Near-real time Coronal Mass Ejection Alerts as part of an Early Warning Forecasting System for Solar Energetic Particle (SEP) events

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ABSTRACT

The NCAR Mauna Loa Solar Observatory (MLSO) COSMO K-Coronagraph (K-Cor) issues near-real time coronal mass ejection (CME) alerts to the community and to NASA's Community Coordinated Modeling Center Solar Energetic Particle (SEP) scoreboard for use by the NASA Space Radiation Analysis Group in support of the Artemis mission. The COSMO K-Cor observes the low and middle solar corona from 1.05 to 3 solar radii in polarized broadband white light at very high time cadence and with very low data latency, making it ideally suited to study the onset and dynamics of coronal mass ejections (CMEs). The K-Cor automated data processing system includes CME detection code that can provide the first warning of an in-progress CME. This information can lead to improvements in SEP forecasts (see St. Cyr et al. 2017). We show that **most of the K-Cor alerts were issued *before* the CME entered the LASCO field-of-view**. When LASCO data latency is included**,** the K-Cor alerts provide, on average, tens of minutes to an hour warning of an in-progress CME before it can be seen in space-based coronagraph images. We discuss the CME detection system and present statistics on performance. We present ongoing work to improve performance and highlight the benefit of ground-based coronagraph network (ngGONG mission).

MOTIVATION

SEPs are highly energized particles from the Sun moving at relativistic speeds. They pose radiation hazards to astronauts, aircraft crews, and satellites, and impact airline, Dept. of Defense, and HF radio communications. Minutes count in SEP forecasting. The COSMO K-Coronagraph is ideally suited to be part of an early warning forecasting system for SEP events. ***K-Cor provides the first detection of an in-progress CME in near-real time.*** This is possible due to its low latency, high cadence (15 sec), unique white light field-of-view, and CME-detection software. K-Cor near-real time CME alerts are issued with an average data latency of 2 min 33 sec, significantly lower than space-based coronal imaging.

METHOD

K-Cor automated processing includes CME detection developed by Thompson et al. 2017, based on the Solar Eruptive Event Detection System (SEEDS). It uses fully calibrated K-Cor polarization brightness (pB) images that are mapped to helioprojective-radial polar (HPR) coordinates and averaged over 33 seconds and over 3°, to increase signal. 5-minute running-differences are created and examined over time to identify brightness changes with height. A CME alert is issued when a leading edge with at least 5 measured points, an inferred speed of >=20 km/s, and a fit with a std. deviation < 0.05 $R_\odot$ is identified. **The alert provides the time of the K-Cor CME image, the CME height, the position angle, and an initial speed measurement. A final report provides speed, position angle and height measurements vs time.**

SEP-CME RESULTS

TAKEAWAY: Nearly all K-Cor CME alerts are issued BEFORE the CME has entered the LASCO field-of-view

Richardson recently updated his SEP event list (private communication) which included **31 SEP-associated CMEs** that occurred during times when K-Cor was observing.

Of these 31 CMEs:
20 had valid K-Cor CME alerts
- 2 had alerts of nearby CME rather than the SEP-CME
- 7 were faint CMEs in K-Cor and missed by the detection code
- 2 were too faint to be seen in K-Cor

The 20 CMEs that were detected by the alert software are shown in the table at right. ***All but 4 of the alerts were issued before the CME was visible in the LASCO data.*** In those 4 cases the CME core, rather than the front, was being tracked.

K-Cor provides, on average, 55 minutes warning before LASCO images are even available to the Space Weather forecasting center (includes data latencies).

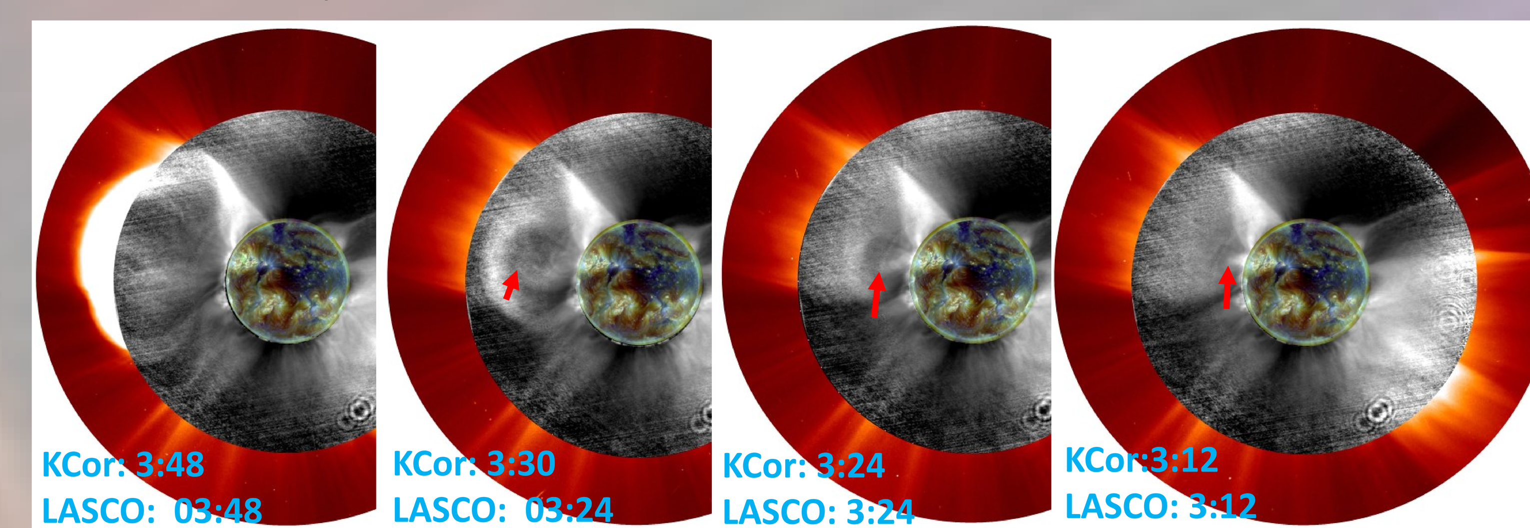
TABLE 1: SEP EVENTS OCCURRING DURING K-Cor Observations

DATE OF SEP-associated CME	Time CME Alert issued Includes K-Cor latency	Time of LASCO first CME image	Time between LASCO and CME alert RED: detection after CME in LASCO BLACK: detection before CME in LASCO	Time between LASCO and alert INCLUDES 40-min LASCO latency
12/9/2013	19:36:57	19:36:05	> 0 min 52 sec	< 39 min 8 sec
12/16/2013	20:49:09	21:39:14	< 50 m 05 sec	< 90 m 05 sec
2/11/2014	19:00:39	19:24:05	< 23 m 26 sec	< 63 m 26 sec
9/24/2014	21:04:20	21:30:06	< 25m 46 sec	< 65m 46 sec
10/14/2014	18:50:24	18:48:06	> 2 min 18 sec	< 37 min 42 sec
2/8/2015	22:30:10	22:36:06	< 5 min 54 sec	< 45 min 54 sec
3/15/2015	01:29:58	01:48:05	< 18 min 7 sec	< 58 min 7 sec
1/1/2016	23:11:55	23:24:04	< 12 min 9 sec	< 52 min 9 sec
4/18/2017	19:31:23	19:48:05	< 16 min 42 sec	< 56 min 42 sec
5/7/2021	19:07:06	19:24:05	< 16 min 59 sec	< 56 min 59 sec
7/9/2021	17:37:43	17:48:05	< 8 min 22 sec	< 48 min 22 sec
7/15/2021	21:31:18	21:36:05	< 4 min 47 sec	< 44 min 47 sec
11/1/2021	01:25:14	02:00:06	< 34 min 52 sec	< 74 min 52 sec
1/31/2022	23:48:21	00:12:05	< 23 min 44 sec	< 63 min 44 sec
2/2/2022	00:22:15	01:25:48	< 63 min 33 sec	< 103 min 33 ec
3/10/2022	19:25:59	18:48:05	> 37 min 54 sec	< 2 min 6 sec
3/31/2022	18:45:57	19:12:05	< 26 min 8 sec	< 66 min 8 sec
5/11/2022	18:35:33	18:36:05	< 0 min 32 sec	< 40 min 32 sec
6/13/2022	03:03:37	03:12:11	< 8 min 34 sec	< 48 min 34 sec
10/2/2022	20:38:27	20:36:05	> 2 min 22 sec	< 37 min 38 sec
AVG time between CME Alert and LASCO 1st image			**14 min 49 sec *before* LASCO**	**54 min 49 sec *before* LASCO**

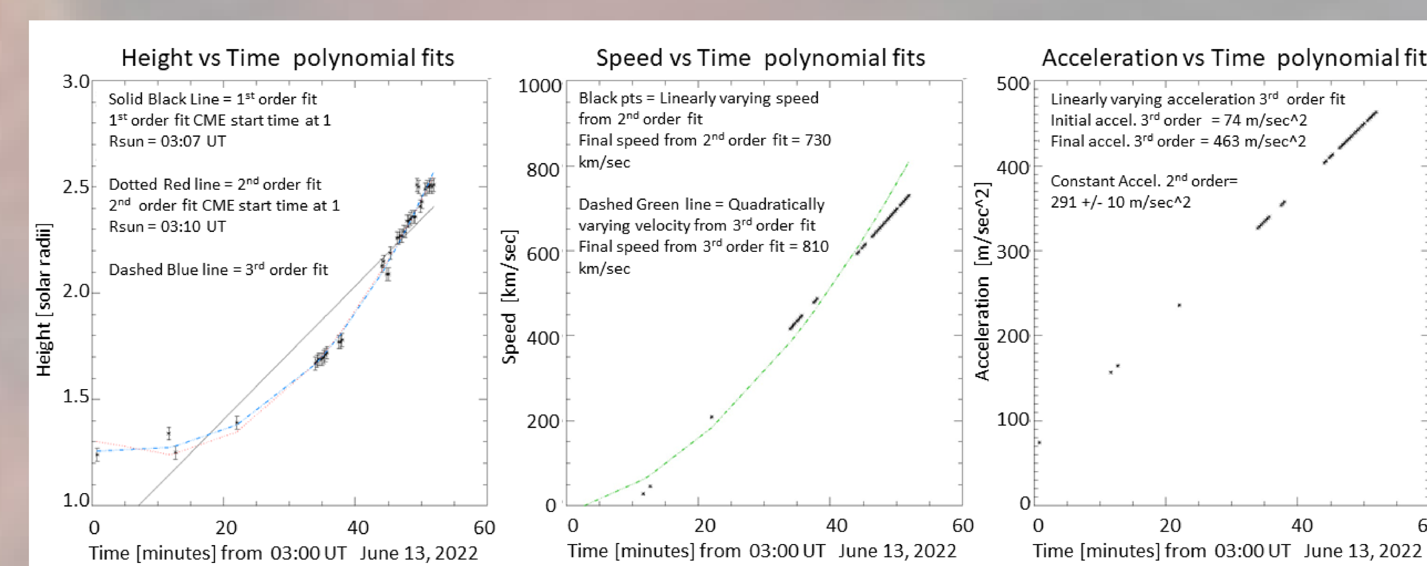
K-COR CME ALERTS PROVIDE CME KINEMATICS

A final CME report is issued when the K-Cor CME is 'over'. It includes the CME time-height trajectory, position and speed vs time. The detection code is being upgraded to: 1) provide trajectory info updates every few minutes, along with the final report when CME is over; 2) use trajectory info to generate CME acceleration and estimate CME start time using polynomial fittings. An example of the new polynomial fits is provided below for the SEP-associated CME on June 13, 2022

June 13, 2022 CME **← TIME INCREASES FROM RIGHT TO LEFT**



At Left: Composite images of **June 13, 2022** CME: AIA (multi-color), K-Cor (b/w), LASCO C2 (red). Red arrow indicates the CME core. The automated code tracked the CME core since this was the brightest part of the CME in the low corona; the CME front was faint and still forming early in event.



The automated code currently provides point-by-point differential speed measurements. No acceleration info is available. The upgraded code will produce CME acceleration and start time info along with speed estimates from polynomial fits as shown in plots at left. These plots were generated with the CME height measurements from the CME detection code.

Note the rapidly increasing acceleration of this SEP-CME in the low through middle corona. Most CMEs that drive large SEP events have peak accelerations in this region of the corona. Providing updates of CME velocities and acceleration every few minutes can expedite the time needed to assess the potential for an in-progress CME to generate SEPs. Forecasters use LASCO (cadence 12 minutes) to observe CMEs. They need to wait for a second LASCO image to get an initial CME speed and third image to get an initial CME acceleration. This takes tens of minutes**.** ***K-Cor CME kinematic reports can significantly reduce time needed by forecasters to identify fast, rapidly accelerating CMEs, that are more likely to generate SEP events.***

K-COR IMPROVEMENTS:

Since 2019 improvements have been made to the K-Cor instrument to reduce noise. These include better objective lens cleaning and installation of 'ultra-black' light-absorbing materials to reduce stray light. These improvements can be seen in the increased percentage of detected CMEs since 2019. 10 of the 11 'missed' SEP-CMEs occurred prior to 2019. **Since 2019, K-Cor alerts identified 11/12 (91.7%) of the SEP-CMEs that occurred during K-Cor observations.**

Current work includes reducing false alarms by 'identifying' rising material that stops or fades below 2 solar radii. Alerts sent for this type of material account for most false alarms. We are working to increase the number of valid alerts by improving subtraction image quality and modifying the detection thresholds used to find regions-of-interest.

CCOR CORONAGRAPH GOES-U

The upcoming CCOR coronagraph will have lower data latency than LASCO, but CCOR has a higher inner field-of-view [see Table 2 at right]. ***CMEs need to travel farther to be seen in CCOR***. This additional time significantly reduces the advantage of the lower CCOR latency. The K-Cor 1.05 to 3 solar radii FOV fills in the observing gap in CCOR data.

TABLE 2	K-COR	LASCO C2	CCOR
Inner FOV	**1.05 Rsun**	2.1 Rsun	3.6 Rsun
Data Latency	**2.5 min**	40 min	15 min
Image Cadence	**15 sec**	12 min	15 min

K-Cor alerts provide valuable first alerts and trajectory measurements of in-progress CMEs

GROUND-BASED CORONAGRAPH NETWORK

Ground-based instruments can provide very low latency data, lower cost, and decades-long observations with instrument upgrades. ***The largest disadvantage is low duty cycle***. A single good coronal site can only observe a fraction of CMEs. In addition, some of the CMEs observed are already in progress when observations begin, which reduces CME warning time. A ground-based coronagraph network with 3 to 6 coronagraphs can provide duty cycle for CME-SEP forecasting. NCAR is a partner on the NSO next-generation GONG (ngGONG) mission that includes K-Cor and emission line coronagraphs (UCoMP). ***A network can observe most CMEs and increases the avg warning time.***

CONTACT: If you would like to be added to the CME alert list, or if you want a copy of this poster, more detailed alert statistics, or other information please email Joan Burkepile [NCAR] at iguana@ucar.edu