

Considerations of a Solar Mass Ejection Imager in a Low-Earth Orbit

B.V. Jackson ¹, D.F. Webb ², R.C. Altrrock ³ and R. Gold ⁴

¹Center for Astrophysics and Space Sciences,
University of California at San Diego, La Jolla, CA 92093, USA

²Institute for Space Research, Boston College,
Newton Center, MA 02159 USA

³Phillips Laboratory/PHS, National Solar Observatory/Sacramento Peak,
NOAO, Sunspot, NM 88349 USA

⁴Johns Hopkins University, Applied Physics Laboratory,
Johns Hopkins Road, Laurel MD 20707 USA

Abstract: We are designing an imager capable of observing the Thomson scattering signal from transient, diffuse features in the heliosphere[1]. The imager is expected to trace these features, which include coronal mass ejections, co-rotating structures and shock waves, to elongations greater than 90° from the Sun from a spacecraft in an ≈ 800 km Earth orbit. The predecessor of this instrument was the zodiacal-light photometer experiment on the HELIOS spacecraft which demonstrated the capability of remotely imaging transient heliospheric structures [2]. The HELIOS photometers have shown it possible to image mass ejections, co-rotating structures and the density enhancements behind shock waves. The second-generation imager we are designing, would have far higher spatial resolution enabling us to make a more complete description of these features from the Sun to 1 AU. In addition, an imager at Earth could allow up to three days warning of the arrival of a solar mass ejection.

1 Signal Levels and Number of Photons

Because the signal levels present from the features to be measured are small compared to the solar brightness, the Solar Mass Ejection Imager (SMEI) must be designed carefully to eliminate unwanted stray light and other sources of unwanted brightness. Table 1 estimates the signal levels expected for various phenomena at 1 AU. The brightnesses of coronal mass ejections (CMEs) and streamers were derived from features traced outward from the Naval Research Laboratory (NRL) SOLWIND coronagraph to the HELIOS photometer field. For CME brightnesses the assumption is that the CME in question moves outward from ~ 0.3 to 1 AU at constant velocity and without dispersion. Shock brightnesses were estimated from the *in situ* plasma density enhancements behind shocks observed from the HELIOS spacecraft [3] and assumed to be viewed at 60° and

90° from the Sun-spacecraft line. A more complete description of these calculations is given in [4]. Signal levels in the following table are given in terms of "S10 units" which are equivalent to the flux of one tenth magnitude star per square degree.

TABLE 1 Signal Levels Expected at 1 AU

Feature	Elongation (degrees)	Signal Intensity (S10)	Signal Duration (days)
Bright CME	60	3	1.5
	90	2	1.5
Bright streamer	60	2	1
	90	1	1
Bright shock	90	1-2	0.5
Major unidentified <u>in-situ</u> fluctuation	60	3	2
	90	2	2
Comet shock	20	3-10	0.1

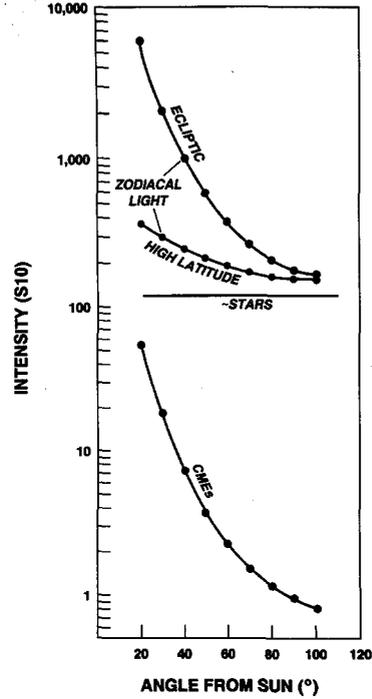


Fig. 1. The brightness of various signals that will be observed by the imager versus elongation at 1 AU.

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 Gegenschein; and the stars, either individually as bright point sources or collectively as a contribution to the diffuse sky brightness. Figure 1 is a plot of estimates of the brightness contributions from these signals to be observed from an Earth-orbiting SMEI at different angular distances (elongations) from the Sun.

The ultimate limit of diffuse-light sensitivity should be set by photon counting statistics; this limit depends upon the optics and scanning configuration, spectral bandpass, and total detector efficiency. The total detected photon count N can be approximated as in [5] by

$$\log N = 6.65 - 0.4m_v + 2\log D + \log(\Delta t) \quad (1)$$

where m_v is the equivalent stellar visual magnitude, D the aperture (diameter) in cm, and Δt the integration time in seconds. The background sky brightness varies roughly over the range 100-6000 S10 units between the darkest sky and the ecliptic plane at solar elongations $\geq 20^\circ$. If we presume that $D = 1.43$ cm (the size of a one-half inch square

aperture as in a design for the WIND spacecraft [6]) and $\Delta t = 1$ s, then from equation (1) we obtain 920 photons available per given 1° square degree brightness of 1.0 S10 unit ($m_V = 10$). Detector bandpasses and instrument quantum efficiencies further limit the number of photons which can be detected.

In general, the signal-to-noise ratio of the instrument will be limited by integration times, viewed area of sky, and the size of the aperture. If the spacecraft gathers only a tiny fraction of the necessary counts to detect a signal in the darker areas of sky on a single pass, then we conclude that we must count photons with our detectors. The WIND imager design intended to use photon-counting image intensifiers to do this. The limit of the signal to noise for a stable photon-counting instrument is purely statistical; how many detected photons are necessary to measure the signal above the far brighter zodiacal light background. If longer times are spent on any given section of sky, such as with a slowly rotating low-Earth orbiter, then many signal photons can be present in each pixel. It then becomes possible to use a CCD detector that integrates the incoming photons to build up a sufficient signal above a statistical noise readout level as well as detect the signal above the zodiacal-light background.

2 The Preferred Spacecraft and Orbital Configuration



Fig. 2. Orbit of a typical Sun-synchronous satellite (9am – 9pm). The spacecraft orbit is circular at ≈ 800 km above the surface of the Earth and maintains its relation with respect to the Sun-Earth line.

Although the Solar Mass Ejection Imager instrument could be designed for successful operation on nearly any spacecraft, one of the simplest and most effective configurations would be on a near-Earth orbiting zenith-nadir pointing spacecraft. From such an orbit, the brightest objects to be eliminated from the instrument view are 1) the Sun, 2) the Earth, and 3) the Moon. From low-Earth orbit the Earth can be nearly as bright as the Sun and covers nearly 180° of the sky. Figure 2 gives a schematic of the SMEI

instrumentation in a typical polar Sun-synchronous orbit. Although the most simple orbit for the imager would be a terminator orbit (a 6am – 6pm one), we depict a 9am – 9pm orbit, more typical of DMSP-type orbits. Figure 3 gives one layout of the proposed instrumentation for the mass ejection imager front end to be operated in an ≈ 800 km orbit.

SMEI BLOCK DIAGRAM

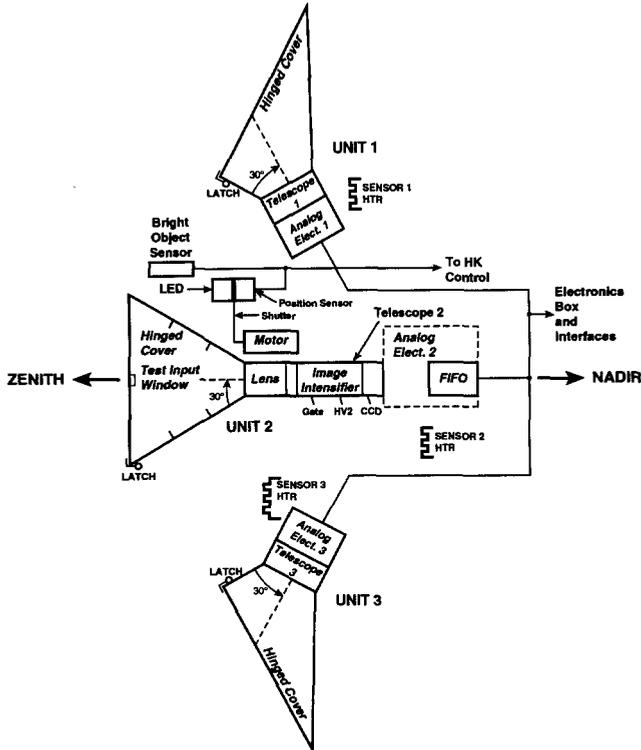


Fig. 3. Schematic of the proposed spacecraft Solar Mass Ejection Imager front end; baffles, optics and electronics.

3 Background Signals from Zodiacal Light, Stars and Other Sources of Low-Level Light

Low-level sources of light from the cosmos such as zodiacal light and the Milky Way are generally brighter than the variable Thomson scattering signal we wish to detect. We must be able to subtract these signals from the background, or at least keep them constant from orbit to orbit. The zodiacal light appears to be unchanging and smoothly varying from the HELIOS deep-space orbit to levels near the lower levels of brightness

to be viewed by the imager. By determining the pointing direction for each pixel it will be possible to remove this unwanted source of background light either by means of a lookup table, a mathematical algorithm, or by assuming an unchanged value from previous orbits. Stars can be dealt with in the same way. However, because stars are point sources of light, the positions of each pixel boundary will necessarily need to be accurately known (within $\sim 0.1^\circ$) to eliminate their brightnesses from the record.

3.1 Zodiacal Light and the Gegenschein

The Zodiacal Light brightness approximately follows the plane of the ecliptic (Figure 1). In principle, this source of background light should present no problem for the imager as long as its signal, which is far brighter than the Thomson scattering signal, does not statistically overwhelm the faint signal we wish to detect, or saturate the imager.

We are extremely fortunate that the HELIOS spacecraft has provided a working model for the Solar Mass Ejection Imager. A hypothetical small percent variation in the zodiacal cloud at the spatial or temporal scales of features we wish to detect might mask their signal. This is not the case for the HELIOS spacecraft to approximately 1 S10 unit. We presume that at the spatial and temporal scales of heliospheric brightness changes the zodiacal cloud remains smooth and temporally non-varying even below this level. Gegenschein light, thought to be due to backscatter from the zodiacal cloud, is present in the direction opposite the Sun and should not interfere with a sunward-looking imager.

3.2 Starlight

Starlight in general is present as discrete sources of light. However, the brightnesses of stars are comparable to 119 S10 units in all directions [7] (Figure 1). There is approximately one 8th magnitude star in every square degree. Certain portions of the sky are brighter than others and may present certain problems for the imager. These include the Milky Way and other large diffuse objects such as M31 and the large and small Magellanic Clouds. Some imager pixels may contain a bright or variable star that overwhelms the Thomson scattering signal at that solar elongation. These "bad" pixels will need to be identified and removed from the record on each orbit. If the option is available to transmit all the data to the ground, as is presumed possible from most low-Earth orbiters, then the on-board spacecraft electronics becomes simpler to construct than for spacecraft in high orbits. The necessary algorithms, if needed, can be developed and adjusted once the data are on the ground.

3.3 Auroral Light and the Geocorona

Light from aurora on rare occasions has been reported as high as 1000 km above the surface of the Earth [8]. Auroral light intensities vary greatly with geomagnetic latitude and solar activity, so that at times these emissions could be visible from the mass ejection imager. To determine the extent to which auroral intensities could be present, we note that measurements of the brightest aurorae from the ground at the zenith can be $\sim 4 \times 10^3$ rayleighs for the H_β and similar wavelength lines at geomagnetic latitudes of $\sim 65^\circ$ [9]. One S10 unit equals $0.0036 \text{ rayleighs } \text{\AA}^{-1}$ [7]. For the solar mass ejection

imager which is sensitive over $\sim 3000\text{\AA}$, 1 S10 unit $\approx 0.0036 \times 3000 = 10.8$ R. Thus, one auroral line within the wavelength range of the instrument could be as bright as 370 S10 units, and total brightnesses from the many spectral lines of brightest aurorae of several thousand S10 units when observed from the ground. However, we expect this light to be negligible above 800 km. This is because to first order the brightness of auroral light will decrease with molecular density. The integrated fraction of molecules above 800 km relative to that over a 20 km column from 120 to 140 km (the height of normal auroral formation) is $\sim 10^{-4}$ [9]. Following this argument, to be brighter than 1 S10 unit above 800 km, an aurora would have to be as bright as 10^4 S10 units when observed from the ground. Typical brightnesses of the brightest aurorae above 800 km should thus seldom become greater than 1 S10 unit. If such aurorae exist over time intervals short relative to successive orbital passes of the spacecraft, they could interfere with the operation of the mass ejection imager, but only in the darkest parts of the heliosphere at very specific positions relative to Earth's geomagnetic equator.

The geocorona has been detected at various wavelengths, but especially in hydrogen Lyman radiation as a glow in the direction towards the Sun [10]. Typical brightnesses of the geocorona in Balmer α emission (6563\AA) are known to be as great as 20 rayleighs or as bright as ~ 2.0 S10 units. The brightness fall-off with height above the surface of the Earth is unlike aurorae in that the geocorona is brightest at heights of $>10^3$ km. This emission, if included in the imager bandpass, could contribute a background comparable to the signal photons observed by the solar mass ejection imager at 90° elongation and greater. However, the geocorona to first order remains approximately constant relative to solar elongation and is brightest towards and to the west of the Sun [11]. The relative invariability of the geocorona at a given solar elongation on the time scales of mass ejections implies that this source of brightness should pose no problem for an Earth-based imager, especially if Balmer α is not included significantly in the instrument bandpass.

3.4 Ram Glow and Other Spacecraft-Produced Illumination

Ram Glow is a low-level light source which forms a comet-like halo and tail near a spacecraft in low-Earth orbit. The glow is caused by many different sources [12] including: 1) a concentration of the ambient gasses which peak in the ram direction, 2) outgassing from the spacecraft, 3) leakage, 4) venting and 5) thruster firings. In visible light from low-Earth orbit some of the constituent molecular glows are significantly above the ~ 100 S10 unit zodiacal light background at 90° elongation. The amounts of this glow vary from spacecraft to spacecraft. Extrapolating from Shuttle measurements, at heights below 400 km the glow rivals or can be greater than the background zodiacal light. If the source of this light were to vary, it could cause significant problems for the imager at these heights. With the possible exception of sources on the vehicle such as emissions from other experiments, these sources of light extrapolate to well below the level that could cause a detrimental effect on the imager at the 800 km orbit.

4 Conclusions

We envision a imager capable of tracing solar mass ejections and other heliospheric features from near the Sun out to the orbit of the Earth. Such instrumentation would have the capability of forecasting the arrival at Earth of these features in real time. Results from the HELIOS spacecraft have demonstrated that such instrumentation is feasible, and they also give limits on the signal to noise required for such instrumentation. Although several instrument designs are possible depending on the type of spacecraft and its orbit, most of our preliminary designs depend upon the rotation of the spacecraft to scan the sky. Such an instrument will compile an image in a plane parallel to the spacecraft rotation axis. In the case of an instrument in Earth orbit on a nadir-pointing vehicle, this rotation is provided by the orbital motion.

References

1. B. Jackson, R. Gold and R. Altrock: *Adv. Space Res.*, **11**, 377, (1991)
2. B.V. Jackson: Yosemite 1988 Conference on Outstanding Problems in Solar System Plasma Physics: Theory and Instrumentation, Yosemite National Park, California, February 2-5, 1988, (1989)
3. B.V. Jackson: *Adv. Space Res.*, **6**, 307, (1986)
4. B.V. Jackson: AFGL-TR-88-0195, (1988)
5. B.V. Jackson, H.S. Hudson, J.D. Nichols and R.E. Gold: Yosemite 1988 Conference on Outstanding Problems in Solar System Plasma Physics: Theory and Instrumentation, Yosemite National Park, California, February 2-5, 1988, (1989)
6. B.V. Jackson, H.D. Zink and R.E. Gold: JHU/APL SDO 8416, Report to the USAF and NASA, (1987)
7. C.W. Allen: *Astrophysical Quantities* (Athlone, London, England) (1964)
8. George Carruthers: private communication (1991)
9. A.V. Jones: *Aurora*, ed. by B.M. McCormac (Reidel, Dordrecht, Holland) (1974)
10. R.R. Meier and P. Mange: *Planet. Space Sci.*, **21**, 309, (1973)
11. D.E. Anderson, Jr., R.R.Meier, R.R. Hodges, Jr. and B.A. Tinsley: *J. Geophys. Res.* **92**, 7619, (1987)
12. D.G. Torr: NASA Conference Publication **3002**, (1988)