Integrating automated coronal mass ejection detection alerts from a ground based coronagraph for use in solar energetic particle event forecasting

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Abstract

St. Cyr et al. (2017) proposed using a ground-based coronagraph as an early warning system for solar energetic particle (SEP) events driven by coronal mass ejection (CME)-generated shocks. That work investigated numerous observations and forecasting model output related to a single SEP event produced by a CME on January 1, 2016.

An early warning system for SEP events requires automated detection of CMEs low in the corona. We make use of the CME detection algorithm created by Thompson et al. (2017) that was adapted from the Solar Eruptive Event Detection System (SEEDS) package. This system was incorporated by Mauna Loa Solar Observatory (MLSO) into the near real-time K-Cor coronal white light processing system and has been operating at the MLSO since 2018. These alerts are also available to interested community members via an email list.

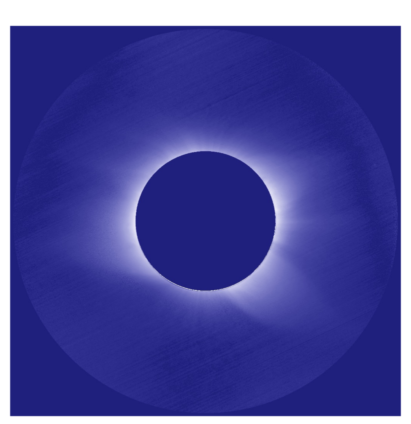
MLSO is working with the Community Coordinated Modeling Center (CCMC) at NASA to integrate this near real-time CME detection information into the SEP Scoreboard at Goddard Space Flight Center (GSFC). We discuss the detection software, provide examples of CMEs detected in near real-time including the detection code alerts, report typical lag time and accuracy of the generated CME alerts, the ability for observers to retract the automated alerts, and identify planned improvements in the software.

The results emphasize the importance of low latency, high time cadence, low corona observations for near real-time forecasting of SEP events.

Mauna Loa Solar Observatory at 3400 m elevation on Hawaii.

Method

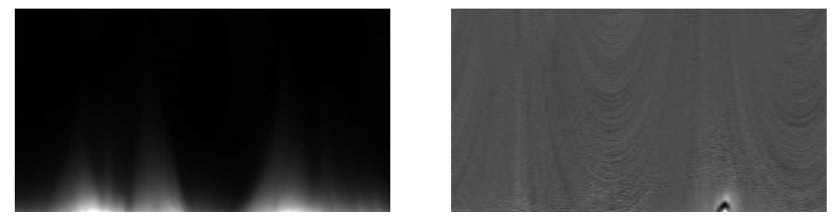
The CME detection program of [Thompson] uses the standard level 2 polarization brightness images (pB) produced by the K-Cor near real-time pipeline. Every 5 seconds it checks for new images and runs through the steps of the method described below. We use a CME detected on 27 March 2017 as an example throughout this explanation of the method.



*K-Cor level 2 pB image from the time the alert was originated at 17:30:30 UT on **27 March 2017**. The CME is not easily seen in this image, but becomes apparent in the steps that follow.*

The steps of the automated detection method are:

1. First, remap any new images to helioprojective-radial polar (HPR) coordinates and create 5 minute running difference images. Average over 3 degrees to increase signal-to-noise.
2. Next, collapse the HPR difference map in the radial direction to look for position angles of interest.
3. Track position angle regions to determine if they persist.
4. If so, look for strong gradients in the radial direction to find the CME leading edge.
5. Lastly, the algorithm looks for evidence of upward motion by fitting leading edge measurements over the last 5 minutes using a simple linear fit that uses statistics to minimize anomalies. A fit is considered successful and alerts are generated if all of the below conditions are met:
    1. at least 5 leading edge measurements are given to the fit,
    2. most of the given measurements are used (more than half and at least 5),
    3. the used points cover at least 2 measurements,
    4. time gaps between used measurements must be less than 2 minutes,
    5. speed inferred from the fit must be at least 20 km/s, and
    6. the standard deviation of the fit must be less than 0.05 $R_\odot$.



(Left) Original image L1 pB from the time the CME was detected mapped to HPR coordinates. (Right) 5 minute difference image.

See the GitHub repository for the code for the K-Coronagraph near real-time processing pipeline, as well as the automated CME detection code:

`https://github.com/NCAR/kcor-pipeline`

Results

K-Cor CME alerts are the **"first line of defense."** K-Cor observes down to 1.05 $R_\odot$, allowing it to track CMEs as they form.

K-Cor has a cadence of about 15 seconds with clear skies during operating hours. Data is transferred for processing by the pipeline and processed with 2 minutes. The automated CME detection code has ingested the processed data with another minute, giving **a very low total latency of about 3 minutes** from observation to assimilation by the detection code.

Energetic protons				Coronal Mass Ejections (CMEs)			
Date	**Rise time**	**Flux $p^+/(cm^2 *s*sr)$**	**Detected by**	**K-Cor 1st image time**	**Detection alert time**	**LASCO 1st image time**	**Δ between time alert & LASCO 1st image**
20140924 disk center CME	23 UT	3000 [1.8 – 10 MeV] 100 [14 - 100 MeV]	STEREOA	20:55:08	21:01:49	21:12:08	**10 min 17 sec**
20150315	4 UT	100 [> 5 MeV] 7 [> 10 MeV]	GOES	01:20:45	01:27:27	01:48:05	**20 min 37 sec**
20160101	24 UT	40 to 50 [> 5MeV] 10 [> 10 MeV]	GOES	22:56:09	23:18:25	23:24:04	**5 min 39 sec**
20170904 disk center CME	23 UT	175 [> 5 MeV] 75 [> 10 MeV]	GOES	18:28:21	NONE Too faint	19:00:05	**N/A**
20210507	24 UT	0.1 [2.2 - 12 MeV] 1.5 [0.62 - 2.2 MeV]	STEREO-A/SolO	18:54:43	19:03:56	19:24:05	**20 min 9 sec**
20220511	18 UT	5 [> 10 Mev]	GOES	18:17:29	18:37:19	18:48:05	**10 min 46 sec**

We reviewed all GOES proton data to search for SEP fluences above background that were strongly correlated with timing of K-Cor observations of a CME. We found six CMEs that met this criteria and list them in the table above. We then measured the CME properties in K-Cor and compared these with LASCO C2 observations of the same CME. The detection code found 5 of the 6 events and issued alerts. For all five events alerts were issued before the CME appeared in the LASCO field-of-view; with times ranging from 5.6 to 20.6 minutes before visibility in LASCO. These times do not include the data latency times. K-Cor has a latency <= 3 minutes. We monitored recent NOAA SWPC data to determine the latency of the LASCO observations. LASCO latencies ranged from 47 minutes to 3 hours 13 minutes. K-Cor alerts provide very early warnings of CME activity.

Alerts

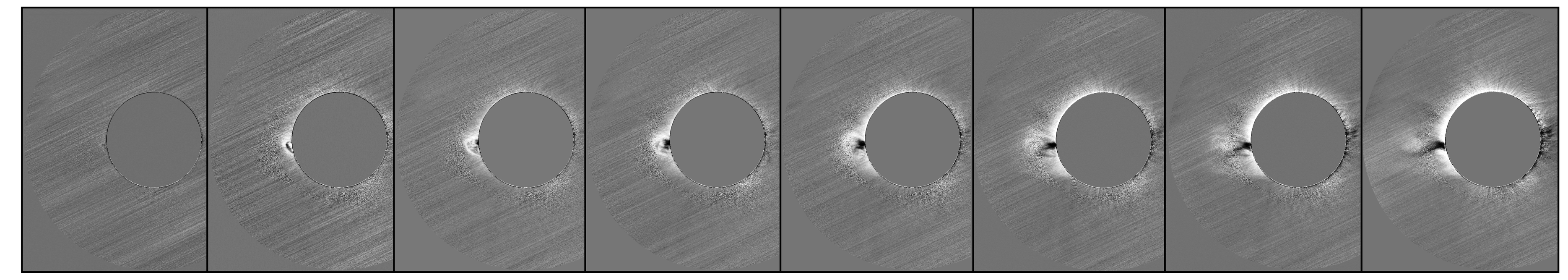
Email alerts are sent for events found both by the automated CME detection code and by the human observers monitoring the data:

1. Initial alert: time detected, initial speed, height, position angle
2. Summary alert: attached plot of the speed, height, and position angle over the time the code has been tracking the CME
3. Observer alert: time detected, confidence level, position angle, width, and possible comments

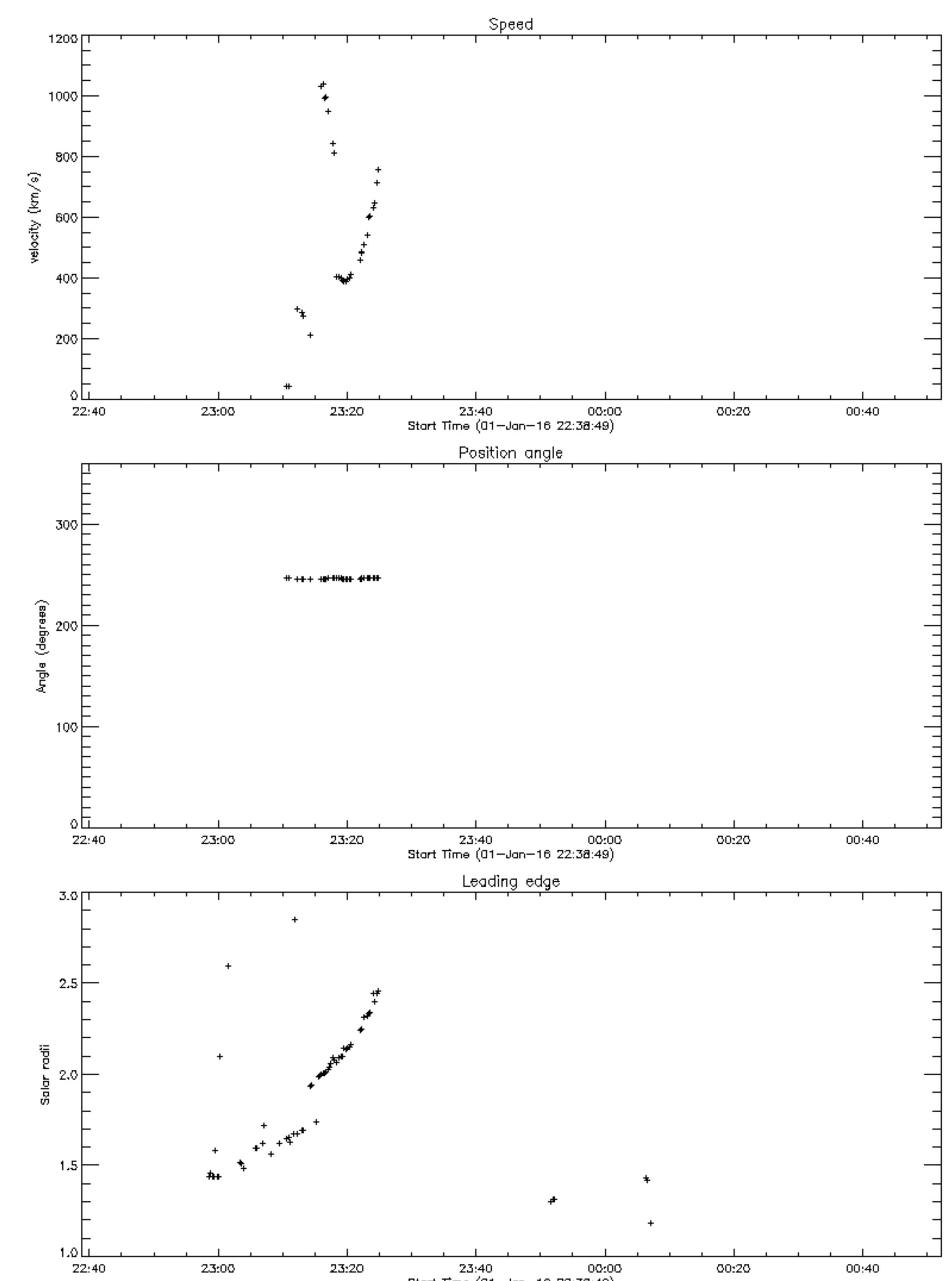
For example, the initial email alert for the 1 January 2016 CME was:

```
The Mauna Loa K-coronagraph has detected a possible
CME at 23:10:40 UT with the following parameters:

Radial distance from Sun center: 1.65 Rsun
Position angle: 247.5 degrees
Initial speed: 44.11 km/s

CME detected when images up to 23:10:40 UT have been
processed
```

The summary alert tracking plot sent at 23:24:50 UT is shown below. It shows the trajectory of the accelerating CME and relatively constant position angle. There is a fair amount of noise in the velocity and position plots, but an approximation of the trajectory can be determined from it.



*Difference images of the **27 March 2017** event at 17:32:33, 17:40:08, 17:46:42, 17:50:30, 18:07:26, 18:19:35, and 18:41:34 with original image at 17:31:02.*



An example observer alert is shown below for a CME on 20 June 2022:

```
****Possible CME in Progress mcotter**** : Mon Jun 20
19:20:52 GMT 2022
Observer reports with medium confidence a CME seeing
launching near PA 245 deg, with a minimum width of 10
deg, at UT time 18:00:11.
This CME appears very faint and was identified using
the combination of Kcor NRGF and Kcor Diff images.
```

To sign up for email alerts of CME events detected by the MLSO K-Coronagraph, make a request to:

mlso_data_requests@ucar.edu

There are currently four types of automated alerts in JSON format sent to the SEP Scoreboard, with a fifth type being implemented:

1. The *initial alert* is sent when the automated detection code first detects a CME. This corresponds to the initial email alert also sent by the automated detection code.
2. A *summary alert* is sent when the detection code determines the CME has completed. This alert corresponds to the summary email alert sent by the automated detection code.
3. An *observer retracting alert* is sent when a human observer has determined the automated alert is a false positive detection and sets a flag for the automated pipeline to retract its initial alert.
4. A *heartbeat alert* is sent by the automated code every 5 minutes to indicate the status of the K-Coronagraph observations.
5. The *observer initiated alert* is planned to be sent when the human observer detects a CME. This will correspond to an observer email alert.

Images and movies are planned to be sent along with the JSON alerts to provide context and verification for the alerts.

As an example JSON alert, below is the initial alert for the 2016-01-01 CME:

```
{
  'sep_forecast_submission': {
    'inputs': [{
      'coronagraph': {
        'instrument': 'K-Cor',
        'observatory': 'MLSO',
        'products': [{
          'last_data_time': '2016-01-01T23:10:18Z',
          'product': 'White Light'}]}}],
   'issue_time': '2022-01-21T10:26:21Z',
   'mode': 'nowcast',
   'model': {
     'short_name': 'MLSO K-Cor',
     'spase_id': 'spase://MLSO/K-Cor/AutoCMEDetect'},
   'observations': [{
     'alert': {
       'alert_time': '2022-01-21T10:26:21Z',
       'alert_type': 'ALERT'},
     'all_clear': {
       'all_clear_boolean': 'false',
       'all_clear_type': 'cme'}}],
   'triggers': [{
     'cme': {
       'catalog': 'MLSO_KCOR',
       'pa': 247.5,
       'speed': 44.107505744170794,
       'start_time': '2016-01-01T23:10:18Z',
       'time_at_height': {
         'height': 1.649,
         'time': '23:10:40'}}}]}}
```

Conclusion and future work

Ground-based network of coronagraphs would significantly improve duty cycle for SEP forecasting: NSO/NCAR are designing the next generation of ground-based space weather forecasting network (ngGONG), which includes coronagraphs.

The main areas of further work will focus on the ability to track and differentiate simultaneous CMEs, continue to improve the accuracy of the detection algorithm, estimating CME widths and acceleration, and the implementation of the ability for human observers to retract the automated alerts. We can produce multiple difference movies to aid in detection of CMEs of different speeds.

K-Cor data is accessible from the MLSO website at:

`https://www2.hao.ucar.edu/mlso/mlso-home-page`

References

K-Cor Team (2013). COSMO K-Coronagraph (K-Cor) white light polarization brightness images, doi: 10.5065/d69g5jv8.

Thompson, W. T., O. C. St. Cyr, J. T. Burkepile, and A. Posner (2017), Automatic near-real-time detection of CMEs in Mauna Loa K-Cor coronagraph images, *Space Weather*. 15, 1288-1299. doi: 10.1002/2017sw001694.

St. Cyr, O. C., A. Posner, and J. T. Burkepile (2017), Solar energetic particle warnings from a coronagraph, *Space Weather*, *15*, 240–257, doi:10.1002/2016SW001545.