Automated Detection of Solar Eruptions

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ABSTRACT

Observation of the solar atmosphere reveals a wide range of motions, from small scale jets and spicules to global-scale coronal mass ejections. Identifying and characterizing these motions are essential to advancing our understanding the drivers of space weather. Both automated and visual identifications are currently used in identifying CMEs. To date, eruptions near the solar surface (which may be precursors to CMEs) have been identified primarily by visual inspection. Here we report on EruptionPatrol (EP): a software module that is designed to automatically identify eruptions from data collected by SDO/AIA. We describe the method underlying the module and compare its results to previous identifications found in the Heliophysics Event Knowledgebase. EP identifies eruptions events that are consistent with those found by human annotations, but in a significantly more consistent and quantitative manner. Eruptions are found to be distributed within 15Mm of the solar surface. They possess peak speeds ranging from 4 to 100 km/sec and display a power-law probability distribution over that range. These characteristics are consistent with previous observations of prominences.

Key words. Sun – Eruptions – solar image processing – data mining

1. Introduction

Eruptions in the low solar atmosphere are key elements in generating space weather. Large eruptions can evolve into coronal mass ejections (CMEs) that can plow through the solar wind and ultimately impact the earth's magnetosphere (Munro et al.(1979), Gosling(1993)). The source of many of these CMEs has been associated with prominence eruptions (Gopalswamy et al.(2003), Yan et al.(2011)) finds that approximately half of active region filament eruptions are associated with CMEs and over 90% are associated with flares. Smaller eruptions may provide the ultimate source for the solar wind (Tian et al.(2014)). Regardless of their magnitude, eruptions play a significant role in the structure and dynamics of the solar atmosphere.

Identifying eruptions occurring near the solar surface is complicated by the presence of a wide variety of features and scales. Active regions, coronal holes and filaments persist for long periods, while the short-lived eruptions pass through and among them. Flares and other sudden changes in intensity add distractions that can mask or mimic motions that would otherwise be visible. As a result, automated detection of these eruptions has been challenging.

Previous studies have developed automated methods to detect and track filaments primarily in H-alpha images (Gao et al.(2002), Wang et al.(2010), Schuh et al.(2014)). These methods typically use image-based feature detection followed by a tracking step comparing the results of sequential detections. Similarly, Gissot et al.(2008) used an optical flow method to analyze the motion of a filament in three dimensions as observed in the 304 Angstrom images acquired by the EUVI instruments on the two STEREO spacecraft (Kaiser et al.(2008)). Measured velocities for prominence eruptions in these studies tend to lie in the range of 10-100 km/sec while quiescent prominences show velocities around 4 km/sec or less.

We take a different approach by first extracting velocities from a sequence of images and then identifying features within the resulting velocity fields. Here we use an optical flow method to identify regions of significant motion. Using derived velocity fields to define regions of interest rather than working directly from the images removes many of the distracting features and permits us to identify and characterize the flows in sufficient detail for further analysis.

In the following sections we present the underlying method used by Eruption Patrol, assess its performance, survey the statistical properties of the resulting detections and summarize our findings in the conclusion.

2. Method

Our approach to identifying solar eruptions is to extract velocity fields from sequences of solar images using the opflow3d method described in Hurlburt and Jaffey(2014) as applied to images obtained by the Atmospheric Imaging Assembly on the Solar Dynamics Observatory (SDO/AIA, Lemen et al.(2012)). Ten sequential He II 304 Ångstrom images (spanning two minutes) of full-resolution Level 1 data are and processed to create a single velocity map. These images have had dark current and flat-field corrections and have had spikes caused by bad pixels and radiation hits removed.
The velocity field obtained by applying our method to two minutes of SDO/AIA 304 data starting at 2010-Aug-01T21:20. The arrow are aligned with the local velocity with areas proportional to the speed. The corresponding image is shown in the color background. Two regions are seen to be erupting: a long filament on disk is ascending into the corona; and another region in the upper left that may be part of the same eruption, or a sympathetic response. Only velocities over 1 km/sec are displayed and solar rotation is not removed. The peak velocity here is 3.8 km/sec.

After square-root compression these images are fed into opflow3d to extract a time-averaged velocity field with an effective spatial resolution of 60 arc-seconds. The opflow3d method uses a least squares approach that has been shown to minimize the effects of detector noise, transient intensity variations and other sources of measurement error. This presents a trade off between the sample size in space and time versus accuracy and computational speed. With the choice of 60 arc-second (100 pixels) and 10 frames, we expect statistical errors of less than 1% and a computational time for a single velocity fit of approximately one minute on a 2013-vintage Apple iMac.

Previous studies found velocities exceeding 100 km/sec, which translates to about 17 arc-seconds during one velocity fit. This is within our chosen resolution so systematic error due to smearing should be small; it also suggests that the maximum reliable velocity estimate we can expect for our sampling choice is about 350 km/sec. Fitting for higher speeds would require either smaller time samples or larger spatial windows. For instance, we could detect speeds approaching 3.5 Mm/sec over 60 arc-seconds by using the maximum AIA cadence of 12 seconds. (If we were to apply this method to the coronal images collected by AIA, say 193 Ångstroms, where velocities are expected to reach these ranges, we would need to adjust our parameters accordingly.)

An example of the resulting flow field is displayed in Figure 1. The spatial resolution of our velocity fit was doubled to 30 arc-seconds here to better define the regions. The flow associated with the large filament eruption near the northern pole is clearly captured, as well as a few smaller-scale flows around the limb.

The derived velocity fields are composed of multiple components, some of which are sources of error for our application: these include solar rotation, super-granulation and other quasi-static motions. Most of these motions are small and reasonably isotropic. The solar rotation profile is neither, with a peak value of about 2.2 km/sec. This can introduce a bias when using a thresholding technique to identify eruption sites. Hence, EruptionPatrol subtracts a background velocity corresponding to that of solid-body rotation (but not for the smaller effects of differential rotation and meridional circulations).

EP samples velocities every 20 minutes and records the time, location and velocity at the point of maximum speed within each sample is recorded. As described above, this velocity corresponds to the best-fit over a region of about 60 arc-seconds in a two minute interval. Hence the precise position of the peak is only known to that resolution. Figure 2 displays the raw output of the patrol over a seven week period starting on 29 March 2014. The effect of the rotation removal can be seen as a drop in the floor of the velocity measurements to values consistent with those expected from super-granulation (e.g. Shine et al.(2000)) and other sources. Peaks corresponding to eruptions and spacecraft motions are also clearly visible. The later are excluded in the production version of the method.

Sub-sampling the images as we risks missing short-lived events. However eruptions with lifetimes shorter than this probably have little impact on their surroundings. Our goal here is to identify eruptions that may have significant impacts, so the computational cost savings outweigh the loss of information. Our in-
Fig. 2. The peak speeds reported by EruptionPatrol in 3000 samples taken between 2014-03-29 to 2014-05-16. The preliminary results for April did not remove the effects of solar rotation, and hence have a floor of about 2km/sec. Data in May have that correction applied, and the remaining floor is a combination of differential rotation, meridional flow, super-granulation and other ubiquitous sources. Spacecraft maneuvers and other calibrations are also present in the April results, most notably during April 23.

The results of this first pass are then processed to identify time periods of where velocity exceeds the threshold of 3.6km/sec. This value was settled upon by the need to exclude the background motions seen in Figure 2 while generating a moderate detection rate. It also corresponds to the level of motion found by Wang et al.(2010) in quiescent prominences. These periods, along with the largest velocity and its position, are then recorded to the Heliophysics Events Knowledgebase (HEK, Hurlburt et al.(2012)) as preliminary reports of eruptions. Our intent is to analyze these more carefully in a second “characterization” routine and then replace or update these entries with more details.

3. Results

3.1. Comparison with manual selection

We assess the performance of our method by comparing it to eruptions recorded manually the HEK. These entries are primarily provided by members of the SDO/AIA science team who monitor data as it arrives at the AIA Validation Center (see Hurlburt et al.(2012) for details). Volunteer annotators to regularly sign up for three-day shifts. Thus all the datasets used by EruptionPatrol, along with other AIA channels, have also been reviewed by this team. Over the interval from 18 April 2014 to 17 July 2014, a total of 43 filament eruptions and 44 eruptions were recorded by the team. For this case we consider an eruption to be any of two classes accepted by the HEK: eruptions and filament eruptions. The first is a catch-all category that may or may not be associated with a filament; the later is associated with a filament that the observer considered to have ejected material into the corona.

As a first test, we queried the HEK for both classes of eruptions using iSolsearch (http://www.lmsal.com/isolsearch) to select the events and then exporting them into SolarSoft (Freeland et al.(2000)) and using the hek_match_events routine. For this study we considered events that overlapped within an hour in time. The results are displayed in Table 1. Of the 43 filament eruptions reported by humans, 37 (79%) matched times reported by EP. The success drops to 24 (44%) when we also require a separation of less than 120 arc-seconds. Human reports of eruptions displayed a similar behavior, which is partly due to some observers selecting both when the generate their reports. We will discuss this further below.

As a second test, we selected the 29 events with speeds exceeding 30km/sec from EruptionPatrol over the same interval and compared them to entries reported by human annotators. Nine (31%) match the human annotations in time, while the remaining 20 did not. Only 7 of those 9 also overlapped spatially. All of these missed events were reviewed visually using the daily movies posted at http://sdowww.lmsal.com and were found to be associated with significant eruptions.

These patterns persist over the entire AIA dataset, as can be seen in Table 2. Overall EP finds about 70% of all time periods manually reported as erupting in either category. This mod-
Table 1. A comparison between filament eruptions (FE) and generic eruptions (ER) reported manually and EruptionPatrol reports (EP) over the time interval from 4/18/2014 to 7/17/2014. Two comparisons are shown: one based solely on time (t) and one with both time and position (x,t).

| Comparison        | Count | Hit (t) | Miss (t) | Hit (x,t) | Miss (x,t) |
|-------------------|-------|---------|----------|-----------|------------|
| EP from manual FE | 43    | 79%     | 21%      | 44%       | 56%        |
| EP from manual ER | 44    | 84%     | 16%      | 55%       | 45%        |
| Manual from EP    | 29    | 31%     | 69%      | 24%       | 86%        |

Table 2. The same as Table 1 over the time interval from 5/15/2010 to 11/17/2014, as in Table 1.

| Comparison        | Count | Hit (t) | Miss (t) | Hit (x,t) | Miss (x,t) |
|-------------------|-------|---------|----------|-----------|------------|
| EP from manual FE | 813   | 68%     | 32%      | 27%       | 73%        |
| EP from manual ER | 327   | 70%     | 30%      | 53%       | 47%        |
| Manual from EP    | 289   | 24%     | 76%      | 11%       | 89%        |

Table 1 and Table 2 show the accuracy of EruptionPatrol (EP) compared to manual reports (ER) for different time intervals. The overall accuracy of EP is lower than manual reports, with hit rates ranging from 24% to 70% for different types of eruptions. The success rate drops further when considering the position of the event (x,t). This indicates that EP may not always detect the exact location of eruptions, especially for filament eruptions, where the accuracy drops to 27% in the larger sample. The success rate for generic eruptions remains higher, with hit rates ranging from 70% to 79%, suggesting that EP is better at identifying larger, slower eruptions. The lower success rate for filament eruptions is likely due to their smaller spatial extent and the difficulty in capturing them accurately.

3.2. Statistical properties

The Eruption Patrol module described above was run over the entire SDO mission up to July 12, 2014, thus spanning just over four years. Here we give an overview of the statistical properties of this sample. The left panel in Figure 3 displays the histogram of peak speeds detected for each recorded eruption. The distribution has an inverse square dependence on the speed, with the largest event having a speed of 96 km/sec. These are consistent with previous studies, such as Gopalswamy et al.(2003) and Wang et al.(2010). The right panel in Figure 3 displays the distribution of velocities as a polar plot. There does not appear to be a significant directional bias in the sample.

Figure 4 displays the spatial distribution of all events over this period. Eruptions are detected almost everywhere on the disk, as seen in the left panel, but are clearly clustered near the activity belts and the limb. This distribution appears to be independent of the magnitude of the events (as indicated by the color of the dots). There is a clear lack of eruptions reported near the poles which may be due to relatively slow-moving polar crown filament eruptions being masked by more dynamic regions as described in the last section.

The apparent clustering near the limb is examined in the right panel, where the histogram as a function of radius (r) for these events is displayed. The distribution rises from zero near disk center (r = 0) until the active region bands begin to contribute at r ≈ 0.4R\text{sun}, where R\text{sun} is the solar radius. The distribution remains relatively constant between that point until near the limb (r ≈ R\text{sun}), where the counts climb rapidly before falling back to zero. This distribution is consistent with that expected in the case of a shallow, optically-thin, formation layer (between 3-15 Mm) containing a uniformly random distribution of eruptions. Gopalswamy et al.(2003) reports that (relatively-large) eruptive prominences have heights between 1.1 to 1.5 R\text{sun}. This suggests that there may be some scale dependence in the distribution that is neglected in our simple model, which might also explain the deviations from our model for r > R\text{sun}. Some level of scale dependence is expected in the structuring of the solar atmosphere by magnetic fields, as in the magnetic carpet model of Title and Schrijver(1998).

Another source of systematic error may result from projection effects. If all eruptions were predominantly radial, we would expect a radial dependence in the magnitude and direction of the reported velocities. Gopalswamy et al.(2003) found this to be the case overall, but with many eruptions possessing tangential motions on the order of 10km/sec. In contrast, the motions we de-
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Fig. 3. (Left) Histogram of speeds (black dots) of all eruptions from 5/15/2010 to 7/12/2014. Eruptions appear to possess a power law distribution near that of an inverse square (solid line). (Right) A polar plot of the velocity vectors show them to be reasonably isotropic with a maximum speed of 96.2 km/sec. For clarity, only speeds over 10 km/sec are displayed.

tect are randomly-oriented and show no significant projection effects. We may resolve this discrepancy by noting that the former study was effectively tracking the centroid of a prominence while our method is measure local velocities, which includes twisting, writhing and streaming motions that frequently accompany eruptions. Hence we can identify times and location of eruptions based on these associated motions regardless of where they appear on the disk. A more complete reckoning these velocity contribution falls to the future characterization module.

4. Conclusion

We have developed an automated method for finding eruptions in the lower solar atmosphere and have deployed it within the SDO/AIA Event Detection System which operates on the data as it arrives. The method has been found to measure velocities with statistical properties consistent with previous studies. The reported eruptions also appear to be consistent with those reported by human reviewers. The automated detections are less prone to lapses in attention or skewed by personal interests, but may miss slow, long-duration eruptions. They also provide a more complete characterization of eruptions by reporting both the location and plane-of-sky velocity. The reported events are found to be distributed in a layer near the solar surface and possess a power law distribution in peak speed. Details of these events, including summary movies, can be found using a variety of tools including Helioviewer (http://helioviewer.org), iSolsearch (http://www.lmsal.com/isolsearch) and SolarSoft. As part of the HEK, they are automatically cross-referenced with solar datasets obtained by the Hinode (Kosugi et al.(2007)) and Interface Region Imaging Spectrograph (IRIS, De Pontieu et al.(2014)) missions.

Subsequent papers will explore how these eruptions compare with those found with other automated processes recording in the HEK and will describe a characterization module that confirms and extracts more detailed information on the eruptions reported by the Eruption Patrol.

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Fig. 4. (Left) The distribution of all eruptions from 5/15/2010 to 7/12/2014 show clustering near activity belts and the limb. Black, blue and red circles display weak (≤10km/sec), medium (≤30km/sec) and strong (≤30km/sec) eruptions respectively. (Right) Histogram of radial positions. Dots represent number of events in 10 arc second bins. Solid line is theoretical PDF assuming the formation layer is a uniform 15Mm thick (15Mm), dashed is same for 3.5-thick layer - with both scaled to match the maximum. The distribution is compatible with a layer thickness somewhere within the range of 3-15Mm.

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