smoothed out by ten pixels in the radial direction. The polar regions are chosen as they have fewer foreground structures (e.g. loops). This radial profile is used to make an azimuthally uniform background that is used as a radial filter. Each of the images in dataset are then divided by this radial filter. By applying these techniques, coronal structures were clearly seen to greater distances (see Figure 2b), especially when compared to Figure 2a, which is unfiltered. As we are interested in off-disk features, we block the solar-disk emission by applying an artificial mask up to 1.02 R⊙. The images are then converted to polar (θ–r) coordinate, where θ is the position angle (PA) in the counter-clockwise direction measured from solar north, and r is the distance from center of the Sun projected in the plane of sky. Figure 2c shows the polar-transformed image.
2.2. Fourier Motion Filtering

The inner corona shows many static and quasi-static structures such as coronal loops, prominences, etc., near the solar limb. Any changes in their intensity or morphology may appear as bright ridges in time-difference images, which may create false detections of solar eruptions. To avoid this, we use the Fourier motion filtering technique of DeForest, Howard, and McComas, 2014 to separate solar eruptions from these background structures. We generate height–time \((r–t)\) plots at each PA and take the Fourier transform giving spatial frequency \([k]\) along the \(x\)-axis and temporal frequency \([\omega]\) along the \(y\)-axis. In the \(k–\omega\) plot the first and third quadrants indicate the inbound features, whereas the second and fourth correspond to outbound features. Any outward-moving structure will have a positive gradient in an \(r–t\) plot and would correspond to velocities given by slopes of lines falling in the second and fourth quadrants of \(k–\omega\) plot. By masking the first and third quadrants of the \(k–\omega\) plot, the inbound and outbound solar eruptions were separated. The static features, which do not change over time and space, were removed by masking out the low-frequency components in \(k–\omega\) space. It was found that for the given resolution in Fourier space, the cut-off speed corresponding to a single pixel below which detection will not happen in AIA, SWP, and EUVI are 14 km s\(^{-1}\), 19 km s\(^{-1}\), and 76.45 km s\(^{-1}\) respectively. It has been found that during the slow-rise phase, the CMEs have speeds in the range of 5 – 80 km s\(^{-1}\) (Zhang et al., 2001), most of which fall above the cut-off speed limit in the Fourier space for AIA and SWP observations. The lower cadence of EUVI images prevents the capture of such a slow-rise phase of CME propagation. The inverse Fourier transform of the masked \(k–\omega\) data gives the Fourier filtered \(r–t\) plot, which is stacked at each PA to generate polar images with only outward-moving features present. Figure 2d shows the coronal structures after Fourier
motion filtering has been applied and the data have been filtered for outward-moving structures.

2.3. Automatic Identification of Solar Eruptions

A quick inspection of Figure 2d reveals a solar eruption, seen as a bright structure, spanning some PAs near 290°. To identify the solar eruptions, the Fourier filtered polar images are converted to 1D arrays by summing up intensities along radial directions at each PA as shown in Figure 3a, (similar to SEEDS). Since solar eruptions appear brighter than the background, which corresponds to a higher intensity in 1D intensity plots. All polar image are integrated along the radial direction to create 1D arrays and stacked with respect to time, to generate a so-called CME map with time along the vertical axis (Figure 3b). However, artifacts can be seen at the top and bottom of the CME map (approximately the first and last ten images). These are believed to be created by the Fourier filtering technique, which also introduces faint ringing patterns in the CME map. These artifacts are bright enough to trigger false detection and are therefore removed from the map (see Figure 3c). The cropped
Figure 3 Outlining the automatic identification of solar eruptions in the Fourier motion filtered images; (a) 1D intensity plot created by summing up intensities along each PA, (b) CME map created after stacking 1D intensity plots in time, (c) Cropped CME map, (d) CME map after intensity thresholding, (e) After labeling regions with different colors.

CME map is then passed through an intensity threshold algorithm using the relation,

\[ I_{\text{map}}_{\text{th}} = \text{mean}(\text{cmemap}) + f \times \text{stddev}(\text{cmemap}), \]  

(1)

where \( I_{\text{map}}_{\text{th}} \) is the binary CME map after applying an intensity threshold to the cropped CME map (cmemap), and \( f \) is an adjustable constant parameter dependent on the instrument response, which may vary with instrument and pass-band. The value of \( f \) was determined to be 3.25 by running CIISCO on various different eruptions in order to capture the most of them with minimal false detections whilst maximizing the detection efficiency by comparing with manual detection. Figure 3d shows the CME map after intensity thresholding. Different regions obtained in \( I_{\text{map}}_{\text{th}} \) are then labeled and marked with different colors, as shown in Figure 3e. Regions with widths greater than 5°, and persisting for at least three frames, were considered to be the signatures of possible solar eruptions. These thresholds applied on the CME map regions reduced the possibility of false detection in subsequent steps. An estimate of the angular extent of the possible solar eruptions was made by determining the minimum and maximum PAs of these regions from the CME map. It can be seen from Figure 3e that the region in red at PA \( \approx 290^\circ \) satisfies both of these criteria and is therefore a potential solar-eruption detection.
2.4. Application of Parabolic Hough Transform

Once a probable solar eruption is identified, the next step is to track it in both temporal and spatial domains. In a recent work, Yashiro et al. (2020) used the centroid of prominences listed in the SDO/AIA 304 Å prominence eruption catalog mentioned in Section 1 to track them in successive frames rather than the leading edge of the eruption. The existing CME auto-detection methods (Robbrecht and Berghmans, 2004; Olmedo et al., 2008; Pant et al., 2016; Byrne et al., 2012) identify the leading edge of the CMEs to derive their characteristics. However, the leading edge of the EUV eruptions gets distorted during their propagation outwards making it difficult to identify them satisfactorily in subsequent frames. Therefore, we track solar eruptions as a whole in the EUV images. For this we determine the difference of maximum and minimum PAs from the CME map of the identified solar eruptions, which gives an idea of the maximum width of the observed erupting structure. We then sum up the intensities along PAs of each motion-filtered polar image within this width at each height. Summing up the intensities also enhances the signal to noise ratio (SNR). Such arrays of subsequent images are then stacked in time to create $r$–t plots for the identified solar eruptions. The outward-moving feature appears as a bright ridge in the $r$–t plot (see Figure 4a), and the identification of this ridge provides a representation of the tracked eruption.

Previous studies and observations have shown that most of the solar eruptions show acceleration in the inner corona (Bein et al., 2011). Thus, due to acceleration, they appear as parabolic ridges in $r$–t plots that can also be seen from Figure 4a. For a general form of a parabola, a hidden parameter $\theta$ determines its orientation with respect to the horizontal axis. As solar eruptions start with zero velocity, the slope of parabola (velocity) at $r_o$ has to be zero. The slope of the parabola (velocity) at the origin $(r_o, t_o)$ is zero if $\theta = 90^\circ$. The parabolic ridges in $r$–t plots will then have the form

$$r - r_o = S(t - t_o)^2,$$

where $r_o$ and $t_o$ are the spatial and temporal starting points of the parabolic ridges in the $r$–t plots, $S$ is a coefficient defining the curvature of the parabola, and hence representing the acceleration of the solar eruption, and finally $\theta$ defines the orientation angle of the parabola, counter-clockwise from the positive x-axis.

The detection of a solar eruption represented by a parabolic ridge in images using the Hough transform requires all four parameters: $t_o, t_o, S$, and $\theta$ (Ballard, 1981). Identifying the position of these parameters in 4D-parameter space to define a parabola is computationally expensive, but it can be improved by reducing the degrees of freedom in Equation 2. As we aim to detect off-disk eruptions, we take the value of $r_o$ where the eruption first appears outside the solar disk. To determine the value of this parameter we measured the height of first appearance of limb and near limb eruptions observed in SDO/AIA images taken at 171 and 304 Å from 1 January 2012 to 30 April 2012 using JHelioviewer (Müller et al., 2017). We identified 234 eruptions during this period and plotted a distribution as shown in Figure 5. Out of these 234 eruptions, $\approx 64\%$ show a starting height in the bin of 1.00 to 1.025 $R_\odot$. Therefore, we fixed $r_o$ to the lower limit of this bin as 1 $R_\odot$. This assumption is more appropriate for the eruptions occurring near the solar limb than for those occurring near Sun center. Thus, we reduce the 4D ($S, t_o, r_o, \theta$) problem to a 2D ($S, t_o, r_o = 1 R_\odot, \theta = 90^\circ$) problem. Equation 2 can be further written in the form

$$t_o = t - \sqrt{\frac{1}{S}(r - r_o)}.$$

(3)
To identify parabolic ridges in Figure 4a defined by Equation 2, a 2D array called the accumulator matrix is made using Equation 3 with horizontal and vertical axes $t_\circ$ and $S$ respectively. From the $r$–$t$ plot, for each value of $t$, $t_\circ$ is calculated iteratively by varying the values of $S$. The value at $(t_\circ, S)$ in the accumulator matrix is increased by one whenever a pixel corresponding to a parabolic bright ridge is detected in the $r$–$t$ map. The resulting accumulator matrix appears as shown in Figure 4b. It can be seen that the accumulator matrix consists of parabolas with different intensities. Each point of the accumulator matrix gives a pair of $t_\circ$- and $S$-values corresponding to different parabolic trajectories in the $r$–$t$ plot. However, the one corresponding to the brightest parabolic ridge of Figure 4a will have pixel values increased by most of the iterations. As a result, that pixel in the accumulator matrix will appear the brightest. This is the basic principle of the Hough transform to identify a feature from a noisy background that we have utilized to identify parabolas. Ideally, the pixel in the accumulator matrix with the maximum intensity should correspond to the parabolic ridge to be identified in the $r$–$t$ plot. The coordinates of this pixel will give the values of $t_\circ$ and $S$ defining the identified ridge. As can be seen in Figure 4a, the bright parabolic ridge corresponding to the solar eruption is a group of pixels with a certain width and different intensities along the width, and it will eventually lead to a group of pixels in the accumulator matrix that corresponds to this ridge. The set of brightest pixel coordinates in the accumulator matrix shown in Figure 4b provides the $t_\circ$- and $S$-parameters defining this parabolic ridge. Therefore, an intensity threshold is applied to the accumulator matrix with a threshold of 90% of the maximum intensity to identify the combination of $t_\circ$ and $S$ for the desired identification. This is followed by a morph-closing operation to avoid values being missed after thresholding. The accumulator matrix after intensity thresholding and the morph closing operation is shown with labeled regions in blue and red colors over-plotted on Figure 4b. As the parabolic ridges have a width of a few pixels, we have taken the median of all values of $(t_\circ, S)$ of the connected pixels of the thresholded accumulator matrix with a width greater
Figure 5 Distribution of heights of first appearance of eruptions outside the limb observed by SDO/AIA in 171 and 304 Å pass-bands from 1 January 2012 to 30 April 2012.

than ten pixels, which in this case is the blue region overplotted in the accumulator matrix in Figure 4b. This may result in a family of parabolas being identified for a given solar eruption in $r$–$t$ plots if more than one region satisfying this criterion is identified. Parabolas close in time are considered to be identified for the same solar eruption in the $r$–$t$ plot. Figure 4a also shows the identified parabola over-plotted in a red dashed line on parabolic ridge. Note that this particular set of thresholds in Hough space is successful in identifying the solar eruption from other background, spurious parabolic signatures.

2.5. Determination of Solar Eruption Properties

Once a solar eruption has been identified using the parabolic Hough transform, several characteristics, describing each eruption, are extracted. These characteristics are derived by detecting and tracking the eruption as a whole and not just the leading front. These include:

i) Estimation of central position angle (CPA): The CPA of a solar eruption is calculated from the CME map as the midpoint of the maximum width of the corresponding labeled region in the direction of the PA.

ii) Estimation of solar eruption onset time [$t_o$]: The onset time is estimated from the parameter $t_o$ in Equation 3. As a set of parabolas are identified for a given solar eruption, we take the mean of $t_o$ of all of these parabolas to estimate the onset time of the solar eruption.

iii) Estimation of solar eruption kinematics: The average apparent velocity [$v$] was determined by calculating the slope of the line joining the two extreme points in the identified parabola. The average apparent acceleration [acc] of the solar eruption was determined from the constant $S$ of the parabola. Comparing the equation of motion,

$$s = s_o + ut + \frac{1}{2}at^2,$$

and Equation 2, we found that the apparent acceleration was $2S$ with an assumption that the initial velocity of the solar eruption [$u$] was zero. We determined the average
apparent velocity and acceleration for each of the parabolas in the family and take the mean value to be recorded for solar eruption kinematics.

For the example of SW AP images taken on 24 December 2011, we obtained that the solar eruption onset time is 11:28 UT, CPA is 287°, average apparent velocity is 102 km s\(^{-1}\), and average apparent acceleration is 67 m s\(^{-2}\) after the application of CIISCO.

3. Results

We applied CIISCO to EUV images of SWAP, AIA, and EUVI over several short time periods. The results can be seen in Figure 7, where solar eruptions are identified as parabolic ridges in \(r-t\) plots in EUV images. The results are summarized in Table 1. The following properties of a solar eruption are determined by CIISCO: the solar eruption onset time \([t_o]\), the central position angle (CPA), the average apparent velocity \([v]\) and the average apparent acceleration \([\text{acc}]\). The range of apparent velocities and accelerations obtained from CIISCO are recorded and indicated by their extremes as \(\text{min}_v\), \(\text{max}_v\), \(\text{min}_\text{ac}\), and \(\text{max}_\text{ac}\) respectively.

For completeness, we have also manually identified the eruptions, tracked their leading front in consecutive images, and calculated the average apparent speed \([v_m]\) and average apparent acceleration \([\text{ac}_m]\) measured in the plane of sky for comparison with CIISCO. A contour was manually fitted to the outermost boundary of the eruption that could be visually identified. To take the fitting accuracy into account, the height of the leading edge was estimated by taking the average of all those points whose heights are greater than 0.95 times the maximum height obtained by fitting the contour. In Table 1, the instrument used, pass-band of the observation, and the date of the solar eruption are included. A serial number of the eruption on a particular date is given in Column 3. The last column indicates if the detection was a false positive, where no eruption was observed following manual inspection. False positives were often triggered by rising plasma motions in loops or moving features on the limb created by solar rotation. The remaining detections are treated as true if a radially outward-moving feature is present in images and has been visually identified.

A closer inspection of Table 1 reveals:

i) CIISCO works well with different EUV datasets. It detected 22 eruptions, of which 7 were false positive following manual analysis.

ii) The kinematic properties of most of the correctly identified solar eruptions derived from CIISCO are close to the values obtained by manual identification. Most of these values obtained after manual tracking are within the range of speed and apparent acceleration determined by CIISCO. For such cases, the average speed derived by CIISCO and those computed manually agree within 50 – 100 km s\(^{-1}\). The eruptions 2 and 7 are prominences erupting from a height \(>1\ R_\odot\) and show deviations in the kinematics properties but are detected adequately. The value of apparent acceleration after manual analysis comes within the range of values given by CIISCO for 12 out of 15 true detections. For the remaining 3 true cases, the difference in the values of apparent accelerations \([\text{ac}_m\) from either \(\text{min}_\text{ac}\) or \(\text{max}_\text{ac}\)] is less than 50 m s\(^{-2}\).

iii) The kinematics derived by CIISCO are compared with manual estimates as shown in Figure 6 with the error bars representing the range of values determined by CIISCO. For the speed estimates there is a correlation of 50% between the two methods when all of the data points are considered. This value increases to 84% when the rightmost value of 724 km s\(^{-1}\) is considered as an outlier. The acceleration values shows a good correlation of 67%. If the one decelerating eruption is left out, then the agreement increases to 96%.
iv) CIISCO is able to identify multiple solar eruptions produced at the same location with similar, but different, onset times. The two solar eruptions identified in AIA 304 Å observations on 8 April 2012 at CPA 228° have onset times of 00:15 UT and 00:41 UT respectively.

v) CIISCO also identified solar eruptions at different locations erupting with a time difference of \(\approx 30\) minutes as can be seen for solar eruptions 2 and 3 observed on 13 May 2013 by EUVI-A at 304 Å.

vi) CIISCO wrongly identified a decelerating solar eruption 8 July 2014 as an accelerating one. This is due to the fact that only ridges defined by Equation 2 are identified.

vii) The eruption of 24 August 2014 was tested in AIA as well as the SWAP FOV in a similar pass-band. It could be seen that the speed range is similar for the two cases, with the difference of the eruption being accelerating in lower heights.

We also identified the location of the eruptions that had been correctly identified by CIISCO. We found that eruptions 5 and 10 occurred near \(-65°\) longitude, eruptions 11 and 20 were found to have their origin near \(-75°\) longitude whereas eruptions 6, 13, 15, and 22 happened at around \(\pm 80°\) longitude. The remaining correctly detected eruptions were the off-disk ones. Thus the eruptions tested here occurred within \(\approx 25°\) longitude from the limb and have been identified as radially outward-moving features. It can be noted from Table 1 that eruptions 2 and 7, which are prominence eruptions, occurring at the limb, show some deviation in the kinematics. Other than these two, we also found that except for eruptions 5 and 10, which occur near \(-65°\) longitude, the range of kinematics estimated by CIISCO have values close to those found by manual identification. The estimates of kinematics of these eruptions located within 25° from the limb are also complemented with Figure 6. This emphasizes that CIISCO is well suited to detect eruptions very close to the limb but can also provide an approximation of the eruption characteristics for other events such as 5 and 10.

Further for comparison and eruption identification we used the Coordinated Data Analysis Workshops (CDAW) LASCO CME catalog (Yashiro et al., 2004) and JHelioviewer (Müller et al., 2017). As there is no overlap between the AIA and SWAP FOV and the LASCO-C2 coronagraph, these eruptions could not be tracked in the intermediate region and one-to-one comparison could not be made. However we attempted to identify different structures that could be traced in both EUV and white-light images. It turned out that eruption 2, observed by AIA (171 Å), detected on 27 June 2012 and eruption 5 (AIA 171 Å) detected on 31 August 2012 correspond to the cores of the CMEs observed in the LASCO-C2
Table 1  Solar eruption parameters derived from the application of CIISCO algorithm to EUV images.

| Instrument | Date       | Serial No. | \(t_0\) [HH:MM] | CPA [Degree] | \(v\) [km s\(^{-1}\)] | \(v_{\text{min}}\) [km s\(^{-1}\)] | \(v_{\text{max}}\) [km s\(^{-1}\)] | \(v_{\text{fit}}\) [km s\(^{-1}\)] | \(\text{acc} \) [m s\(^{-2}\)] | \(\text{inac} \) [m s\(^{-2}\)] | \(\text{maxac} \) [m s\(^{-2}\)] | \(\text{acm} \) [m s\(^{-2}\)] | Remarks          |
|------------|------------|-------------|-----------------|-------------|-----------------|-----------------|-----------------|-----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| AIA (171 Å) | 8 Apr 2012 | 1           | 02:00           | 115         | 1742            | 1361            | 2449            | 16836           | 8726            | 29145          | False          |
|            | 27 Jun 2012 | 2           | 09:28           | 315         | 79              | 60              | 98              | 324             | 69              | 37             | 100            | 33             | False          |
|            | 27 Jun 2012 | 3           | 10:34           | 315         | 279             | 217             | 507             | 394             | 219             | 1210           | False          |
|            | 27 Jun 2012 | 4           | 11:37           | 73          | 593             | 389             | 773             | 1735            | 754             | 2693           | False          |
|            | 31 Aug 2012 | 5           | 19:41           | 110         | 428             | 417             | 439             | 522             | 803             | 773            | 833            | 896            | False          |
|            | 24 Aug 2014 | 6           | 12:04           | 102         | 407             | 384             | 543             | 433             | 794             | 509            | 1362           | 1318           |                |
| AIA (304 Å) | 8 Apr 2012 | 7           | 00:15           | 228         | 175             | 79              | 254             | 724             | 161             | 29             | 298            | 110            |                |
|            | 8 Apr 2012  | 8           | 00:41           | 228         | 220             | 96              | 249             | 222             | 227             | 169            | 285            | 328            |                |
|            | 8 Apr 2012  | 9           | 01:24           | 228         | 256             | 244             | 263             | 309             | 278             | 324            | False          |
|            | 8 Jul 2014  | 10          | 16:15           | 63          | 393             | 360             | 487             | 428             | 718             | 601            | 850            | −284           | Decelerating eruption |
| EUVI-A (304 Å) | 13 May 2013 | 11          | 05:36           | 143         | 174             | 130             | 226             | 166             | 40              | 22             | 68             | 20             |                |
|            | 13 May 2013 | 12          | 07:56           | 282         | 154             | 66              | 232             | 142             | 38              | 6              | 70             | 32             |                |
|            | 13 May 2013 | 13          | 08:26           | 81          | 122             | 76              | 238             | 158             | 22              | 8              | 72             | 84             |                |
| EUVI-B (304 Å) | 31 Aug 2012 | 14          | 07:16           | 267         | 237             | 171             | 256             | 72              | 33              | 148            | False          |
|            | 31 Aug 2012 | 15          | 19:26           | 249         | 407             | 213             | 906             | 399             | 305             | 55             | 1004           | 284            |                |
| SWAP (171 Å) | 24 Dec 2011 | 16          | 11:28           | 287         | 102             | 96              | 105             | 99              | 67              | 29             | 35             | 34             |                |
|            | 16 Apr 2012 | 17          | 17:57           | 81          | 279             | 151             | 382             | 234             | 262             | 74             | 457            | 269            |                |
|            | 16 Apr 2012 | 18          | 21:04           | 76          | 349             | 301             | 391             | 424             | 280             | 547            | False          |
|            | 1 May 2013  | 19          | 02:23           | 76          | 321             | 280             | 405             | 408             | 326             | 253            | 521            | 367            |                |
|            | 21 Jun 2013 | 20          | 03:04           | 110         | 380             | 273             | 575             | 343             | 511             | 234            | 1264           | 677            |                |
|            | 21 Jun 2013 | 21          | 17:20           | 287         | 586             | 452             | 723             | 1188            | 725             | 1857           | False          |
|            | 24 Aug 2014 | 22          | 12:03           | 124         | 482             | 456             | 509             | 417             | 712             | 636            | 787            | 760            |                |
Figure 7  \(r-t\) plots and identified solar-eruption parabolas generated by applying CIISCO to EUV images. Panels \(a\) and \(b\) show the solar eruption identified in AIA-171 Å observations on 31 August 2012 without and with (respectively) identified parabolas over-plotted. Similar to panels \(a\) and \(b\); \(c\) and \(d\) show observations from EUVI-A-304 on 13 May 2013.

FOV (see Figure 8a,b). Eruption 7 (AIA 304 Å) observed on 8 April 2012 is a prominence eruption that formed the flux rope of the CME seen in the LASCO-C2 coronagraph (see Figure 8c,d). However, eruption 8 (AIA 304 Å) on 8 April 2012 is actually part of eruption 5, which split after the prominence erupted and was therefore detected as separate solar events. Eruption 10 (AIA 304 Å) on 8 July 2014, Eruptions 11 and 12 (EUVI-A 304 Å) on 13 May 2013, and eruptions 16, 17, 19, 20, and 6 and 22 on 24 December 2011, 16 April 2012, 1 May 2013, 21 June 2013, and 24 August 2014 (SW AP) respectively appear to form the flux rope in their corresponding white-light CMEs. Eruption 13 observed in EUVI-A 304 Å on 13 May 2013 is a spray (see cdaw.gsfc.nasa.gov/CME_list/autope/) type of eruption, often identified as giving rise to narrow CMEs in coronagraph imagery. Figure 9a shows such an example, where the arrow points to a narrow jet-like eruption from an active region that has been identified by CIISCO. Finally, eruption 15 (EUVI-B 304 Å) on 31 August 2012 appears to form the core of a CME observed in the STEREO/COR1-B FOV.

We also found that there are certain cases where CIISCO has detected the coronal material tethered to CMEs creating a false detection of a separate CME. These include eruption
Figure 8 Solar eruptions as seen in EUV imagers followed in the LASCO-C2 coronagraph. Top: Solar eruption observed on 31 August 2012 in AIA 171 Å that forms the CME core as seen in LASCO-C2. Bottom: Solar eruption observed on 1 May 2013 at SW AP 174 Å that forms CME flux rope as seen in LASCO-C2. The arrow shown in yellow points to the EUV emission material that propagates and appears as a part of CME in LASCO-C2.

3 (AIA 171 Å) observed on 27 June 2012, eruption 9 (AIA 304 Å) on 8 April 2012, and eruption 18 observed by SWAP on 16 April 2012. These eruptions have been marked as false positives as they do not correspond to separate outward-moving features. An example of such a detection can be seen in Figure 9b, where the arrow points to the coronal material bound to the surface. Eruption 4 (AIA 171 Å) on 27 June 2012 was also a false detection triggered by the movement in coronal loops. Also, eruption 14 (EUVI-A 304 Å) on 31 August 2012 was a false detection created by a prominence near the western solar limb; solar rotation of this extended feature created a detection recorded as an outward-moving structure. This may also be due to the prominence appearing to rise after it had rotated on the limb in subsequent frames. Finally it is noted that an artificial ringing pattern was detected in the threshold of the \( r-t \) map of the eruption 1 observed in AIA 171 Å pass-band on 8 April 2012 and eruption 21 (SWAP) on 21 June 2013. The faint ringing patterns introduced in the motion filtered images due to Fourier filtering are identified as the primary reason for this, creating false detections. These preliminary results indicate an initial detection efficiency of CIISCO to be 68%, as 7 out of 22 detections have been identified as false positives.

To determine the false negatives, we looked for eruptions missed by CIISCO during the period of application. We found that for AIA 171 Å observations on 8 April 2012, a narrow eruption taking place at ≈01:00 UT at CPA of ≈230° was missed. There was also a narrow jet-like eruption of 8 July 2014 at 17:02 at CPA ≈110° observed in the 304 Å pass-band of AIA, which was missed by CIISCO. These two eruptions being narrow in
width may not have satisfied the thresholds and hence were unable to be identified. This implies that out of 17 actual eruptions taking place during our period of analysis 15 have been correctly identified by CIISCO giving an efficient detection rate of \( \approx 88\% \). We have also tested CIISCO for the period when no CMEs were reported in the CDAW and CACTus catalogs. These include periods from 00:00 UT to 06:22 UT on 17 March 2018 and a similar time period for images observed on 2 May 2018. We used AIA 171 Å images for this test and found that CIISCO does not detect any eruption in the tested time period (Figure 10).

For the two test cases, we found that CME regions have been identified in the CME maps as shown in Figure 10a,b. This is due to the presence of bright pixels after Fourier filtering. It can also be seen from Figure 2c, d that after the removal of loops by Fourier filtering, bright regions are present near the foot-points of these loops. Similar persistent bright regions are also evident just above the masked height from Figures 7 and 10c, d in the \( r-t \) plots. As the intensities have been integrated after Fourier filtering to generate the CME map, the intensity threshold applied at this stage is being satisfied to detect CME regions. Nevertheless, the height–time plots generated in the successive steps do not show the presence of bright ridges (Figure 10c, d). The absence of any ridge and application of parabolic Hough transform with the set thresholds do not yield any eruption in these two cases. This validates CIISCO to be also effective when there is no observed eruption.

4. Conclusion and Discussions

It has long been known that a CME’s kinematics vary throughout its propagation in the heliosphere (Byrne et al., 2012). An important period in a CME’s evolution is near its onset, in the lower corona. Limited understanding of CME onset and initial progression is reflected in our inability to accurately predict CME arrival times, which currently have an average accuracy of \( \pm 10 \) hours (Riley et al., 2018). To automatically detect the solar eruptions in the inner corona, we have developed an algorithm, CIISCO, inspired by CACTus and SEEDS, using the parabolic Hough transform assisted by Fourier motion filtering and a SEEDS inspired 1D integrated-intensity plot. Due to the difficulties in making white-light observations of the
Figure 10 CIISCO applied to images of AIA 171 Å pass-band with no solar eruptions. Top: CME map generated for the test datasets without eruptions. Bottom: height–time plots for the two test cases. The left panels show the output of images taken on 17 March 2018, whereas the right panels show output for those taken on 2 May 2018. As expected, no ridges are detected in either of the two cases.

lower corona, we have used the EUV regime to identify the solar eruptions in this region. CIISCO automatically identifies and tracks CMEs’ EUV counterparts as a whole, unlike other automated CME-detection algorithms. To the best of our knowledge, this is the first successful demonstration of the application of parabolic Hough transform to automatically detect solar eruptions. We have tested this algorithm on different EUV datasets from AIA, EUVI, and SWAP. The preliminary results show that when accurately detected the average apparent speed and acceleration of solar eruptions are in good agreement with the values computed manually with correlation of over 80%. CIISCO is also able to identify successive solar eruptions produced by the same source, but separated by short periods of time. In the sample on which CIISCO was tested, it was able to identify ≈88% of the eruptions correctly.

As discussed in previous sections, the solar eruptions observed in the EUV will not have a one-to-one correspondence with those detected in white-light, due to the inherent problems of going from the EUV emission regime into a white-light scattered regime. The eruptions observed in the two wavelength pass-bands are still a matter of debate. Therefore, we also
traced the EUV eruptions into the coronagraph FOV to identify their white-light counterparts. We found that 3 positively detected EUV eruptions correspond to the cores of CMEs observed in white-light, whereas 11 correctly identified eruptions corresponded to CME flux ropes. There was also one case of a spray-type eruption that is observed as a narrow CME in coronagraph observations.

CIISCO is currently a proof of concept, as a significant fraction of detected “eruptions” are false positives. 32% of the detections made by CIISCO have been identified to be false after visual inspection. As the algorithms mature this number should improve. Some of these false detections such as for the case of the 08 April 2012 detection observed in the 304 Å pass-band of AIA, proved to be post-eruption material tethered to the site of eruption (Figure 9b). It needs to be worked out how to reduce such detections as solar eruptions. Few false detections were a result of artifacts produced from the ringing pattern introduced in images after Fourier filtering. The ringing pattern arising from the filtering limits the application to detect the eruptions with insufficient brightness with respect to the background. In the future, to improve this, we will test different masking techniques (e.g. the Hanning window) in Fourier space, that will act to preserve the structures and at the same time reduce the ringing patterns. Also, a reduction in the artifacts will help us to reduce the intensity threshold which in turn will allow the algorithm to detect fainter solar eruptions. There are a few cases where the rising coronal material gave an impression of outward movement, and therefore it created a false detection by CIISCO. Such false positives can be reduced by selecting the range of velocities to be filtered out by the Fourier filtering technique. Such filters can be improved with more CME observations and therefore better CME statistics. Increased CME observations will also provide additional knowledge about the kinematics of these eruptions in the lower corona. We also tested CIISCO for the period when there were no reported CMEs in CDAW and CACTus CME catalogs. We applied CIISCO for the images observed in the 171 Å pass-band of AIA on 17 March 2018 and 2 May 2018 for a period of six hours. We found that CIISCO successfully did not identify any eruption in the tested time period in spite of the shortcomings mentioned above. This also implies that the chances of a false detection in the absence of eruptions are very low, and they can be minimized further after including improvements.

It should be noted that although the majority of the eruptions appear first in the FOV with heights in the range of $1 - 1.025 \, R_\odot$ (Figure 5), in the case of the prominence eruption of 8 April 2012, the eruption of the prominence initiates at a greater height ($\approx 1.1 \, R_\odot$). Nonetheless CIISCO has been able to detect the eruption and provide its approximate properties. It is seen from Table 1 that eruptions 2 and 7 have disparities in the kinematics values despite the fact that they occurred at the limb. Such cases may need further inspection to understand their behavior subsequent to eruption. Due to the inherent problems with determining large diffuse structures in EUV observations, CIISCO is probably not suitable for individual case studies that would require individual visual inspection to accurately determine the CME characteristics. However, CIISCO can certainly provide approximate measurements of the eruption properties allowing the user to decide if an individual event deserves further attention.

Currently we have implemented a parabolic Hough transform using 2D parameter space against the 4D space by fixing two parameters ($r_\circ = 1 \, R_\odot, \theta = 90^\circ$) out of the four free parameters ($S, t_\circ, r_\circ, \theta$). The difficulty in identifying parameters in 4D parameter space and computation cost led us to fix the two free parameters. The primary goal of this work is to automatically detect solar eruptions in the inner corona, which has been achieved by fixing the two parameters. Determination of the starting height of such eruptions will be an improvement to the current version of the algorithm and will be a part of future work. This may be
attained by including techniques such as the fast Hough transform (Li, Lavin, and Master, 1986; Guil, Villalba, and Zapata, 1995) in addition to the present method. It should also be noted that CIISCO has been applied to identify near-limb and off-limb solar eruptions only. The eruptions occurring near the disk center will suffer from a host of uncertainties in the measurement of height. Moreover, in EUV wavelengths, the on-disk eruptions may not be observed as distinct features to be automatically identified effectively. This limits us to test the algorithm in mostly off-disk eruptions.

Following such improvements, CIISCO will be applied over a larger dataset to generate a catalogue of EUV eruptions and their properties, which will be the first of its kind. We intend to enhance this algorithm for its application to the white-light coronagraph images of STEREO/COR1 and K-Cor. Since these images suffer from a high amount of noise, no automated algorithm has been successful in automatically detecting CMEs in these datasets. It should be noted that the types of CME that CIISCO can potentially detect are open for debate and can be adjusted as such. The community does not adhere to a standard definition of what a CME is and what characteristics a CME has. Some smaller CMEs may be construed as flows (Robbrecht and Berghmans, 2004) near the Sun. The CACTUS algorithm has certain thresholds in place that broadly differentiate between flows and CMEs, where flows are classified as dubious in nature being often narrow and of low speed. The level to which a CME becomes a flow can be adjusted by the internal parameters in the algorithm. Similarly, the parameters that govern CIISCO can be adjusted according to the users’ needs.

It is worth noting that future solar missions, such as Aditya-L1 (Seetha and Megala, 2017), PRoject for On-Board Autonomy-3 (PROBA-3: Renotte et al., 2014), and Solar Orbiter (Müller et al., 2013) will have coronagraphs observing the inner corona and full-disk UV imagers. This algorithm can be applied to these datasets, and it will help improve our knowledge of CME evolution during and after their eruption. The use of CIISCO as a viable Earth-orientated eruption forecasting tool relies on observations out of the Ecliptic, near 90° to the Sun–Earth line. To date such observations have only been made by NASA’s STEREO (Kaiser et al., 2008) spacecraft at varying points of their orbits. However, CIISCO would be an important tool for ESA’s Lagrange mission, a mission being designed to be positioned at the L5 Lagrangian point to specifically monitor space weather from its source on the Sun, through the heliosphere, to the Earth. Onboard Lagrange will be the Lagrange eUv Coronal Imager (LUCI: West et al., 2020), which is being designed with a wide FOV specifically to detect eruptions, in their infancy, close to the Sun–Earth line. From the L5 perspective, LUCI will offer observations from approximately 60 degrees to the Sun–Earth line in near real time. With small changes to the CIISCO algorithm, it could be also be run in semi-real-time offering an early-warning system for potential Earth-bound eruptions. A more generalized form of this algorithm using the generalized Hough transform (Ballard, 1981) should be able to identify the changes in profile of CMEs throughout their propagation from the lower corona to the heliosphere and hence improve our current CME-propagation models, leading to better space-weather forecasts.

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