The Solar Mass Ejection Imager (SMEI)

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ABSTRACT

The Solar Mass Ejection Imager (SMEI) experiment is designed to detect and measure transient plasma features in the heliosphere, including coronal mass ejections (CMEs), shock waves, and structures such as streamers which corotate with the Sun. SMEI will provide measurements of the propagation of solar plasma clouds and high-speed streams which can be used to forecast their arrival at Earth from one to three days in advance. The white light photometers on the HELIOS spacecraft demonstrated that visible sunlight scattered from the free electrons of solar ejecta can be sensed in interplanetary space with an electronic camera baffled to remove stray background light. SMEI promises a hundred-fold improvement over the HELIOS data, making possible quantitative studies of mass ejections. SMEI measurements will help predict the rate

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of energy transfer into the Earth's magnetospheric system. By combining SMEI data with solar, interplanetary and terrestrial data from other space and ground-based instruments, it will be possible to establish quantitative relationships between solar drivers and terrestrial effects. SMEI consists of three cameras, each imaging a 60° × 3° field of view for a total image size of 180° × 3°. As the satellite orbits the earth, repeated images are used to build up a view of the entire heliosphere.

Keywords: solar mass ejection, solar corona, interplanetary disturbances

1 INTRODUCTION

1.1 Background

SMEI is an imaging instrument designed to view the entire sky for transient heliospheric disturbances ejected from the Sun and affecting the Earth's environment. SMEI is designed to detect, measure, track and forecast the arrival at Earth of coronal mass ejections (CMEs) and high speed, corotating solar wind streams emanating from coronal holes. Both phenomena consist of solar plasma with embedded magnetic fields traveling at several hundred to > 1000 $km\ s^{-1}$ and can cause geomagnetic disturbances on arrival at Earth. CMEs traveling in the heliosphere can attain higher speeds and contain greater plasma and magnetic field densities than the typically recurring high speed streams. CMEs often drive interplanetary shock waves which can produce the largest geomagnetic storms at the Earth. There is currently no reliable way to predict accurately the arrival of these disturbances at Earth or to study them in the inner heliosphere.

SMEI records the Thomson-scattered brightness from free electrons in the interplanetary medium (IPM). In principle it operates like a solar coronagraph, but its design heritage follows directly from the HELIOS zodiacal-light photometer experiment. There are several descriptions of the SMEI experiment and the requirements it must meet to measure CMEs.[9,13,14,15] Development of the SMEI instrument is now underway, with a goal of launching before the next solar maximum. This paper reviews the SMEI concept and its role in space weather forecasting.

1.2 Heritage of Instrument

The basic operating principle of SMEI is derived from broadband, white light coronagraphs which artificially occult the bright solar disk to allow viewing of the inner solar corona. Coronagraphs operate on the principle of imaging dense coronal structures by detection of photospheric light scattered from the free electrons (Thomson scattering). CMEs were first analyzed in detail using a coronagraph on the Skylab spacecraft. Coronagraphs are still the best way to view these huge ejections of material while they are still near the Sun.

The twin European HELIOS interplanetary probes were launched into solar orbits between 0.3 and 1 AU in the 1970s. One of the goals of that mission was the measurement of the zodiacal light, but when the data were reduced, it was noticed that time-dependent fluctuations were present. Further analysis showed that these fluctuations were due to scattering of sunlight from clouds of interplanetary electrons via the Thomson scattering process.[23] The clouds have been identified as having distinct solar origins: CMEs; corotating, dense elongated regions (streamers or stream interfaces); and interplanetary shock waves. HELIOS data have proven to be extremely useful in measuring and understanding the characteristics of such features in the inner heliosphere.[5,6,7,8,11,12,17,18,26,27,28] Both HELIOS probes have ceased operation.

Based on the success of HELIOS, we have designed an advanced system to yield high signal-to-noise observations of these phenomena with high spatial and temporal resolution, to study their propagation and evolution through the inner heliosphere. Progress, especially on developing new effective baffling systems, has been very encouraging and has led to feasibility studies of building and flying such an instrument on various spacecraft. Images from the LASCO coronagraphs on SoHO show that a 10^{-12} reduction in unwanted scattered background light has been achieved through baffling and precision optics.

Observations of interplanetary disturbances have also been attempted from the ground in the radio and radar regime. They cannot be observed from the ground in any other regime due to interference by the atmosphere. Observations of interplanetary scintillations (IPS) of signals from extragalactic radio sources show that a dense, turbulent region in the interplanetary medium produced by the passage of a high-speed cloud of plasma can be detected from the ground.[25] However, efforts have failed to produce reliable detection of most disturbances that strike the Earth, and the ability of this technique to distinguish between recurrent, corotating high speed streams and transient CMEs is very much in question. Also, the IPS method has relatively poor spatial and temporal (normally once per day) resolution for sensing disturbances. Such marginal detection and analytical capabilities are not adequate for monitoring, analyzing and forecasting geoeffective disturbances.[22] Radar has been used to measure flow speeds of CMEs out to about 5 solar radii.[24] Radar velocity measurements of CMEs near the Sun along with the continuous imaging of CMEs by SMEI would permit development of accurate propagation models.

2 DESCRIPTION OF PROPOSED INSTRUMENT

SMEI must image faint sources propagating against a bright background. This drives several instrumental requirements, which have been thoroughly documented.[9,14,15,18] Many of the requirements presented in these papers were developed at UCSD and are available from B. V. Jackson and A. Buffington in a series of technical memos. The following specifications were taken from these documents.

A photometric precision of $\sim 0.1\%$ is required to separate the relatively faint CMEs and other propagating disturbances from the greater brightnesses of the zodiacal dust cloud and stars. This zodiacal and stellar background must be subtracted from each sky image, thus requiring precise angular registration of the images (to about 10 millipixels or 0.002°). To reach these limits and to average out microscopic photometric variations on the CCD, individual star images must span more than several CCD pixels.[3,4] Other potential sources of background are scattered sunlight, moonlight and Earth glow. For these measurements, aperture baffling of the instrument and optics with low scattered-light levels are combined, to reduce stray light below one part in 10^{12}.

The SMEI instrument under development will meet these requirements. The main subsystems of the experiment will consist of three electronic camera/sensor systems and an electronics box with harness. Each of the three sensor systems will have a wide slit aperture, carefully baffled to minimize stray light, and optics feeding an electronic detector. Baffles that achieve a scattered light reduction of 10^7 to 10^8 have been designed and tested.[15] Optical systems reducing stray light by a factor of 10^5 to 10^6 have been designed at UCSD.[1,9] The baffle/optical systems will be rigidly mounted to a nadir-pointing spacecraft, whose orbital rotation permits a nearly complete survey of the sky once every 100 min. Each of the three sensors covers a different $3° \times 60°$ field of view (FOV) such that together they view a thin 180°-long slice of the hemisphere of the sky. The plane of the detector slits will be oriented perpendicular to the spacecraft velocity vector. Thus, during every complete orbit each detector sweeps out a complete circular swath in the sky and, together, the three detectors will cover 180° and will sweep over the entire sky. Each baffle system has a "Sun sensor" to activate a shutter mechanism while sunlight is within about 15° of the FOV. This protects the detectors from direct exposure to sunlight. The baffle design permits viewing beyond about 18° of the Sun.

The detector system is perhaps the most critical component of SMEI and requires a CCD with an extremely uniform spatial response. Several CCD systems are being analyzed to determine their suitability for SMEI. The choice of CCD will be based on the requirements for photon-counting capability, low readout noise, compatible thermal constraints and small inter-pixel and intra-pixel variations. The latter requirement is driven by both the photometric specification and the need to precisely locate background sources, especially stars.

3 INSTRUMENT SENSITIVITY

3.1 Signal Levels at 1 AU

At 1 AU the SMEI should be able to detect CMEs at large solar elongations. The expected CME brightnesses can be estimated from Thomson scattering theory. From observations with the HELIOS photometers we know how bright CMEs are above the background.[6,26] From Thomson scattering we can estimate the total contribution to the brightness signal of the ambient corona integrated along the line-of-sight.

TABLE 1 Signal Levels Expected at 1 AU

Feature	Elongation (degrees)	Signal Intensity (S10)	Signal Duration (days)
Bright CME	60	2	1.5
	90	1	1.5
Bright streamer	60	2	1
	90	1	1
Bright shock	90	0.5-1	$\leq$0.5
Major unidentified	60	3	2
in situ fluctuation	90	2	2
Comet shock	20	3-10	–

The Allen coronal model[2] decreases in density outward from the Sun approximately as r^{-2}. If the excess density in a plasma cloud like a CME does not decrease much faster than this rate, then the CME will retain its brightness excess above the ambient. We can estimate the expected contributions due to increased density from CMEs at 1 AU for given elongations. For instance, the rms transient signals at 60° and 90° elongations are of order S10 unit, or about the same magnitude as the ambient corona. An "S10 unit" is the equivalent flux of one tenth magnitude star per square deg. of sky. Table 1 gives the expected signal levels and durations at 1 AU for various transient heliospheric features.

Table 2 gives estimates of background-noise levels based on HELIOS photometric data taken at 0.85 ± 0.06 AU.[9] Col. 2 gives the durations over which changes in the electron density content are expected to occur (cf Table 1). Col. 3 gives the ambient medium brightness assuming a constant 5 electrons cm^{-3} at 1 AU Col. 4 estimates the variable brightness observed by HELIOS at these elongations, extrapolated to 1 AU. The final column gives a noise estimate expected for SMEI in each one deg. sky bin.

The Thomson-scattered coronal light must be detected in the presence of background diffuse light from many sources: scattered light from bright sources such as the Sun, Moon, or Earth; the zodiacal light; and the stars, either individually as bright point sources or collectively as a contribution to the diffuse sky brightness. The Sun is the equivalent of 5×10^{14} S10 units.

A fundamental limit of diffuse-light sensitivity is set by photoelectron counting statistics; this limit depends upon the optics and scanning configuration, spectral bandpass, and total detector efficiency. The total photon count N can be approximated[14], for a wavelength band between 0.4

TABLE 2 Background Noise Estimates

Elongation (deg.)	Duration (days)	Ambient Medium[a] (S10)	HELIOS S + N Estimate (S10)	SMEI (S10)
60	0.2-4	1.0	1.6	0.5-1
90	0.2-4	0.5	1.3	0.5-1

a Assumes an Allen[2] $1/r^2$ heliosphere

and 1 micron, by

$$\log N = 6.75 - 0.4 m_{\rm V} + \log A + \log(\Delta t), \quad (1)$$

where $m_{\rm V}$ is the equivalent stellar visual magnitude, A is the aperture area in cm^2, and Δt the integration time in seconds. Background sky brightness varies roughly over a range 200-6000 S10 units between the darkest sky and the ecliptic plane at solar elongations $\leq 20°$. Taking $A = 2\ cm^2$ for a one by two cm rectangular aperture as in the design for the proposed SMEI[15] and $\Delta t = 4s$, then equation (1) yields 4500 photons available for a brightness of one S10 unit ($m_V = 10$). Bandpass, detector efficiency, and other instrumental factors further decrease the number of photoelectrons actually detected, typically by a factor of four. In the darkest sky, then, the counting statistics noise contribution from a single exposure is about 0.5 S10 units for each one square degree sky bin. Total noise, of course, includes also contributions from subpixel-response-gradient errors on the CCD, flat-fielding errors, registration errors in assembling a sky map from the individual 4 sec. exposures through an orbit, and in removing the stellar background.

For a slowly rotating low-Earth orbiter having many signal photons in each pixel, a CCD detector integrates the incoming photons. Individual 4 sec. exposures combined over an orbit yield a nearly complete sky map. The proposed SMEI instrument has been developed around the possibility of using a Thomson TH7863 CCD chip. Current design efforts suggest that it is feasible to use an even larger format CCD detector, provided it has a similar low pixel to pixel and subpixel variation response. The ultimate angular resolution is determined by the smallest sky resolution element in which heliospheric signals are detectable above the far brighter zodiacal light background.

3.2 Background Sources

The scattered visible light from transients must be detected in the presence of background light from many sources, the brightest of which from Earth orbit are Sun, Earth, Moon, zodiacal light, and stars. From a DMSP-type orbit, the brightest background signals are respectively Sun, Earth, and Moon.[10] From low Earth orbit the Earth can be nearly as bright as the Sun and will cover nearly 180° of sky. We have designed the SMEI to view only the spacecraft Zenith-facing half of the sky so as to eliminate as much of the Earth glow as possible. Even so, we will probably not be able to acquire useful data within about 5°-10 ° of the limb of the Earth.

The zodiacal light approximately follows the plane of the ecliptic. By itself it is far brighter near the Sun than any transient signals we wish to detect. Fortunately, from the HELIOS results we know that zodiacal light intensity is unchanging over periods of years and decreases smoothly from near the Sun to large elongations.[21] This background source can be removed by knowledge of instrument pointing together with either a spatial model of the zodiacal light [26], or an average of SMEI data over many orbits.

Starlight contributes to the background either individually as discrete point sources or together as a contribution to the diffuse sky brightness. The total star brightness averaged over the whole sky is about 120 S10 units, and on average there is one 8th magnitude star in every square deg.[2] Portions of the sky contain the Milky Way and other bright diffuse sources such as M31, Magellanic Clouds, and star clusters. Most of these diffuse sources can be removed along with individual stars, by constructing and subtracting a sky map from SMEI data, averaging over many orbits. As with HELIOS, locations of the very brightest stars, and the worst variable stars, will be known so their noise contribution can be minimized in the sky map on each orbit. We have included a sufficient data transmission rate to permit a satisfactory integration of the data acquired on each orbit into a sky map, and an appropriate removal of the stellar background . We anticipate saving and storing these stellar data not only to enable the background subtraction described above, but also since they are a useful data set for those wishing to study the brightnesses of individual stars or their long-term variability.

We have found that the molecular glow from the Earth's upper atmosphere should not be a factor at the height proposed for the SMEI mission.[15] However, outgassing, leakage, venting, and thruster firings, and particulate contamination can be sources of unwanted visible light for the experiment. These sources should not be a major problem so long as they are carefully controlled, because such contamination should decrease with time in orbit and we will view only a small area at any one time.

3.3 Stray Light Suppression

As with any coronagraph system, stray light must be eliminated as much as possible so that the faint coronal light can be detected. For SMEI, even with an appropriate baffle system, stray light falling on the optics must be minimized by occulting or shuttering the optics within about 15° of the Sun and keeping portions of the spacecraft, such as antennas, which scatter light from the Sun, Earth or other experiments, as far from the field of view as possible.

For low levels of scattered light, it is only necessary to ask that stray light not vary from one orbit to another with the same or higher frequency of the signal from the mass ejections and other heliospheric structures we want to detect. If low-level stray light in a given direction relative to the signal remains invariant, it can be removed as easily as the zodiacal light signal.

The Sun is as bright as 5×10^{14} tenth magnitude stars. The signal from brighter mass ejections at 22° elongation from the Sun can be over 200 times brighter than the background level there. Thus, to detect CMEs at this distance, the variable stray light signal must be held at or below the level of $\sim$1 part in 2.5×10^{12}. To observe CMEs at 90° elongation, the stray light level must be held to one part in 10^{14} or better. To be safe, we plan to design the instrument so that we are certain that the variable component of stray light reduction is an order of magnitude less than the signal at 22°, about two parts in 10^{13}. The HELIOS photometers were good to at least one part in 10^{15}, although the actual amount of stray light rejection in space was never measured. As noted in Section 2, a clean optical system that can reject stray light at the level of at least 10^{-5} or 10^{-6} has been designed. Further reduction requires baffling of the optics.

The total stray light reduction at the 1 x 2 cm aperture at the base of the baffle hole governs how much light reaches the optics from the baffle. The baffle parts scattering light into the optics are the vane edges and the surfaces viewed through this aperture by the optics. The goal is a reduction of the parts of the baffles viewed through the aperture, to just the vanes and not the side baffle walls. Vane edges should be constructed so that their images lie outside of the field of view of the optics as much as possible. When this is accomplished, the detector views only empty space through the baffle's aperture. Then, the only stray light reaching the image plane has been scattered by the baffle through the hole and then scattered again by the optics to the detector. This process is multiplicative and has been discussed.[10,20]

A three-stage baffle was constructed at the University of California - San Diego (UCSD) and tested at Johns Hopkins University (JHU). The stray light rejection of the initial design was calculated using formulae from,[20] and simulated by using a Breault baffle computer code at JHU. Both approaches showed that the stray light rejection should be greater than 10^7 when the Sun is 22° off-axis.

Initial tests of the total stray light rejection with the actual test baffle uncoated and coated by the Martin Black process have been performed at JHU. There is reasonable agreement between the actual test and the simulations of the total baffle light rejection. Recently, the same baffle was also tested by S. Koutchmy in France. These tests again showed that the baffle eliminated stray light to the level of at most one part in 10^7. In fact, the test baffle blackened with Martin Black has performed better than expected. This baffle was made relatively crudely with more surfaces and thicker edges than were needed and only the four critical vanes. A flight-quality baffle, for example with inner vanes to further attenuate scattering from inside the baffle, should perform considerably better than the one tested, probably to the level of one part in 10^8. We believe these tests demonstrate that even the existing baffle design is capable of the performance required for the SMEI instrument design.

4 SMEI SCIENCE AND FORECASTING OBJECTIVES

SMEI is a prototype for a monitoring system which will improve geomagnetic-disturbance forecasting by identifying solar-generated disturbances and predicting their arrival time at Earth. As demonstrated with HELIOS photometer data, SMEI will be able to track CMEs, shock waves, and structures corotating with the Sun, such as streamers. Because of its high sensitivity and good spatial and temporal resolution on heliospheric scales, SMEI will measure characteristic parameters of CMEs and shocks in the IPM. These characteristics are of fundamental interest because of the role they play in transferring mass and energy from the Sun through the IPM to the Earth where they drive geomagnetic storms. Important parameters of CMEs that SMEI will be able to determine include the mass, pressure, energy, momentum flux, speed, pressure, size scale and shape, and frequency of occurrence.

SMEI will provide measurements vital for understanding the coupling and energy transfer from disturbances in the solar wind to the magnetosphere. Thus, it will provide insight into the causes and development of geomagnetic storms and other transient phenomena which can affect both civilian and military spacecraft and ground systems. When combined with in situ solar wind measurements from an upstream monitor such as WIND, these data will permit measurements of the components of CMEs likely to be most important for magnetospheric coupling. These components include the momentum flux, total pressure (gas plus magnetic), interplanetary magnetic field strength and level of turbulence, and the temporal characteristics of these flows. SMEI alone will provide up to 3 days warning of the arrival of a CME aimed toward the Earth. A combined system consisting of an Earth-orbiting SMEI and an upstream solar wind monitor can provide unprecedented detailed measurements and prediction of an impending storm at the Earth.

SMEI can detect all major mass ejections propagating through near-Earth space. There are more small mass ejections than large ones down to some limit and SMEI can detect them to a threshold similar to the smallest masses observed by the SOLWIND coronagraph, or about $3 \times 10^{14} gm.$[16] Earth-orbiting coronagraphs such as SOLWIND best observe CMEs over the limb of the Sun and miss or only partially detect those events originating from further onto the solar disk. Although SMEI also must avoid viewing close to the solar disk, it will more easily be able to detect an Earth-directed mass ejection as it approaches the Earth. Unlike a coronagraph, SMEI is designed to work best at large elongation angles from the Sun, and views areas of the sky that have a much smaller range of intensities. Therefore, as mass ejections move out from the Sun, they can be more easily distinguished relative to the background.

There are other heliospheric features that SMEI will measure. It can separate those events which corotate with the Sun from those, like CMEs and shocks, that move nearly radially outward. Corotating structures include sector boundaries and streamers which extend from the Sun, where they form the locus of the source region of the heliospheric current sheet. We can determine the mass-flow and speed within these structures. With appropriate modeling of these interaction regions viewed to the east of the Sun-Earth line by SMEI, we can forecast the arrival at Earth of these denser features of the current sheet, which also can drive geomagnetic disturbances. How mass ejections interact with and or are part of these corotating regions should also be apparent in SMEI data.

Finally, SMEI will detect other features of interest to researchers in space physics and astronomy. The interplanetary sky background is composed primarily of three components: the zodiacal light (the dust component), Thomson-scattered coronal light, and starlight. In terms of its primary mission, these are noise sources to SMEI which can swamp the faint transient plasma features it is trying to detect. However, the data gathered by SMEI on these sources are of fundamental interest in their own right. As with HELIOS, SMEI will make accurate measurements of the zodiacal dust cloud. Taking SMEI sky bins of 1 sq. deg., fluxes of individual stars will dominate the brightness of many such bins. To remove this stellar contribution, the orientation of each SMEI CCD frame upon the sky must be determined to an accuracy of 0.1°. Individual stars whose brightness has varied will be recognizable through their residue once the background is subtracted. Thus, SMEI will provide a unique long-term data base of discrete variable astronomical phenomena, including variable stars and galaxies, novae and supernovae. Such data are of great interest to astronomers. Comets and their bow shocks can also be detected by SMEI and their plasma and dust components studied. SMEI will also be able to detect near-Earth asteroids.[18]

5 DATA REDUCTION, ANALYSIS AND DISTRIBUTION

The present operational concept is to digitize data continuously from the three detectors, then downlink the data for reduction and all-sky map production on the ground. The initial data set from SMEI will consist of apparent brightness measurements from the cameras, over a 3° × 180° section of sky. These data are then mapped to a position in the sky to an accuracy of 0.1°. The brightness in each sky bin is corrected through a calibration procedure involving the stars present in the FOV.

Initially, data reduction from SMEI will consist of obtaining a sky map of brightnesses at approximately 1° resolution. This sky map will have the stars and long-term background brightness variations removed. Residual brightness, when differenced over time, gives a record of the interplanetary Thomson-scattered flux present, that persists at least as long as one spacecraft orbital period, about 100 minutes. In calibrated form these maps will be available on a regular basis to those wishing to use them. Original, uncalibrated sky-bin to sky-bin brightnesses, suitably tagged by time and position, will also be available on data tapes. These brightness data will be useful for other forms of analyses involving the sky maps, such as for determining the brightness and variations of stellar or galactic sources.

For forecast operations, we need to reduce and analyze the data in as near real time as possible. This will involve mapping brightnesses to a given sky position, removal of stars, differencing from previous images or a longer-term average map, and presentation of the image in convenient formats, for example, as a contoured printout map or on a monitor screen once per orbit.

We encourage wide dissemination of the appropriately reduced data from the instrument through normal channels. We are prepared to participate with other researchers in the distribution, analysis, and publication of the results using these data. Toward this end, at the appropriate time we will make the data available to the community through the NSSDC in compatible formats.

6 SUMMARY

SMEI represents a unique opportunity to causally link events on the Sun with terrestrial disturbances. Using SMEI in conjunction with other space-based and ground-based instruments, it will be possible to develop a three dimensional view of the portion of the heliosphere traversed by the Earth. SMEI provides a critical, missing element needed for accurate space weather predictions.

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