

**The Automatic Detection of Coronal Mass Ejections Using
the Solar Mass Ejection Imager**

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14. ABSTRACT The most severe space weather is known to arise from large eruptions of plasma and magnetic field from the Sun. These eruptions, called Coronal Mass Ejections (CMEs) are an important mechanism in the evolution of the solar cycle. Because of their known association with geomagnetic storms and their resulting costly damage, there has been a large amount of resources dedicated in recent years to understanding these phenomena. In the present document, we report on recent efforts toward extracting three-dimensional characteristics of CMEs using heliospheric imagers. We have developed two techniques for this purpose, called the Tappin-Howard (TH) Model and the Automatic Interplanetary CME Detection (AICMED) models. When combined, these have shown the capacity for high-speed, highly accurate CME detection and reconstruction. We have found that these models produce an arrival time prediction almost two orders of magnitude better than currently-existing models, and so the potential for space weather forecasting is highly favorable.						
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AIR FORCE RESEARCH LABORATORY TECHNICAL REPORT
THE AUTOMATIC DETECTION OF CORONAL MASS EJECTIONS
USING THE SOLAR MASS EJECTION IMAGER

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1. OVERVIEW

Developments by the authors over the last 12 months have revealed two techniques that have improved the accuracy and speed of coronal mass ejection detection and tracking to levels not yet seen by the space physics and space weather communities. The first was the development of a phenomenological model based solely on white light heliospheric image observations of coronal mass ejections (CMEs). This model, called the Tappin-Howard (TH) Model, extracts three-dimensional structure and kinematic parameters of CMEs in a high-speed, high-accuracy manner. The second is the automatic detection of interplanetary coronal mass ejections from heliospheric images. Using innovative techniques involving previous automatic detection strategies for coronagraphs and knowledge of projection effects this new technique (called AICMED) enables CME detection and tracking in heliospheric images.

The next step in this work is to combine the AICMED and TH models to produce an automated coronal mass ejection forecasting tool. We have shown that the information required to run the TH Model can be extracted automatically using AICMED, and the TH Model can then extract the three-dimensional properties of the CME and produce a forecast. The entire process can be performed within one hour of the arrival of the heliospheric image at the computer – well within the cadence of currently-operating heliospheric imagers.

In the following report, we present recent work toward the goal of automatic CME detection using heliospheric imagers and then the production of a high-speed, highly accurate space weather forecasting tool. We have found that by combining two newly-developed innovative techniques we can devise a tool that can automatically detect CMEs, extract the 3-D structural and kinematic properties and predict their arrival time and speed at the Earth. Preliminary work has shown that a working model could perform these tasks within an hour of acquisition of the heliospheric images, and with accuracies almost two orders of magnitude more accurate than existing space weather forecasting techniques.

2. BACKGROUND

The most severe space weather effects, called (geo)magnetic storms have long been known to cause a number of adverse technological effects. These effects include power station and spacecraft damage, and increased radiation dosage for aircraft passengers, pilots and astronauts. It is widely accepted that the energy responsible for large geomagnetic storms arises from the Sun in the form of a coronal mass ejection [Baker *et al.*, 2009].

Coronal mass ejections (CMEs) are large-scale, massive eruptions of plasma from the Sun into interplanetary space. Typically containing masses of the order of 10^{12} kg and with structures often spanning several 10's of degrees in solar latitude [e.g. Yashiro *et al.*, 2004], they are the largest eruptions of matter and energy from the Sun. They are also believed to be crucial for the removal of built-up coronal plasma and helicity [Low, 1996] and so play an important role in the evolution of the Sun's magnetic field throughout the solar cycle. Near the Sun CMEs have traditionally been observed with white light coronagraphs, from the early days of *OSO-7* [Tousey, 1973] and *Skylab* [Gosling *et al.*, 1974], to the more recent *LASCO* on board *SOHO* [Brueckner *et al.*, 1995] and the CORs on *STEREO* [R. Howard *et al.*, 2008].

Further from the Sun, CMEs are often detected *in situ* by non-imaging spacecraft in this medium (e.g. *Wind*, *ACE*, *Ulysses*) and are identified by their signatures in magnetic field and solar wind plasma instruments. More recent times have seen the emergence of a new class of white light imager, namely the heliospheric imager, which observes the inner heliosphere beyond around 0.3 AU from the Sun. There are currently three heliospheric imagers capable of observing white light CMEs at these distances from the Sun. They are the Solar Mass Ejection Imager (SMEI) on *Coriolis* [Eyles *et al.*, 2003], which was launched in January 2003, and the Heliospheric Imagers (HI-2s) on *STEREO* [Eyles *et al.*, 2009], launched in October 2006. These are capable of tracking Earth-directed CMEs through the heliosphere until their impact with the Earth.

2.1 SPACE WEATHER FORECASTING

When CMEs impact the Earth they compress the magnetosphere, allowing the cusp region to move equatorward and the polar caps to grow. If the magnetic orientation of a CME is southward, magnetic reconnection also allows the injection energetic particles into the magnetosphere, leading to a geomagnetic storm [Dungey, 1963].

The two most important properties governing severe space weather are hence the ram pressure exerted on the magnetosphere by the CME (Proportional to NV^2 where N is the density and V the speed) and the orientation of its magnetic field. So the forecasting of CME-related space weather is the identification of the following four properties:

1. The arrival time of the CME at 1 AU;
2. The likelihood of impact with the Earth, given the size and direction of the CME;
3. The ram pressure of the CME upon impact.
4. The orientation of the magnetic field of the CME.

Contemporary efforts have focused on the identification of the first two properties. For the most part, these efforts are based on models that impose the physics of CME evolution on an erupting structure, often using near-Sun empirical data such as coronagraph CME properties, solar flares or CME-related radio bursts. Evolutionary physics imposed on CMEs varies from aerodynamics [Cargill, 2004; Tappin 2006] to shock mechanics [Hakamada & Akasofu, 1982; Fry *et al.*, 2001] to magnetohydrodynamics [Chen, 1996; Xie *et al.*, 2004].

2.2 IMPROVING FORECASTING

A summary of the accuracies of various CME arrival time prediction techniques over the years has been presented by Webb *et al.* [2009a] (their Section 4.2.1). The most accurate predicted arrival time cited was ± 11 hours from the ISPM magnetohydrodynamic model reported in 1995 [Smith & Dryer, 1995]. Recent years have seen little progress in improving CME arrival time prediction accuracy.

One reason for this lack of progress could be that CME evolution models couple two separate problems associated with CME observation:

1. The physics describing the appearance of the CME
2. The physics describing the evolution of the CME

The former is governed by the geometry of the CME and the laws of Thomson scattering by which white light CMEs are observed. The latter requires predetermined assumptions of CME evolution through the heliosphere and then modifies boundary conditions, often in an *ad hoc* fashion, to fit new datasets as they become available. The coupling of these two problems means that if either of the assumptions is incorrect or inaccurate, then an inaccurate prediction of CME trajectory can easily result. So it seems reasonable to suppose that if the CME structure and kinematics could be described using only the physics describing its appearance, then these parameters could be derived from the data alone without the need to apply the physics describing its evolution. The result could lead to more accurate CME impact probability, speed and arrival time forecasting.

It is not possible to extract three-dimensional (3-D) properties from white light images alone when observing close to the Sun (within around 50 solar radii). This is because the geometry and scattering physics near the Sun impose linearity. So the assumptions we can apply to simplify geometrical measurements of coronagraph CMEs near the Sun also restrict our ability to extract 3-D information [Howard & Tappin, 2009a].

When CMEs are observed by imagers at greater distances from the Sun, the linearity assumption breaks down and more detailed treatments of geometry and scattering need to be applied. While the analysis becomes more complex, the advantage is that 3-D information arises that is not available when CMEs are close to the Sun. Hence it is possible to extract 3-D kinematic and structural information on a CME using white light images alone, provided the CME is a large enough distance from the Sun.

2.3 USING HELIOSPHERIC IMAGERS FOR SPACE WEATHER

The utility of heliospheric image data to investigate space weather and estimate CME arrival time at the Earth was first attempted by Howard *et al.* [2006], using SMEI data. They found that of the 22 geomagnetic storms during their observing period, 14 were associated with a CME observed by SMEI. By projecting trajectory trends to 1 AU they predicted the arrival time of the CME at the Earth and compared it with the actual arrival time of the interplanetary shock at ACE. The difference between predicted and actual arrival times was on average around 11.5 hours, but the difference was within two hours for two events. In their SMEI CME survey paper, Webb *et al.* [2006] discussed a study involving the geoeffectiveness of Earth-directed CMEs. They found that of the 14 geomagnetic storms, 10 were associated with SMEI CMEs, with first detection just under 30 hours before the storm on average. Another study reported in the same paper revealed 39 out of 46 SMEI event related storms with first detection within 2 days prior to storm onset. Webb *et al.* [2009a] studied some 14 geoeffective CMEs using SMEI and found predicted arrival times with accuracies around 10.5 hours which was found to be more accurate than any of the other compared prediction methods.

These studies show that heliospheric image data alone can be used to predict CME arrival times with accuracies better than current space weather forecasting models, but at the cost of later detection and forecast time. It seems likely that a more precise application of the physics responsible for the appearance of the CME will lead to more accurate predictions of arrival time at the Earth.

3. WORK TO DATE

3.1 EXTRACTING 3-D INFORMATION FROM HELIOSPHERIC IMAGERS

Efforts to extract 3-D distances from heliospheric imagers have developed in sophistication since the launch of SMEI seven years ago. Early work utilized the Point P approximation [e.g. Howard *et al.*, 2006; Webb *et al.*, 2006] which assumes that the observed part of the CME is a spherical arc oriented such that the line of sight is tangent to the surface of the CME. This is the same approximation applied

to near-Sun coronagraph images of CMEs [e.g. T. Howard *et al.*, 2008] and has been found to be appropriate to around 30° elongation (~0.5 AU).

Later efforts accommodated for the relative geometry which comes into play when at larger elongation angles. The now-called Fixed-Phi method [Kahler & Webb, 2007] assumes the CME is a single point and considers how the elongation trends change when the trajectory of that point changes. This technique has been employed by Howard *et al.* [2007], Howard & Simnett [2008] and Webb *et al.* [2009b]. Howard & Simnett [2008] developed a technique they called the Cube-Fit which automated the trajectory identification. Cube-Fit constructed a data cube of elongation-time plots describing CMEs of different trajectories and speeds and compared it with actual elongation-time plots measured from the heliospheric image. Studies using Fixed-Phi seem to show that this method is appropriate to elongation angles out to around 45° (~0.7 AU).

3.2 THE TAPPIN-HOWARD (TH) MODEL

Beyond elongations of 45° it became clear that a full 3-D treatment was required incorporating both the relative geometry of an entire CME structure with the Thomson scattering physics responsible for its observation in white light. This led to a series of papers published in *Space Science Reviews* by two of the authors of the present report [Howard & Tappin, 2009a; 2009b; Tappin & Howard, 2009]. The second part of this series [Tappin & Howard, 2009] describes the development of a model for SMEI data now known as the Tappin-Howard (TH) Model. The third paper [Howard & Tappin, 2009b] shows its application to *STEREO*/HI data.

The TH Model is a phenomenological CME reconstruction tool based on leading edge measurements from white light heliospheric images. It does not attempt to reproduce the density structure of the CME, only its leading edge. The Model is a high-speed alternative to complete density reconstruction, based on the assumption that we only require the leading edge of the CME to gain a very good estimate of the arrival time and speed at the Earth. It is a combination of two ideas: the phenomenological comparison devised for interplanetary scintillation by Tappin [1987] and the Cube-Fit concept of Howard & Simnett [2008].

The Model works by comparing simulated leading edges for CMEs of various size, structure and propagation properties with actual leading edge measurements obtained directly from white light images. Version 1 (reported in the *Space Science Reviews* trilogy) began with two base structures which were distorted to simulate the CMEs. These were a spherical bubble with one end at the Sun and the diameter aligned along the direction of propagation, and a spherical shell with the Sun as the

center. Apparent leading edges for each structure can be determined by combining the physics of Thomson scattering with the geometry of the CME relative to a fixed observer, following the theory of Howard & Tappin [2009a].

In Version 1 of the Model, the basic structure is altered via a distortion parameter for the bubbles and latitude and longitude width parameters for the shell. The CME is then directed along a fixed trajectory and the resulting apparent leading edges for an observer at any location produced. Different parameters for structure and trajectory are then incrementally chosen and the observers selected as the SMEI and HI instruments. Hence a hypercube of simulated leading edges is produced with one edge for each combination of parameters. The hypercube contains several hundred thousand simulated leading edges.

When a CME is observed in white light heliospheric images its leading edge can be measured for each image in which it appears. Regions of noise and the time at which the CME no longer appears are noted and the white light leading edge sequence is compared with the simulated leading edges using a genetic algorithm followed by a simplex convergence. The result is the combination of parameters that best matches the measured leading edges, with error contours showing the "goodness" of each parameter conversion. From this parameter combination the 3-D structure of the CME can be reconstructed, along with its trajectory and speed of propagation.

The Model works in two stages. In Stage 1 the speed is a fixed parameter which converges in the same manner as the other parameters, but in Stage 2 it is allowed to vary. This allows a measurement of the acceleration evolution of the CME. Figure 1 shows a 3-D reconstruction of a CME produced by the TH Model.

Version 2 [Howard & Tappin, 2009c] works on the same basic principle as Version 1, but the base structure of the CME has been altered. The two structures from Version 1 were combined to produce a single distorted shell base structure. So, where Version 1 worked with two hypercubes containing combinations of five (bubble) and six (shell) parameters, Version 2 contained a single hypercube of simulated leading edges produced from combinations of seven parameters. The distortion parameter is such that we can vary the 3-D structure of the CME to accommodate for concave-inward, flat and concave-outward CMEs. For Version 2, the programming for the convergence was also rewritten to improve its efficiency.

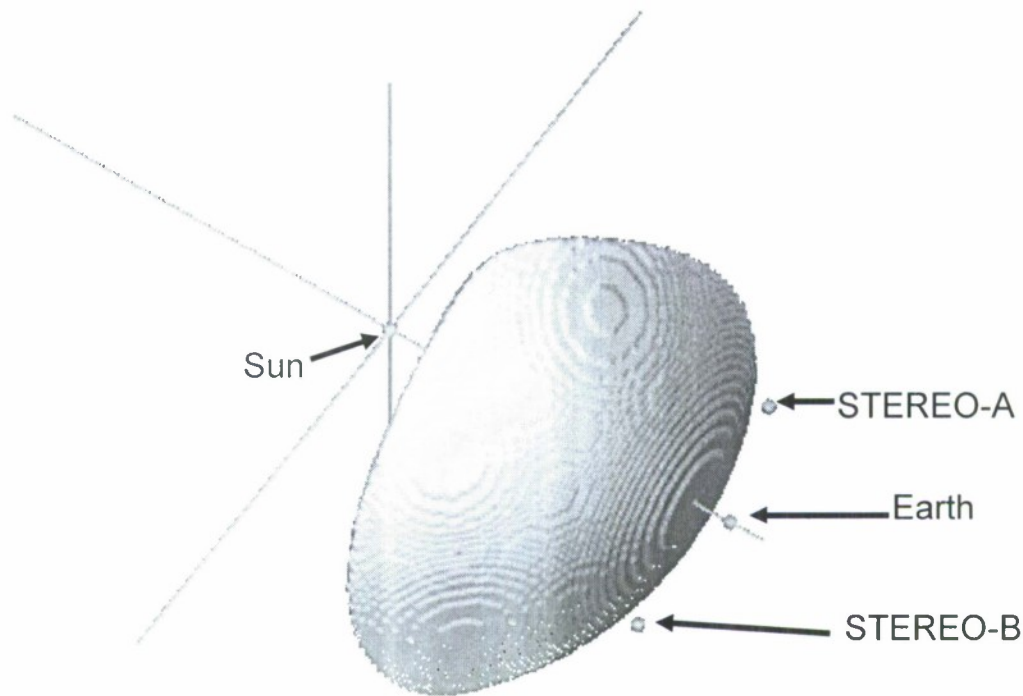


Figure 1: 3-D reconstruction for the CME observed on 15-20 November, 2007 [Howard & Tappin, 2009b]. This event was observed by SOHO, SMEI and both STEREO and the ACE and PLASTIC in situ instruments. The locations of the Sun, Earth (and SMEI) and both STEREO are indicated.

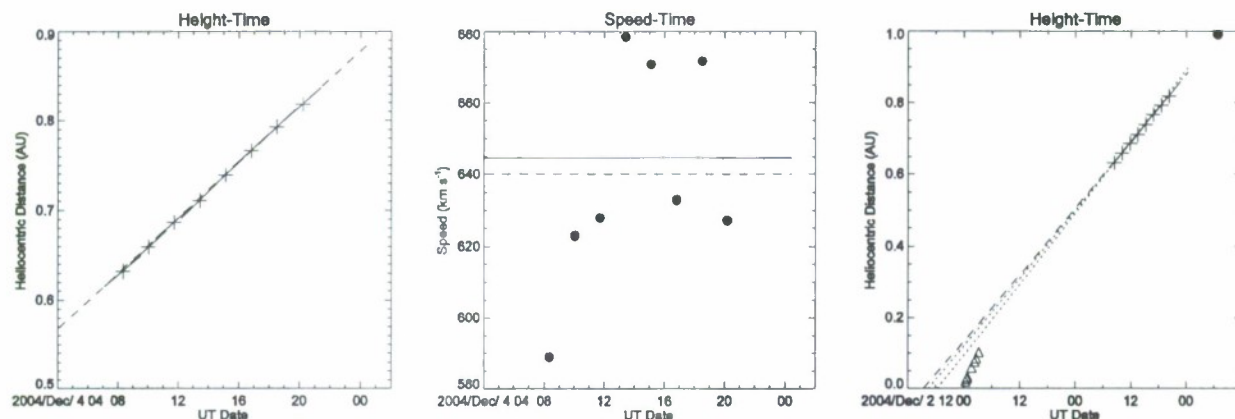


Figure 2: (Left) Heliocentric distance vs time for an event observed over 30 November – 5 December 2004, derived by Version 1 (Stage 2) of the TH Model [Tappin & Howard, 2009]. The dashed line is the height time from the speed determined by Stage 1. (Middle) Speed-time plot for the same CME across the same time range. Here the dashed horizontal line represents the Stage 1 speed and the solid line is the average speed. (Right) the same distance-time plot as in (Left) expanded to include the height-time plot of the associated CME in LASCO, and the time of the shock arrival at ACE.

3.2.1 USING THE TH MODEL FOR SPACE WEATHER FORECASTING

In the TH Model development paper, Tappin & Howard [2009] produced kinematic information on a single event observed by SMEI in December 2004. These results are shown in Figure 2. The right

panel of this figure shows the height-time plot derived from the SMEI data with the height-time plot from the associated LASCO CME and the time of the arrival of the associated shock at ACE. When the SMEI height-time plot was projected forward to 1 AU it was found that its arrival time was only 15 minutes off from the actual arrival time of the shock at ACE. This level of accuracy surpasses current CME prediction models by almost two orders of magnitude.

To demonstrate the utility of the TH Model specifically for space weather forecasting, Howard & Tappin [2009c] performed mock forecasts on three events using Version 2. The events were CMEs that had already been studied by previous workers, all Earth-directed and geoeffective, and occurring in May 2003, December 2004 and November 2007.

Although the events had been studied in prior works, we analyzed the data as if they were being observed for the first time in near real time. We factored in appropriate data latency and kept a log of the times to produce leading edge measurements and run the TH Model. A forecasting code was devised based on the geometry of the CME and the theory described by Howard & Tappin [2009c]. This enabled the determination of whether the CME impacted the Earth and the time of impact if it did, or the distance and time of closest approach if it did not. When each new image became available on the computer a new forecast was produced using the new leading edge measurement appended with the already obtained measurements. This continued until the CME arrived at the Earth, indicated by the concurrent *in situ* and ground data.

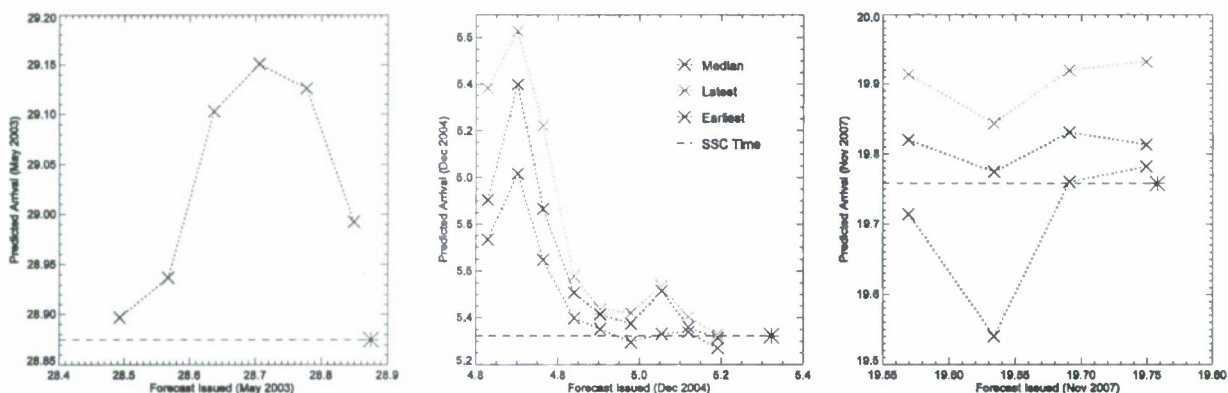


Figure 3: Predicted arrival time vs time elapsed for each of the three mock forecasts for the events in (left) May 2003, (middle) December 2004 and (right) November 2007. Each cross is a prediction and the top and bottom plots in the middle and right panels show the upper and lower limits of each predicted arrival time. The horizontal dashed line represents the time of the arrival of the CME at Earth along the y-axis and the asterisk represents the same time in the x-axis. So the closer the predicted arrival times are to the horizontal dashed line the more accurate the prediction, and the closer the time of prediction is to the asterisk the later the prediction [Howard & Tappin, 2009c].

Figure 3 shows the results of each forecast, shown in the order of occurrence. For the first event, Version 1 of the TH Model was used, which was too slow to produce multiple runs of the Model, and so only the timing of a single forecast is shown. Version 2 was used for the other two events, and so there was time for multiple runs, allowing the median and maximum and minimum forecasts to be issued. These are shown in the middle and right panels. For the third event, we incorporated both the SMEI and HI data into a single collective model to produce the reconstruction and forecast.

The results of the forecasts were very encouraging. Firstly, in all cases the most accurate predicted arrival time was only 30 minutes or better than the actual time of the sudden commencement. Secondly it was found that predictions could be made as early as 17 hours prior to the arrival of the CME at the Earth. This, while not as early as many prediction models, is still adequate time to take advantage of the accuracy of the TH Model. Thirdly for the event for which we could make the largest number of measurements (the second event), the accuracy of the prediction improved with passing time resulting in a predicted arrival time only 15 minutes off from the actual time, made two hours before the onset of the storm. Fourthly the predicted arrival speeds (not shown) were highly accurate, reaching differences of only 40 km/s from the bulk plasma speed of the CME measured by *ACE*. Finally the incorporation of the *STEREO*/HI data was shown to improve the accuracy of the forecast, with all of the four forecasts issued for the third event within two hours of the actual arrival time. These results demonstrate the potential for the TH Model for highly accurate, high-speed CME-related space weather forecasting.

3.2 THE AUTOMATIC ICME DETECTION (AICMED) ROUTINE

Automatic coronal mass ejection detection and measurement has been established in coronagraph data using the Computer Aided CME Tracking (CACTus) tool [Robbrecht & Berghmans, 2004]. This was based on applying the Hough transform (which extracts straight lines from a dataset) to a data cube of LASCO images that have been rotated into polar coordinates. As the strength of this technique depended largely on the number of measured points making up the straight line, it works best for slower CMEs traveling with near constant speed. Accelerating CMEs show a curve in their height-time profiles, so their detection is met with limited success with CACTus.

Likewise "distances" in heliospheric images are measured in units of elongation angle (not distance) and so CME trajectories are rarely perfectly straight in SMEI or HI-2 images. While efforts in automatic CME detection continues within the *STEREO* team, to the best of our knowledge, no working model has yet emerged.

In the summer of 2009 Max Hampson, working as a summer research student under the NSO/SRA program, was set with the task of automatic detection of CMEs in SMEI images. He devised a method that combined a similar technique to CACTus with edge detection techniques that have been employed for LASCO data. The issue of apparent curved trajectory was resolved by parsing the coordinate-rotated image into overlapping sections of elongation, which allowed the detection of the CME using the Hough transform in sections where its trajectory was relatively straight. Other post-processing techniques, such as the application of an intensity mask and the option to modify selection criteria, were also added.

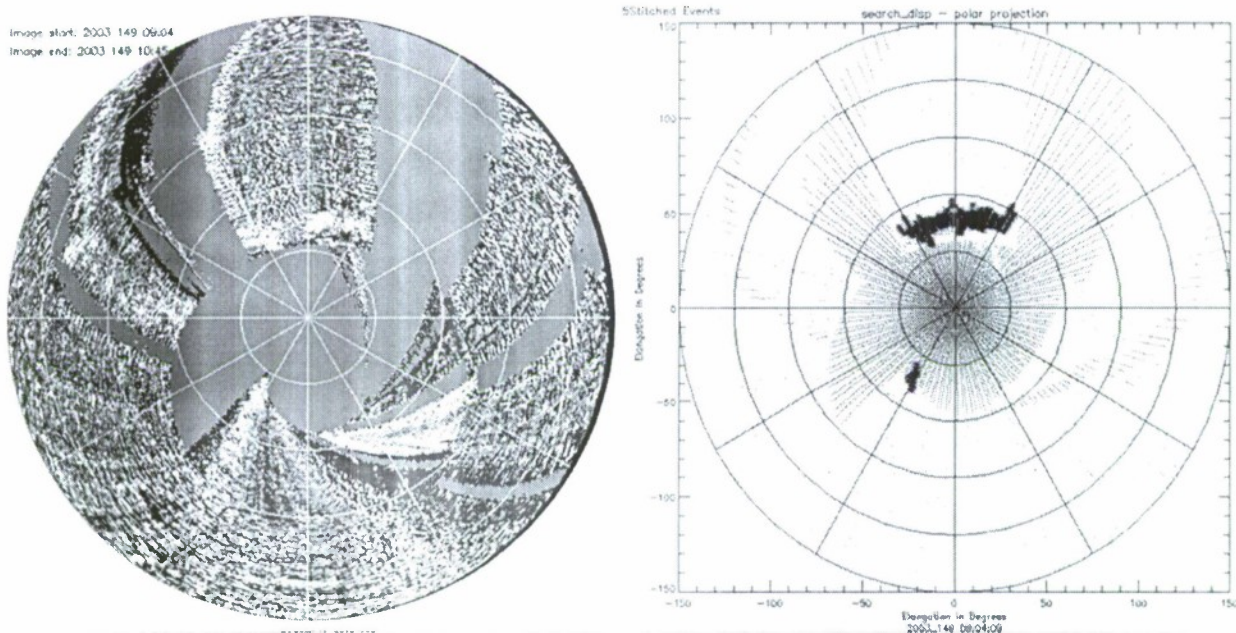


Figure 4: (Left) SMEI zenithal equidistant (fisheye) image for the event observed on 29 May, 2003. (Right) The same image following the application of the AICMED technique. The location of the Sun is at the center, circular contours are in increments of 30° elongation and the straight lines on the grid represent 30° of position angle. On the right image, the heavy black points represent the location of the CME and the faint lines are regions of noise, both determined automatically by AICMED.

Figure 4 shows the results from AICMED for a single event observed by SMEI in May 2003. The image on the left is a zenithal equidistant (fisheye) SMEI image of the event, and the corresponding image resulting from the AICMED technique is on the right. The CME is clearly identified by the heavy black points (even in the small section toward the southeast) and the regions of noise in the SMEI image have also been identified. This demonstrates the ability of AICMED to automatically detect CMEs even in the SMEI dataset, which because of noise limitations is very difficult to work with. Furthermore, leading edge measurements can easily be obtained with AICMED, measurements required for the operation of the TH Model. The report on this technique is currently being prepared and will appear in a publication in the coming year.

4. CONCLUSIONS

The work discussed here demonstrates how heliospheric imager (SMEI, HI) data alone can be used to detect and measure CMEs as well as produce a highly-accurate space weather forecast. A combination of the TH and AICMED models will lead to an automated tool which will detect CMEs, extract their 3-D structural and kinematic properties and produce a space weather forecast of arrival time and speed at the Earth. Preliminary studies have shown that the accuracy of both the reconstruction and the forecast are highly accurate, with arrival times almost two orders of magnitude better than any CME forecasting tool currently available.

It is therefore our hope that the development of this tool will lead to a new era of space weather forecasting, one with high-speed calculations and high degrees of accuracy, based on heliospheric imaging.

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