OPTICAL DETECTION OF LARGE METEOROIDS IN SPACE

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Abstract

CCD sensors placed across the focal plane of large Schmidt telescopes have great potential for detecting and measuring the very low flux in space of meteoroids with diameters larger than 1 meter. With the Palomar "Big Schmidt", a detection rate of 1.4 per hour is obtained for meteoroids between 0.6 and 200 meters in diameter. For the Baker-Nunn "Satellite Tracking Camera", the corresponding rate is about 0.8 per hour. The key to obtaining such high detection rates derives from approximately setting the sensor integration time equal to the time it takes a meteoroid to cross a pixel field of view. This minimizes signal to noise problems and is accomplished, in practice, by multiple summing of short integration time data records to obtain data records of longer effective integration times.

1. Introduction

The Prairie Network -- a network of cameras that recorded meteor fireball trajectories for several years over about 10^6 square kilometers of the midwestern U.S. -- recorded the flux of meteoroids with masses up to about 10^6 g (McCrosky, 1968). Although estimates of the meteoroid masses causing these fireballs have since been revised significantly downward (e.g., Wetherill and Revelle, 1981), the data obtained from this network and from the similar Canadian Meteorite Observation and Recovery Project (Halliday, et al., 1984) have given us a fair estimate of the flux of moderately large (1 to 10^6 g) meteoroids. Little is known, however, about the near-Earth flux of meteoroids with masses much above 10^6 g until one reaches sizes corresponding to the telescopically observed Apollo asteroids (e.g., Shoemaker, et al., 1979). Masses of the latter objects are mostly upward of 10^{15} g.

The recent advent of CCD (charge coupled device) technology, however, now makes it very possible to telescopically detect an extremely low flux of very large meteoroids (or small asteroids and comets) with ground-based optical telescopes. Gehrels (1981) and McMillan and Stoll (1982) have already used CCD detectors to search for faint comets and for asteroids. In this paper, we describe a

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promising technique of using CCD's as meteoroid detectors, and derive an expected telescopic detection rate for meteoroids between 0.6 and 200 meters in diameter. The method can easily be extended to objects outside this size range by adjustment of optical and electronic parameters.

2. CCD Detector Performance

Our analysis will be based on the published performance of an 800x800 pixel array CCD image sensor designed by investigators at the Jet Propulsion Laboratory and at Texas Instruments, Inc. (TI) and built by TI (Blouke, et al., 1983). This sensor is back-illuminated and has a thinned sensor active surface area of 1.22 cm x 1.22 cm with elementary pixel diameters of 15 μm. The exterior dimensions are about 1.7 cm x 1.7 cm x 0.2 cm. Four of these chips are to be used in the wide field/planetary camera on the space telescope. We chose this sensor because of its exceptionally low read-out noise and to illustrate the kind of performance that can be obtained from an existing device. Blouke, et al. (1983) have described the performance of this sensor in excellent detail, and we only repeat some pertinent facts.

The dark current noise is neglible when the sensor is sufficiently cooled. The sensor can be employed as four independent 200 x800 arrays of pixels. We will use the middle two arrays as the imaging section for our analysis and, after an exposure, will rapidly shift the data outward to the two outlying 200x800 arrays which will be shielded from incoming light. While a new image is being built up on the center two arrays, data in the two outlying arrays are to be respectively read to each of two outlying serial shift registers and subsequently read out through each of two read-out amplifiers. It is in the read-out amplifiers that read-out noise is generated. This noise is about 15 electrons at a 50 kpixel/s data rate. We will conservatively assume a read-out noise of 20 electrons for our analysis and will require that our data read-out rate not exceed 50 kpixel/s (so as not to pay an increased read-out noise penalty).

3. Data Acquisition and Analysis Procedure

Consider a CCD sensor placed at the focus of an optical telescope to detect sunlight reflected from objects passing through the sensor field of view. We state as a theorem that the maximum signal to noise ratio for a moving object is obtained when the sensor integration time, t, is such that the image of the object just moves across one pixel (picture element) in time t. This theorem is rather similar to the "dwell-in-the-cell" concept of R. Weber (1979) and so is not a new idea. We now examine the special application of the theorem to the use of CCD's in looking for large meteoroids passing rapidly through a telescope's field of view.

In actual fact, because different meteoroids will have different angular velocities through the telescopic field of view, it is not possible to integrate for just the right length of time such that each meteoroid image will cross just one pixel during an integration time. Thus we cannot strictly satisfy the conditions of our theorem.

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However, we can approximately satisfy the theorem by the following procedure:

1. Integrate for some short time t, read out, integrate again, and so on, producing a record of many frames, each frame of 200x800 pixels and each representing an integration time t.

2. Sum the frames together into a second record consisting of adjacent pairs of frames. In this second record, each pixel in each frame will now have an effective integration time 2 t and the entire record will consist of half as many frames as the first record.

3. Form a third record similarly from the second record for an effective integration time of 4 t. Continue this process to obtain records up to any desired integration time.

4. Examine each record separately for meteoroids crossing the field of view of the sensor. When many sensors are placed across a diameter at the focal surface, this procedure must be separately carried out for each sensor.

In the procedure given above, the records differ from each other by factors of 2 in integration time. Thus, no matter what the angular velocity of the meteoroid, the meteoroid image will move across the sensor at such a velocity that, in some one of the above records, it will not be far from satisfying our theorem; namely, the meteoroid image will not move much more or much less than one pixel in one integration interval. This will be the record in which our theorem will be best satisfied and through which we will best be able to discover that meteoroid which is moving at the correspondingly appropriate angular velocity.

Although the records could be digitally analyzed to discover meteoroids crossing the sensor field of view, we will here consider the video technique successfully used by investigators at the M.I.T. Lincoln Laboratory, (Weber, 1979; Taff et al., 1984) to detect earth orbiting objects with the optical telescopes at the ETS (Experimental Test Site) in New Mexico. They simply play the record back through a video monitor at 30 frames/s and, while viewing it, look for objects streaking across the field of view. They state that objects with a signal to noise ratio of 1.2 are easily detected.

4. Analysis

Space limitations prevent a full analysis being presented here. We therefore present only our fundamental starting equations and our assumptions.

The number of electrons generated and stored in a pixel during the base integration time, t (in seconds), due to background light is given by b where

$$b = C_1 \, B \, \delta \, \eta \, \alpha^2 \, D^2 \, t. \tag{1}$$

B is the assumed background light brightness in 21st magnitude stars per square arc sec. We assume B = 1.6. This accounts for a considerable infrared airglow component while looking at 45° with respect to the zenith. δ is the sensor efficiency for transforming photons to conduction electrons in the CCD semi-conductor. We assume that $\delta = 0.5$ over the wavelength range 0.3μm to 1.0μm. η is the

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fraction of light that makes it through the telescope optics to reach the sensor. We chose η = 0.6 for these Schmidt telescopes. α is the field of view (in arcsec) for each "effective pixel" and depends on the telescope used. Each "effective pixel" chosen as most efficient for the Palomar Big Schmidt consists of a 4x4 array of elementary pixels and is 60 μm across. Because on-chip summing of pixels can be done free of noise before amplifying in the read-out amplifiers, read-out noise relative to signal can thus be reduced. D is the telescope diameter in meters (given in Table 1). With these definitions and units, C_1 has the value C_1 = 194.8.

The number of signal electrons, S, stored in a pixel in time t, (resulting from a meteoroid image in that pixel), is given by

$$S = C_2 \, T \, \delta \, \eta \, p \left(\frac{R_0}{R}\right)^2 \left(\frac{d}{\Delta}\right)^2 D^2 \, E \, t \, . \qquad (2)$$

T is the atmospheric transmission. T=0.8 is assumed. p is the geometric albedo. We assume p = 0.05 (a fairly dark object) and that we can always observe approximately in the anti-sun direction. R_o is the distance of the Earth from the sun and R is the meteoroid distance from the sun. d is the particle diameter and Δ is the distance of the particle from an observer on Earth. δ, η, and D are as previously defined. With these units, $C_2 = 6.02 \times 10^{20}$. E corrects for the fact that the meteoroid signal integration time in a pixel will not normally exactly match the background integration time. E can vary from about 0.75 to 1. E = 1 is assumed in this analysis. The number of noise electrons, N, generated during an integration interval is assumed to be given by

$$N = \sqrt{b + R_n^2} \; , \qquad (3)$$

where R_N is the read-out noise (R_N = 20 assumed).

In this analysis, we will detect meteoroids by processing each record at 30 frames/s through a video terminal and will look for streaks. We conservatively assume that we will detect all objects with a signal to noise ratio, S/N, greater than 2. From a number of computer analyses we have found that if we set the frame integration time to t = 0.25 sec, we get good results for meteoroids larger than about one meter in diameter with the optics we have choosen.

The distance Δ_m out to which objects will be best observed (i.e., best satisfy our theorem) during integration time t, is given by

$$\Delta_m = \frac{C_3 \, v_t \, t}{\alpha} \qquad (4)$$

where v_t is the meteoroid velocity transverse to the viewing direction, α is the pixel field of view in arcsec, and $C_3 = 2.0626 \times 10^3$ arc sec/rad. We assume that $v_t = 10^4$ m/s, is a reasonable weighted average.

We assume that the meteoroid flux, F(d), is given by

$$F(d) = \begin{cases} 10^{-19.4}\ d^{-1.86} & d<1 \text{ meter} \\ 10^{-19.4}\ d^{-3} & d>1 \text{ meter} \end{cases}$$

where F is in number per square meter per second striking one side of a flat surface, and d is the meteoroid diameter in meters. F(d) represents a good fit to both the meteor fireball data of Halliday, et al. (1984) and the observed flux of Apollo asteroids (Shoemaker, et al., 1979).

The smallest meteoroids d_1, that can be detected at distance Δ_{m1} is given by solving equations (1), (2), (3) and (4), and using our assumptions on the parameter values. This meteoroid will also be detected at all lesser distances. We can similarly solve for the smallest meteoroid, d_2 that can be detected out to distance Δ_{m2} (obtained from eq. (4) when t is replaced by $t_2 = 2$ t). We then obtain a lower limit for the number of detections per unit time for meteoroids between diameters d_1 and d_2 by multiplying the flux of meteoroids in this interval, $F(d_1) - F(d_2)$, times twice the area over which all meteoroids in this size interval will be detected. This area is given by $0.5\,\Omega\,\Delta^2_{m1}$, where Ω is the sum of all the angles subtended by each sensor at the focal surface. A "twice" factor comes in because meteoroids can approach from either of two directions. However, a gravitational decrease factor of 2 on F(d) makes the net factor equal to one. The "lower limit" applies because meteoroids larger than d_1, but not as large as d_2, can actually be detected at a greater distance than Δm_1. Similar analyses are now done for the next meteoroid diameter interval, and so on.

5. Results

The results of these analyses are shown in Table 1 for the Palomar Big Schmidt. The total detection rate for detecting meteoroids between 0.6 and 206 meters in diameter using 20 sensors at the telescope focus is about 1.4/hr. Distances at which they are detected and their apparent magnitudes are also shown. The corresponding rate for detecting meteoroids between 0.34 and 71 meters in diameter using 14 sensors at the focus of the Baker-Nunn Satellite Tracking Camera turns out to be about 0.8/hr. The latter telescope is much smaller than the Big Schmidt, but gives rise to only a modest loss in count rate.

The count rates shown in Table 1 will more than double if we can detect streaks with a signal to noise ratio as low as 1. They will also increase by about a factor of 2 due to certain of our approximations. There will, however, be a minor reduction in count rate when E is realistically set to less than 1. The reduction is about 30% at E = 0.8.

The tremendous capability of this technique is demonstrated when we consider that the entire Prairie network with its many cameras covering approximately 1 million square kilometers would only observe about one object larger than 1 meter in diameter every 4 or 5 calendar years.

Table 1. Counts/hr for Palomar "Big Schmidt" with 20 sensors and SN = 2

Diameter Range (m)	Distance (m)	Apparent Magnitude	Counts/hr
0.61--1.02	1.28×10^{8}	19.6	0.15
1.02--1.72	2.56×10^{8}	20.0	0.27
1.72--2.91	5.11×10^{8}	20.4	0.23
2.91--4.92	1.02×10^{9}	20.8	0.19
4.92--8.39	2.05×10^{9}	21.1	0.16
8.39--14.5	4.09×10^{9}	21.5	0.13
14.5--25.6	8.19×10^{9}	21.9	0.10
25.6--47.4	1.64×10^{10}	22.3	0.075
47.4--94.0	3.28×10^{10}	22.6	0.049
94.0--206	6.55x1010	23.0	0.026

Telescope and sensor parameters: Effective objective diameter = 1.22 meters. Effective focal length = 3.07 meters. Diameter of focal surface = 35 cm. Pixel diameter = 60 μm. Pixel field of view = 4 sec/pixel.

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