SPACE WEATHER EFFECTS AND HOW SOHO HAS IMPROVED THE WARNINGS

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ABSTRACT

Transient variations in the particle and EUV flux from the Sun causes disturbances in the Earth's space environment affecting some of the technologies that we depend on both in orbit and on the ground. The Solar and Heliospheric Observatory (SOHO) has obtained significant new information about coronal mass ejections (CMEs), the source of the most severe disturbances in the Earth's environment. Furthermore, by observing the Sun 24 hours a day, SOHO has proved to be an important "space weather watchdog". The importance of real-time monitoring of the Sun will be pointed out.

1. SPACE WEATHER FORECASTING

Today our society is much more sensitive to space weather activity than was the case during the last solar maximum in 1991. The effects of geomagnetic storms extend from the ground to geostationary orbits and beyond (Figure 1). An example is the possible disruption of satellites. Our society depends on satellites for weather information, communication, navigation, exploration, search and rescue, research, and defence systems. Thus, the impact of satellite system failures is more far-reaching than ever before, and the trend will almost certainly continue at an increasing rate. Furthermore, safe operation of the International Space Station depends on timely warnings of eruptions on the Sun. Navigation systems such as LORAN and OMEGA are adversely affected when solar activity disrupts their radio wavelengths. It also introduces position errors and decreases the accuracy and reliability of the Global Positioning System (GPS). Space weather-induced currents can also create galvanic effects in oil and gas pipelines, leading to rapid corrosion at the pipeline joints if they are not properly grounded. Such corrosion requires expensive repairs or can lead to permanent damage. Furthermore signals used during geomagnetic surveys (e.g. search for natural resources such as oil and gas) are significantly affected by the varying magnetic fields during geomagnetic storms. It is therefore important to forecast and warn about major solar storms.

Real-time monitoring and and forecasting of solar and geophysical events have been provided by the Space Environment Center (SEC) in Boulder, Colorado for many years. In the past the forecasters at SEC relied on H-alpha images provided by a network of ground observatories as well as the GOES Soft X-ray monitors and the Yohkoh soft X-ray images. This system could only detect solar flares and dissapearing filaments but not coronal mass ejections (CMEs) that can only be observed using sophisticated coronagraphs. It is CME's, and not flares, that are known to produce the most severe geomagnetic disturbances. Thus, the accuracy of forecasting geomagnetic storms was relatively poor prior to space-born coronagraphs. Between 1987 and 1993 there were 126 storm forecasts by SEC. Only 27% of major magnetic storms (Kp index of 6 or greater) were correctly forecast while 63% were false alarms [1]. New instruments and observing techniques continue to improve the accuracy of SEC's data, and new data sets are constantly being added to improve space weather monitoring and analysis. As discussed below the accuracy of space weather forecasting has improved considerably.

2. THE SOLAR AND HELIOSPHERIC OBSERVATORY

The presence of two satellites located in the L1 Lagrangian point, The Advanced Composition Explorer (ACE) and Solar and Heliospheric Observatory (SOHO), has considerably improved the accuracy of space weather forecasts. ACE provides near-real-time solar wind information with high time resolution and provides advance warning (about one hour) of geomagnetic storms.

SOHO is a project of international cooperation between ESA and NASA to study the Sun, from its deep core to the outer corona, and the solar wind [3]. It carries a complement of twelve sophisticated instruments. Detailed descriptions of all the twelve instruments on board SOHO as well as a description of the SOHO ground system, science operations and data products together with a mission overview can be found in [4].

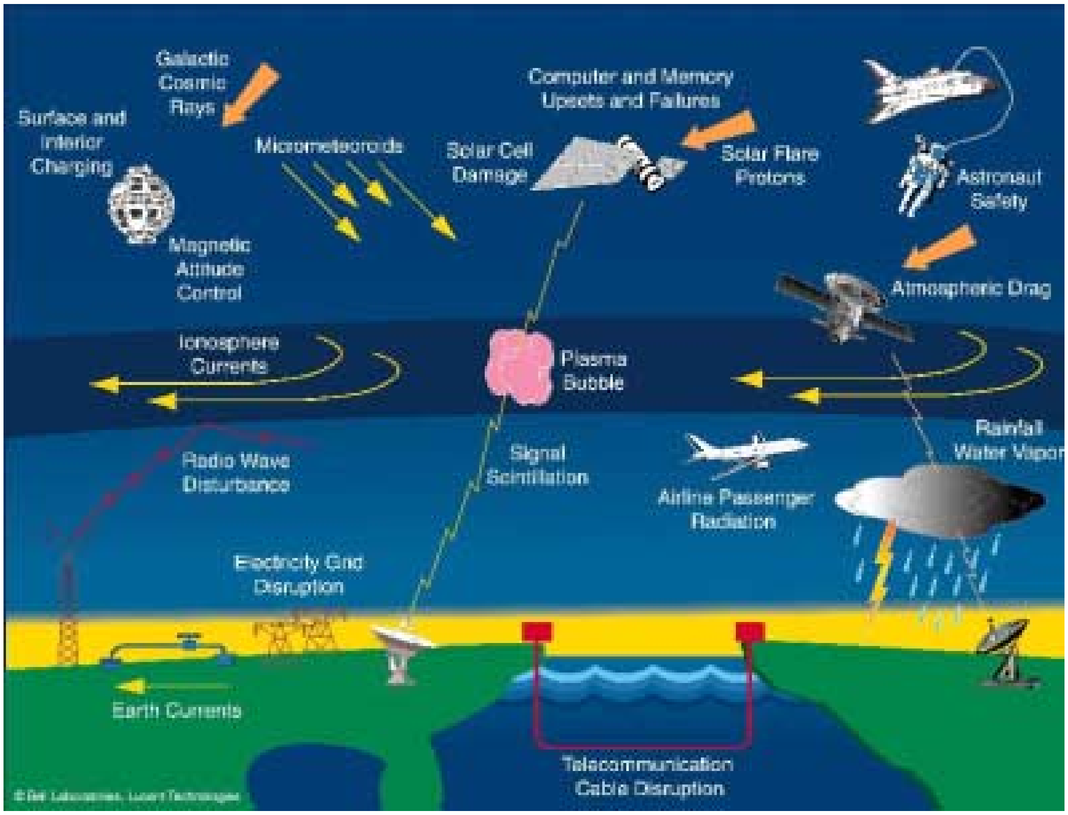

Figure 1. The effects of geomagnetic storms extends from the ground to geostationary orbits and beyond [2].

SOHO was launched by an Atlas II-AS from Cape Canaveral Air Station on 2 December 1995, and was inserted into its halo orbit around the L1 Lagrangian point on 14 February 1996. Commissioning of the spacecraft and the scientific payload was completed by the end of March 1996.

Observations of the solar corona with the Large Angle Spectrometric Coronagraph (LASCO) and the Extreme ultraviolet Imaging Telescope (EIT) instruments on SOHO provide an unprecedented opportunity for continuous real-time monitoring of solar eruptions that affect space weather. LASCO takes images of the solar corona by blocking the light coming directly from the Sun itself with an occulter disk, creating an artificial eclipse within the instrument. It is the perfect tool for detecting CMEs heading towards (or away from) the Earth. EIT provides images of the solar atmosphere at four extreme ultraviolet wavelengths and reveals flares and other associated events in the atmosphere. EIT can usually determine whether CMEs seen by LASCO originated on the near or far side of the Sun, based on the presence or absence of corresponding events on the near side.

2.1. SOHO MONITORING SOLAR ERUPTIONS

LASCO has been collecting an extensive database for establishing the best statistics ever on CMEs and their geomagnetic effects. By August 2001 more than 3500 CMEs have been recorded. CME's are vast structures of plasma and magnetic fields that are expelled from the Sun. CMEs moving outward from the Sun along the Sun-Earth line can, in principle, be detected when they have expanded to a size that exceeds the diameter of the coronagraphs occulting disk. CME's directed toward or away from the Earth should appear as expanding halo-like brightenings surrounding the occulter. An example of a halo-CME is shown in Figure 2 as recorded by the LASCO C3 detector on 6 June 2000. Although halo CMEs were discovered by the SOLWIND coronagraph two solar cycles ago [5] the LASCO experiment is the first to observe a significant number of these events, thanks to its extended field of view and its improved sensitivity compared with earlier coronagraphs.

Reference [6] reported the properties of all the 841 CMEs observed by the LASCO C2 and C3 white-light coronagraphs from January 1996 through the SOHO mission interruption in June 1998 and compared those properties to previous observations by other instruments. The CME rate for solar minimum conditions was slightly higher than had been reported for previous solar cycles, but both the rate and the distribution of apparent locations of CMEs varied during this period as expected (Figure 3). While the pointing stability provided by the SOHO platform in its L1 orbit and the use of CCD detectors have resulted in superior brightness sensitivity for LASCO over earlier coronagraphs, they have not detected a significant population of fainter (i.e., low mass) CMEs. The general shape of the distribu-

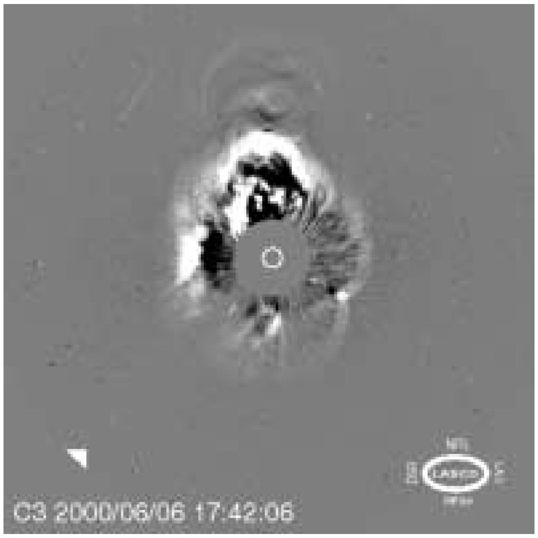

Figure 2. Example of a full halo CME observed by the LASCO C3 coronagraph. The field of view of the image is 3.5-30 solar radii (LASCO/SOHO).

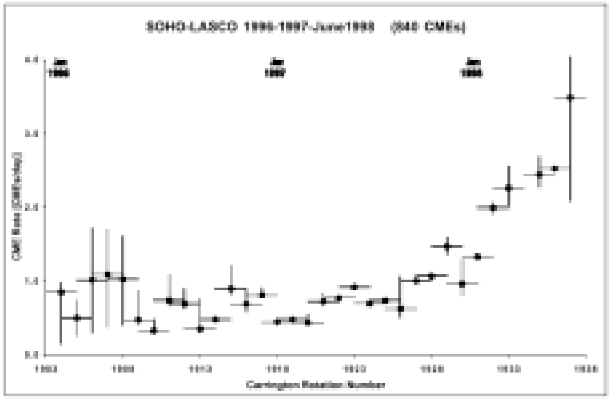

Figure 3. CME Rate plot versus Carrington Rotation (from [6]

tion of apparent sizes for LASCO CMEs is similar to those of earlier reports, but the average (median) apparent size of 72° (50°) is significantly larger.

Reference [7] presented a survey of the geo-effectiveness of Earth directed CME's based on LASCO and EIT observations. During the post solar minimum period from December 1996 to June 1997. Of 14 observed halo CMEs 7 were associated with frontside surface activity. The events are summarised in a stackplot of seven consecutive Bartels rotations of the Dst index (Figure 4). The Dst index gives the strength of the average depression of Earth's magnetic field at the equator and is a commonly used measure of the strength of magnetic storms. The solid triangles at the bottom of each rotation mark the peak times of storms. The onset times for all 14 halo CMEs are denoted by vertical bars, dark grey lines are for the seven probable frontside events, and the light grey lines are for the seven possible backside events. The shading of the plots indicates the sectors of dominant polarity of the interplanetary magnetic field (IMF) and the Wind spacecraft. The occurrence and duration of magnetic cloud structures detected by Wind are indicated by horizontal black bars. The activity for six of these seven occurred in active regions within 0.5 R_s of Sun center and thus consistent with being Earthward-directed. All these events were associated with magnetic clouds and moderate storms at Earths 3-5 days later. Thus, halo CMEs associated with surface activity within 0.5 R_s of Sun center appeared to be an excellent indicator of increased geoactivity a few days later. It was also noted that even partial halo CMEs can be geoeffective if accompanied by surface activity near Sun center.

Reference [6] also reported on the statistics of halo CMEs. Using full disk EIT images they found that 40 out of 92 of these events might have been directed toward the Earth. A comparison of the timing of those events with the Kp geomagnetic storm index in the days following the CME yielded that 15 out of 21 (71%) of the Kp ≥6 storms could be accounted for as SOHO LASCO/EIT frontside halo CMEs. An additional three Kp storms may have been missed during LASCO/EIT data gaps, bringing the possible association rate to 18 out of 21 (86%).

Over the time period January 1996 to December 1998 (i.e the rising phase of solar cycle 23) 68 full halo CME's were observed (Webb 2001, private communication). These events represent only 4.3% of all types of CME's observed with LASCO and about 11.3% of all halo-CME's. Of the 68 full halo events 53% had visible front side sources and were determined to be front side events. Approximately 85% of the front side events were associated with flares while only 53% were associated with EUV coronal waves, the fast waves propagating in the lower corona [8]. Since the CME cannot be detected until its leading edge has emerged from behind the occulting disk, one must extrapolate back in time and space to the solar surface to search for possible associated activity. This is obviously an easier task during solar minimum when there are fewer active regions present on the solar disk. At solar maximum this task can be more difficult due to the large number of active regions and filaments and the more complex magnetic field structures.

2.2. GEOEFFECTIVENESS OF CMEs

In 1997 more than 80% of the full halo events produced geomagnetic storms. In comparison only 40% produced geomagnetic storms in 1998 (Webb 2001, private communication). The average geoeffectiveness over the time period 1996-1998 was 65%. Thus, the geoeffectiveness clearly depends on the solar activity and decreases towards solar maximum. This most probably has something to with the complexity of the magnetic field near solarmax.

CMEs are only geoeffective when they contain or drive several hours of southward Bz when they arrive

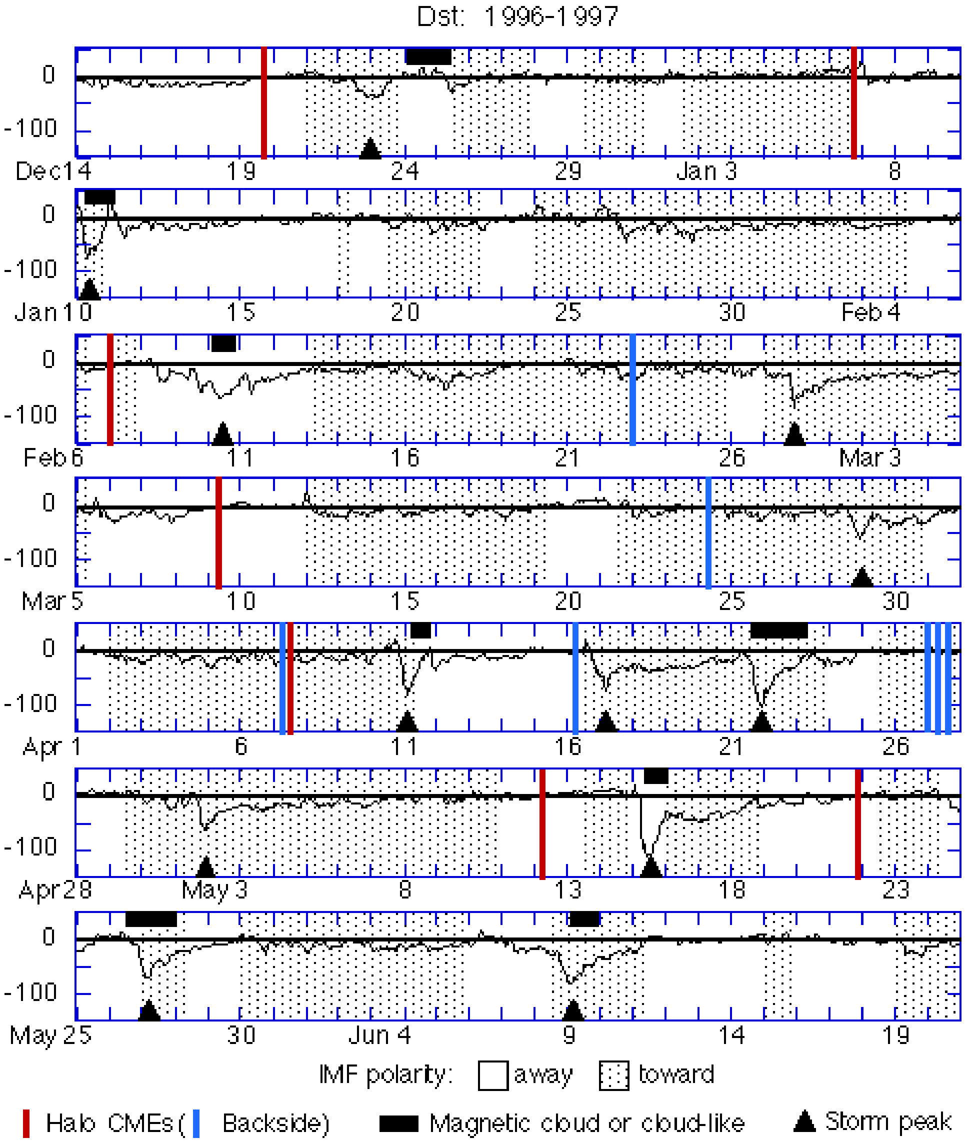

Figure 4. Stackplot of seven Bartels rotations (Numbers 2231-2237) of the Dst level (nT, left scale) showing geomagnetic storms at Earth. The horizontal line marks the zero nT level. The occurrences at Wind of geomegnetic clouds or cloud-like structures are denoted by the horizontal black bars above the zero line on each rotation. Vertical lines mark the onsets at the Sun of LASCO halo CMEs; Dark grey lines are probable front side events, light grey lines are probable backside events. Solid triangles mark the peak times of moderate storms, i.e. $Dst \leq -50$ *nT (from [7].*

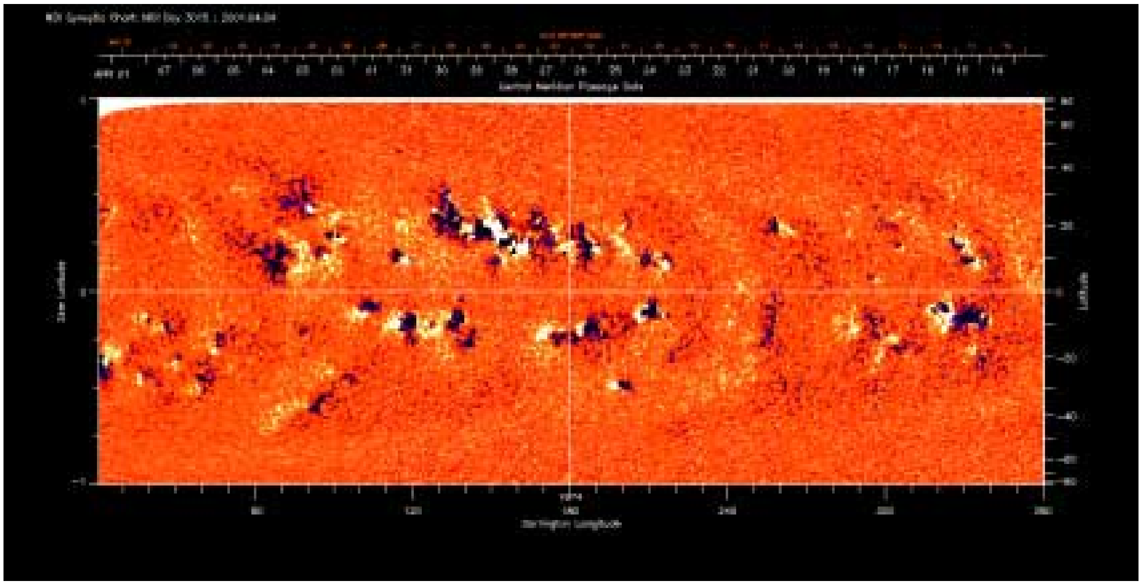

Figure 5. Synoptic maps of the surface magnetic fields derived from The Michelson Doppler Imager (MDI/SOHO) data.

at Earth. Recent studies have demonstrated that the CME's carry the imprint of the solar magnetic field out into the heliosphere. Estimates of the orientation of fields pushed by CMEs show that the pre-existing field estimates for the overlying corona make good predictions of the Bz when the locations of Earth directed CMEs are known (e.g. [9]). Recent developments in processing of MDI magnetograms has led to the concept of "synoptic frame" where synoptic whole-Sun Carrington grids of magnetic field (see Figure 5) are supplemented by rapidly updated magnetic information for the visible disk. Initial analyses of these data are promising and may lead to better estimates of the sign and strength of the Bz component of the field carried by CMEs.

3. SOLARWIND SHOCKSPOTTER

The CELIAS MTOF instrument on SOHO measures the proton flux and the solarwind speed/density. A group at the University of Maryland recently implemented a "Shockspotter" program (developed to identify interplanetary shocks in near-real time using proton monitor data) to analyse the temporal distribution of shocks. The Shockspotter program is now part of the proton monitor real-time data page at http://umtof.umd.edu/pm. The program will alert the users whenever a CME shock front passes the SOHO spacecraft approximately 30-60 minutes prior to the arrival at Earth. The Maryland CELIAS group has also developed Web pages that show the solar energetic particle flux deduced from proton monitor background levels (http://umtof.umd.edu/pm/flare) and the solar soft X-ray flux from SEM measurements (http://umtof.umd.edu/sem/).

4. THE 14 JULY 2000 EVENT

The Sun has produced a series of large eruptions and flares during 2000-2001 and SOHO's role in the early-warning system for space weather has been demonstrated. On 14 July, SOHO's ultraviolet telescope EIT saw the bright flash of a solar flare near the centre of the Sun's disk, at 10:12 Universal Time (GMT). The flare's intensity peaked at 10:24, and half an hour later SOHO's LASCO instrument detected a mass of gas racing out from the Sun (Figure 6).

Next, a burst of energetic particles from the solar explosion hit SOHO. In the imaging instruments it looked like a snowstorm that continued for some hours. Travelling more slowly than the energetic particles, the interplanetary shock wave driven by the gas of the CME arrived at SOHO a day later, at 14:19 UT on 15 July. The solar-wind instrument CELIAS on SOHO registered a jump in the wind speed from 500 to 800 kilometres per second, increasing to over 900 km/s an hour later. As the spacecraft is stationed 1.5 million kilometres out, on the sunward side of the Earth, the CME slammed into the Earth's magnetic field half an hour later than at SOHO, provoking auroral displays that peaked in the early hours of 16 July.

The geomagnetic activity between July 14 to July 19 produced some of the largest space weather events in this solar cycle. This was the largest geomagnetic storm observed since 1989, and one of the most intense solar proton events ever recorded. Several satellites experienced problems, and some permanent damages were reported. The storm left the Advanced Satellite for Cosmology and Astrophysics (ASCA) spinning out of control and it was considered lost. The SOHO spacecraft suffered permanent degrada-

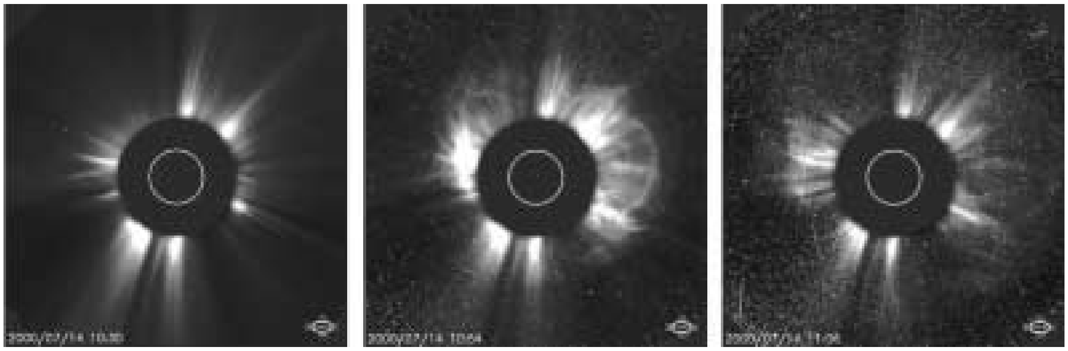

Figure 6. A full halo coronal mass ejection (CME) was recorded on July 14, 2000, by SOHO's LASCO/C2 coronagraph. The many speckles in the last two images are energetic particles bombarding SOHO's electronic detectors (LASCO/SOHO).

tion of its solar panel output (losing the equivalent of 1 year of normal degradation in 24 hours). The WIND satellite experienced 25% power loss on one of the power amplifiers. Power companies reported many disturbances in their systems and one step-up transformer was significantly damaged. There were also severe blackouts of radio communications as well as degraded navigational signals.

5. SUMMARY

SOHO has proved to be an important tool in monitoring eruptions from the Sun that causes effects on the Earth. By observing the Sun with sophisticated new instruments SOHO has furthermore obtained significant new information about CMEs, the source of the most severe disturbances in the Earth's environment. Before SOHO was operational the accuracy in forecasting geomagnetic disturbances was fairly poor. The improvement offered by SOHO is apparent as discussed above and its early-warning capabilities for space weather has been demonstrated. Accurate forecasting and alerting by NOAA's Space Environment Center throughout the sequence of solar eruptions have allowed users such as the electric power industry and satellite operators to be prepared for disturbances. This may have reduced the damages after many of the large solar eruptions that occurred in 2000 and 2001.

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