

## ON THE OPTICAL DETECTION OF METEOROIDS, SMALL NEAR-EARTH ASTEROIDS AND COMETS, AND SPACE DEBRIS.

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Investigators at M.I.T.'s Lincoln Laboratory (1,2) have thoroughly demonstrated the feasibility of optically detecting small, high velocity, particles at great distances using nothing more than scattered sunlight. The particles were typically in orbits 500 km or higher above the Earth and, depending on the albedo assumed, were estimated to range down to 1 to 2 cm in diameter. The detector used was a specially designed intensified vidicon camera placed at the focus of a 31 inch diameter telescope. The technique employed was to record the output of the vidicon camera at 30 frames/s onto magnetic tape and later, after subtracting the background, to simply play it back through a video monitor at the same rate and, while viewing it, look for objects streaking across the field of view.

Zook and Potter (3) later made use of the fact that the signal to noise ratio ( $s_n$ ) for signal detection was optimum when the image of a particle crossed one pixel (picture element) per frame. They analyzed the detection rate of meteoroids with diameters between 1 and 100 meters in diameter with the following  $\log(\text{flux})$  vs  $\log(\text{diameter})$  relationship:  $\log(F) = -19.4 - 3 \cdot \log(d)$ , where  $F$  is in number/(m<sup>2</sup>s) and  $d$  is in meters. In their theoretical analysis, a CCD (charged coupled device) chip, with a quantum efficiency of 0.5 for photon detection (about 7 times higher than that for the intensified vidicon) was employed at the focus of the 1.22 meter diameter Palomar "Big Schmidt" telescope. While maintaining the pointing of the telescope on a single field of view in the sky, 0.25 second duration exposures were taken every 0.25 seconds and recorded digitally onto magnetic tape. They were then to be played back through a video monitor at 30 frames per second while observers looked for bright spots moving across the field of view. It was estimated that a moving image point with an  $s_n$  of 2 or above would be detected by a person observing the CRT. Other digital records were also to be produced by digitally summing together adjacent pairs of frames. Thus records with effective exposure times of 0.25, 0.5, 1, 2, 4, 8, 16, 32, 64, and 128 seconds were to be obtained and played back through a monitor for detection by human observers. It was estimated that a detection rate of 1.4 objects per hour could be obtained by using 20 chips at the focus of the Big Schmidt (or 0.07 detections per hour per chip).

We now examine a technique to analyze digital records, such as those above, with a computer, and thus avoid using the human eyeball to find moving images. We will find that a computer can, indeed, extract moving images with pixel signal-to-noise ratios  $s_n$  as low as 1.0 with a high probability of success. The lowered  $s_n$  increases the detection rates over that obtained by Zook and Potter by a factor of about 2. The reasoning underlying this technique is first developed where the sky background is assumed uniform; that is, it varies in time, and from pixel to pixel, only under statistical photon intensity fluctuations. Similarly, the particles under observation are initially assumed not to rotate and thus not to generate a non-statistical time-varying light curve. These assumptions are easily relaxed later.

Consider searching for an image that crosses an  $N$  by  $N$  (or  $N^2$ ) array of pixels during a single exposure (or "frame") which is, itself, only one in a collection of many frames taken over time. The frame that has the image in it will have a line of "enhanced brightness" pixels traversing it. We numerically search for such a line by summing pixel brightnesses along each possible line in each frame. If a "line" is considered to start on some pixel on one side of the array and end on any other pixel on any one of the other 3 sides of the array, there are  $12N^2$  lines possible across an  $N^2$  pixel array (minus a few lines, when we neglect short lines crossing the corners of the array). Each line sum is compared in brightness with its counterpart background sum to see if it is sufficiently brighter than the background sum to be unlikely to be noise at, say, a permitted rate of one false alarm per year. If so, it is considered a valid signal due to a true particle crossing the field of view of the telescope. We note that if the signal-to-noise level for each pixel along an enhanced brightness line averages  $s_n$ , then the signal-to-noise level for the line itself is  $S_N$ , where  $S_N = \sqrt{N} \cdot s_n$ . For  $N=512$ , the square root of  $N$  is 22.6. One can deduce that if the noise is due only to Poisson statistical photon noise fluctuations, then  $S_N$  need not be larger than 8 or 9 to be quite sure that a valid image line is present due to a true particle crossing the telescope field of view. This approximately

corresponds to individual pixel intensities above background by at least  $s_n=0.4$  for valid detection of a particle crossing the field of view.

Generally, however, because of the variability of angular velocities of detected particles, an image will not cross an entire pixel array in one frame, but will enter the array at one pixel in one frame and leave the array at another pixel some unknown number of frames later. This requires searching for lines in a 3 dimensional space-time array where the two space dimensions are the CCD chip x and y axes and the third dimension is time, in units of frame time. This search must be done at the end of each frame for all possible lines that can end on that frame. If we consider all lines starting as long as  $2N$  frames in time before the last frame, there are  $24N^3$  such lines (again minus some lines across array corners). Each brightness sum along each line must be compared with the background sum for that line in order to detect particle image crossings. Thus  $24N^3$  sums need to be carried out each frame. This is a huge computer effort when we consider that for each line about  $N$  additions need to be taken where  $N$  might be 512, or even larger. It amounts to about  $10^{12}$  floating point operations per frame. This is clearly not presently practical. The computer effort, however, may be greatly reduced if one first sums small subarrays of elementary pixels into larger "macropixels." For example, macropixels that consist of  $32 \times 32$  arrays of micropixels can be initially taken. Also multiple adjacent frames in time can be summed together. One then has the computer look for evidence of lines across the array of macropixels and over longer effective exposure times. Because of the far fewer pixels and lines involved, there is a huge reduction in the computer effort required to do the necessary sums. One then saves only those "macro-lines" whose signal-to-noise levels,  $S_{N1}$ , are above certain preset thresholds. These macro-lines are then reassembled into subarrays of smaller pixels. These subarrays of smaller pixels are further examined for lines and, again, only those lines that lie above a different preset  $S_{N2}$  are saved to be further divided into yet smaller pixels. This process is continued until it can be definitely determined whether or not a true image has crossed the array. This process is repeated at each new frame. However, the computational effort has now been sufficiently reduced that it appears quite practical to detect, in real time, all lines with  $s_n$  equal to or greater than 1. Lines with pixel  $s_n$ 's as low as 0.4 will, however, not reliably be detected with this procedure.

For a non-uniformly illuminated sky background (with stars, etc.) and for time varying images (from, say, rotating particles), a minor modification must be made to the above process. A background value  $b_i$  is established for each pixel (where  $i$  identifies the  $i$ th pixel) by averaging over a number of frames. Then, for each pixel and at each new frame, one then forms the weight  $w_{ij}=(o_{ij}-b_i)^2/b_i$  where  $o_{ij}$  is the observed pixel brightness of pixel number  $i$  in frame number  $j$  (where  $j$  advances continuously with time). One then sums the  $w_{ij}$  along 3-dimensional space-time lines to obtain the chi-squared distribution of observed line brightnesses. When the chi-squared sum lies above a pre-established threshold value, a true event is presumed to be discovered.

In summary, the technique here described has great power to discern, in real time, small (or large) objects crossing rapidly through the field of view of a focal plane sensor placed at the focus of a telescope. Objects of 100 meters in diameter moving at 10 km/s perpendicular to the viewing direction should be easily detectable at ranges up to 0.5 AU away from the Earth. Such objects could include small asteroids or comet nuclei.

REFERENCES: (1) Weber, R. (1979) *Optical Engineering*, 18, 82-91. (2) Taff, L.G., Beatty, D.G., Yakutis, A.J., and Randall, P.M.S. (1985) *Adv. Space Res.*, 5, No. 2 (D. J. Kessler, E. Grun, & L. Sehnal, Eds.), 35-45. (3) Zook, H.A. and Potter, A.E. (1985) In: Properties and Interactions of Interplanetary Dust (R.H. Giese & P. Lamy, Eds.) 293-298.