Adv. Space Res. Vol. 11, No. 1, pp. (1)377–(1)381, 1991
Printed in Great Britain.

0273–1177/91 $0.00 + .50

THE SOLAR MASS EJECTION IMAGER

B. Jackson,* R. Gold** and R. Altrock***

**Center for Astrophysics and Space Sciences, University of California at San Diego, La Jolla, CA 92093, U.S.A.*
***Johns Hopkins University, Applied Physics Laboratory, Johns Hopkins Road, Laurel, MD 20707, U.S.A.*
****Geophysics Laboratory (AFSC), National Solar Observatory/Sacramento Peak, National Optical Astronomy Observatories†, Sunspot, NM 88349, U.S.A.*

ABSTRACT

We have designed an imager capable of observing the Thomson scattering signal from transient, diffuse features in the heliosphere from a spacecraft situated near 1 AU. 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. The instrumentation ultimately may be regarded as a successor to the heliospheric imaging cabability shown possible by the zodiacal-light photometers of the HELIOS spacecraft. The second-generation instrument we have designed, would make far more effective use of in-situ solar wind data from spacecraft in the vicinity of the imager by extending these observations to the structures surrounding it. In addition, an imager at Earth could allow up to three days warning of the arrival of a mass ejection from the Sun.

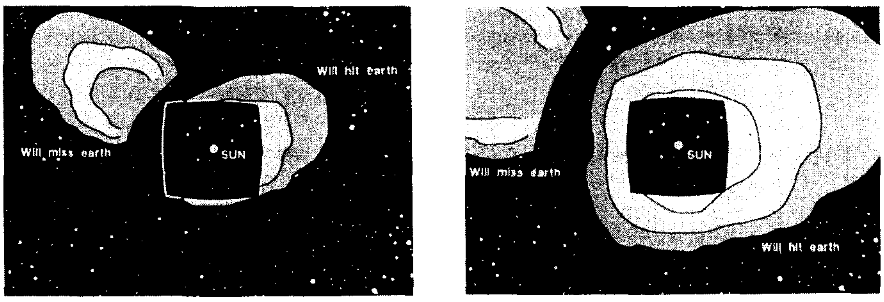

Fig. 1. Artists' depiction of typical mass ejections monitored by the Solar Mass Ejection Imager. The mass ejection centered on the Sun arises from it at the beginning of Day 1 and expands outward. This mass ejection is depicted after it has moved outward from the Sun after two and after three days of travel towards the Earth. The schematic view depicts an area of sky 120° × 170° in size. The event is constructed so that it will reach Earth after four days travel.

INTRODUCTION

For the Solar Mass Ejection Imager, different orbits dictate how bright the Moon and Sun are in each field of view. In addition, the various spacecraft pose different problems for mounting an imager that is intended to look at the whole sky, since bright parts of the spacecraft may reflect differing amounts of light at different locations in the spacecraft orbit. In the following sections we outine what has been done to date to define the spacecraft instrument. We would like the mass ejection imager to produce high-resolution images similar to those depicted in Figure 1. Originally, such an instrument was proposed (/1/) for the ISTP WIND spacecraft and a NASA interface control document produced for that design (/2/). Much of the previous work on that design carries over to ideas about current instrumentation.

†Operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation. Partial support for NSO is provided by the USAF under a Memorandum of Understanding with the NSF.

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 instrumentation must be designed carefully to eliminate unwanted stray light. 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 (/3/). For CMEs the assumption is that the CME in question moves outward to elongations (angular distances from the Sun) of 60° and 90° at constant velocity and without dispersion. Shock brightnesses were estimated from the in-situ plasma density enhancements behind shocks observed from the HELIOS spacecraft (/4/), and assumed to be viewed at 60° and 90° from the Sun-spacecraft line. A more complete description of the current HELIOS data analysis is given in /5/. Signal levels in the following tables are given in terms of "S10 unit" equivalent to the flux of one tenth magnitude star per square degree.

TABLE 1 Signal Levels Expected at 1 AU

Feature	Elongation degrees	Signal 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	60	3	2
in-situ fluctuation	90	2	2
Comet shock	20	3-10	0.1

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. 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 /1/ by

$$\log N = 6.65 - 0.4 m_V + 2 \log D + \log(\Delta t), \tag{1}$$

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 $\geq 20°$. If we presume that $D = 1.433$ cm (the size of a one-half inch square aperture as in the WIND spacecraft design) and $\Delta t = 1$ s, then from equation (1) we obtain 917 photons available per given 1° square pixel brightness of 1.0 S10 unit ($m_V = 10$). Spectral filters and instrument quantum efficiencies further limit the number of photons which can be detected.

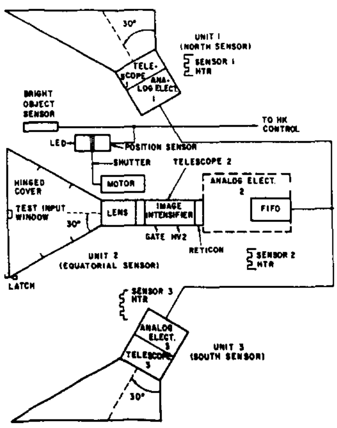

Fig. 2. Schematic of the proposed WIND spacecraft Solar Mass Ejection Imager front end; baffles, optics and electronics.

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. The number of detected photons from a typical heliospheric feature (CME) at 90° elongation (see Table 1 for feature brightness) can be small in one second. 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 (Figure 2) intended to use 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. If longer times are spent on any given section of sky, then it becomes possible to use some detector other than one which counts photons (such as a CCD). Such a device can integrate the incoming photons to build up a sufficient signal above a statistical noise readout level as well as obtain a sufficient number of photons to detect the signal above the constant zodiacal-light background.

THE MOST LIKELY CANDIDATE SPACECRAFT/ORBIT

Although we expect that with care the Solar Mass Ejection Imager instrumentation could be designed for nearly any spacecraft, one of the most easily built types of instrumentation could be placed on a near-Earth orbiting zenith-nadir pointing spacecraft. One such spacecraft is the Air Force DMSP or the NOAA TIROS. From the DMSP orbit, the brightest signals to be baffled out of the imager will be 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 cover nearly 180° of the sky. Figure 3 gives a schematic of the SMEI instrumentation in one typical DMSP orbit.

Fig. 3. Orbit of a typical DMSP satellite (9am – 9pm). The spacecraft orbit is circular at 800km above the surface of the Earth and maintains its relation with respect to the Sun-Earth line (Sun-synchronous). DMSP orbits vary from 6am – 6pm Sun-synchronous to 12noon – 12midnight Sun-synchronous.

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 Solar Mass Ejection 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 0.1°) for stellar identification and removal from the record.

Zodiacal Light and the Gegenschein

The brightness of the Zodiacal Light approximately follows the plane of the ecliptic. In principal 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 either spatially or temporally at the scales of the heliospheric 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 the zodiacal cloud remains smooth and temporally non-varying even below this level. We note that others (/6/) have described 20 S10 unit small-scale variations of the Gegenschein from ground-based observations. These variations are NOT observed by HELIOS, and this leads us to conclude that these variations are caused by clouds or air mass variations in Earth's atmosphere. In any case, 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.

Starlight

Starlight in general is present as discrete sources of light. However, in general the brightnesses of stars are comparable to 119 S10 units everywhere. 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 portions of the sky 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.

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 (/7/) 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 thruster firings, these sources of light extrapolate to well below the level that could cause a detrimental effect on the imager at the 800 km DMSP orbit.

BAFFLE DESIGNS - STRAY LIGHT SUPRESSION

For any spacecraft, stray light suppression must be provided from sunlight, earthshine and moonlight in the design of the imager baffle system. Stray light falling directly on the lens from some of the brighter planets and stars may also adversly affect small portions of the image. In addition, care must be taken so that portions of the spacecraft which scatter sunlight or earthshine are as far as possible from the field of view. Two parts of the imager must be built carefully in order to minimize stray light. These parts are the baffle system (that lowers the amount of stray light which falls on the lens), and the lens itself. Together these imager parts attenuate unwanted light in a multiplicative fashion. We concentrate here on the design of the baffle system and the suppression of stray light by the baffle system.

There are several basic designs for Solar Mass Ejection Imager baffle systems that can be built for existing spacecraft. Because the sky is scanned in one direction by the spacecraft motion for a spinning spacecraft, these baffle systems need to cover a large angular portion of the sky in only in one dimension and are thus slit-type baffle systems. Figure 4 is a photograph of a slit-type test baffle built for the Sun-crossing sensor proposed for the spinning WIND spacecraft. The WIND spacecraft is a spacecraft rotating with its axis perpendicular to the

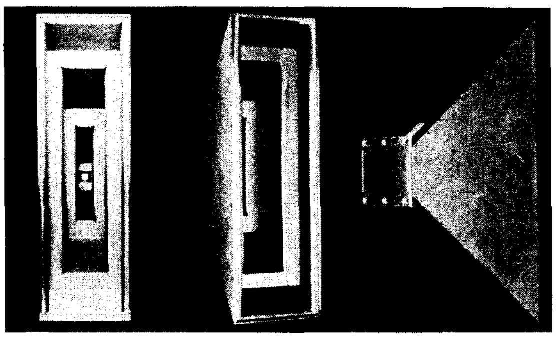

Fig. 4. Photograph of the test baffle constructed at the University of California at San Diego for the proposed WIND imager.

ecliptic plane. This basic slit configuration allows a scan of the whole sky around the spacecraft in a swath that is 60° in width. The test baffle, when coated black internally, performed as specified to reduce stray light to one part in 10^{-7} to within 22° of the Sun and reduced stray light even further at greater angular distances. DMSP and the NOAA TIROS zenith-nadir pointing spacecraft are effectively spinning platforms for the Solar Mass Ejection Imager. However, in this type of instrument, the image must be compiled over the whole of one orbital period – namely 90 minutes. In this instance to be most effective the slit should be oriented in the plane perpendicular to the spacecraft orbital motion.

SPACECRAFT RESOURCE ESTIMATES

We expect differing versions of the Solar Mass Ejection Imager to use differing amounts of spacecraft resources depending upon the type of orbit for which the instrument is designed. Large data rates are generally not available monitored on a real-time basis from spacecraft at the L_1 point. Thus, a great deal of on-board data processing is required for such instrumentation. Larger data rates in real time are possible in lower orbits, but the simpler and smaller computer system requirements for such systems are largely offset by the more complex instrumentation required to deal with stray light from the Earth. Higher resolution instrumentation (more than one pixel per square degree) or more frequent images (more than one per 90 minutes) will require correspondingly more spacecraft resources. Table 3 contains spacecraft resource estimates for the Solar Mass Ejection Imager.

TABLE 3 Spacecraft Resource Estimates

Platform	Bit Rate	Power (watts)	Mass (kg)
800 km Constant Sun $\angle$ Orbit	1–10 kbs	12	15
Geosync., 3–axis stabilized	0.5–1.5 kbs	12	15
L_1 Spinning axis towards $\odot$	0.1–0.5 kbs	10	13
L_1 Spinning axis $\perp$ to ϵ	0.1–0.5 kbs	10	13

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. The HELIOS spacecraft photometers have shown 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. These instruments compile an image along a plane parallel to the spacecraft rotation axis. A test baffle constructed for a rotating instrument shows that the stray light reduction is great enough to allow a 60° scan of the sky in this plane and helps determine the ultimate size of a high-resolution imager on a rotating spacecraft.

REFERENCES

1. Jackson, B.V., H.S. Hudson, J.D. Nichols and R.E. Gold, 'Design Considerations for a "Solar Mass Ejection Imager" on a Rotating Spacecraft', Yosemite 1988 Conference on Outstanding Problems in Solar System Plasma Physics: Theory and Instrumentation, Yosemite National Park, California, February 2-5, 1988, 1989.

2. Jackson, B.V., H.D. Zink and R.E. Gold, Preliminary All-Sky Heliospheric Imager (ASHI) Interface Control Document, JHU/APL SDO 8416, Report to USAF and NASA, 1987.

3. Jackson, B.V., "Scientific Background and Design Specifications for a Near-Earth Heliospheric Imager," AFGL-TR-88-0195, 1988.

4. Jackson, B.V., "Helios Photometer Measurement in In Situ Density Enhancements", *Adv. in Space Res.*, **6**, 307, 1986.

5. Jackson, B.V., "Heliospheric Remote Sensing Using the Zodiacal Light Photometers of the Helios Spacecraft", Yosemite 1988 Conference on Outstanding Problems in Solar System Plasma Physics: Theory and Instrumentation, Yosemite National Park, California, February 2-5, 1988, 1989.

6. Hong, S. S., Misconi, N. V., van Dijk, M. H. H, Weinberg, J. L., and Toller, G. N., "A Search for Small Scale Structures in the Zodiacal Light", in proceedings of Properties and Interactions of Interplanetary Dust, Giese, R. H. and Lamy, P., eds., 33, 1985.

7. Torr, D.G., "Space Station Contamination Study: Assessment of Contaminant Spectral Brightness", *NASA Conference Publication 3002*, 1988.