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PRELIMINARY DESIGN OF AN EARTH-BASED DEBRIS DETECTION SYSTEM USING CURRENT TECHNOLOGY AND EXISTING INSTALLATIONS

from

SOUTHWESTERN UNIVERSITY

of

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INTRODUCTION

Since 1958 there has been a slow, but steady, increase of the population of man-made debris. Some of this increase represents break up into many parts of older payloads and rocket bodies which may be in the future somewhat alleviated by better payload design and construction as well as operational managment. An overall increase in the use of space by all countries will still lead to a non-negligible debris hazard. Assessment of this hazard requires at least that the population of debris down to mm sizes be determined (both for near Earth orbits and near stationary points). It may also be necessary to obtain reasonable orbits for a statistically significant sample of the debris population.

Several ground-based techniques for detection are available. Radar detection has been used to obtain our existing debris population information. Another technique which has been discussed in the past is optical detection. A present epoch (1983) discussion of this technique was needed what follows is a study of the possibilities for optical detection with state of the art instrumentation.

APPROACH

The considerable period of time between sunset at the surface of the earth and sunset at the altitudes characteristic of orbiting debris provides a period of several hours both after sunset and before sunrise each night in which debris can be observed in reflected light. These objects have significant velocities (6 to 7 km/s) relative to terrestrial observers, so fast that these objects are not normally detected by astronomical instruments. Tracking at appropriate rates (0.6-0.8°/sec) and observing repeatedly with short exposures will reveal these objects.

In what follows, a simple instrument based on present-epoch technology for optical detection of orbital debris which we plan to deploy in the near future is described. The limits of detectability at various altitudes and under different operating conditions for this system are assessed. The kinds of information which can be deduced from this data are examined. Optimal systems for debris detection are next discussed. Alternatives and possible improvements from new technologies are also considered.

BASE SYSTEM DESCRIPTION

Detection of faint objects moving rapidly relative to the fixed stars requires an efficient area detector and a large-aperture, fast optical system. The acceptable optical bandwidth should include at least the 0.4 nm to 0.7 nm spectral region which contains the bulk of the solar flux. In practice, the large quantity of data which must be examined per detectable event requires that equal emphasis be placed on data reduction. This includes highly efficient automated modes of data analysis and high density storage capability.

The heart of the system is the detector. The unit chosen is a 25mm square faceplate ISIT camera. This low light level video camèra was originally developed by the QUANTEX corporation and is now available from the SCANCO company. This system, already in use at civilian and military observatories, is a low noise and high quantum efficiency area detector with electronic readout. The optical system chosen is a standard night aerial reconnaissance camera with short focal length, large collecting area, and large field of view. Optics with slightly different characteristics may be scaled from the data below. The characteristics of both the optical system and the detector are given in Table I.

TABLE I

FOV: 2.4°	Aperture: 33.5 cm (coll. area = 698 cm^2)
F/#: 1.8	Arc sec/ pixel:16.8 (2.16×10^{-5} sq deg.)
Bandpass: 400-800 nm	
Photocathode: S-20	Ave QE: 10%
Transmission: 80%	Background:330 10th magnitude stars

The video data stream will be fed into both a video tape recorder and a video data processor. The processor will perform a number of functions both in real-time, and away from the observing period. In essence, this system provides image-to-image addition and subtraction and single image enhancement.

LIMITS OF DETECTION

Ideally one should choose the exposure time in order to maximize system performance in a single frame. However, there are many practical reasons to set the exposure time so that the video data conforms to commercial synchronization rates. Here we have chosen the European PAL system which gives us a frame rate of 25 per second. Now the irradiance due to one 10th magnitude star through a 0.4 to 0.7 m passband is 1.31×10^{-16} w/cm^2. Thus the total sky background is 4.32×10^{-14} w/(cm^2 square degrees). Projecting a single pixel back into the sky gives an irradiance of 2.60 photons/cm^2.s. Assuming 90% sky transparency, we find for the numbers given in Table I that there 130.5 photoelectrons/pixel and second and 5.22 photoelectrons/pixel and frame. If we assume that the minimum detectable signal S is given by

$$\frac{S}{\sqrt{S + 2B}} = 1$$

Then S is 3.80 photoelectrons/pixel and frame or 6.76 10^{-19} w/cm^2 outside atmosphere irradiance. Assuming that the image of the object observed falls equally in 4 pixels,

flux = 2.704 x 10^{-18} W/cm^2

which roughly corresponds to a 14th magnitude star.

RAPID SLEWING MODE

Slewing rapidly along an arc of a great circle passing through the zenith at a rate matching the apparent angular motion relative to the observer of objects in circular orbit at a given altitude effectively freezes the location of the images of these objects within any frame and from frame to frame. For simplicity, suppose both that one is observing from a near-equatorial site and that the slew direction is directly west to east. Suppose the angular velocity of the slew is 0.813°/sec which corresponds to the relative angular velocity of an object in a circular orbit at an altitude of 500 km above the earth (6870 km from the center of the earth) and with approximately 0° inclination.

An object at 500 km and having an inclination within approximately 30° of the preferred inclination will fall into at most 4 pixels and most of these will fall into only 1 in one frame. Particles at 375 km will move three pixels forward during one frame, and particles at 850 km with appropriate inclinations will move backward three pixels in one frame. These two are limiting cases, for all altitudes in between experience less than three pixels per frame relative motion. Our limiting cases will illuminate at most 18 pixels (5x2) and generally only 4 pixels (4x1). A star will illuminate at most 18 pixels (9x2). It should be noted that star centers will move by almost 7 pixels from frame to frame, and stars are thus easily separated from the debris images using simple frame to frame subtraction and background subtraction techniques. One should note here that these differences would be difficult to detect with an emulsion based data storage system.

The limiting flux detectable in a single frame for a given altitude can be determined by multiplying the minimum detectable signal by the number of pixels illuminated. Thus, for an object at 350 km with an acceptable inclination, one finds that the worst case flux is

6.76×10^{-18} W/cm^2;

and the best case flux is

2.70×10^{-18} W/cm^2.

The debris particles will be modeled by assuming them to be Lambertian spheres of albedo 0.5. For convenience the sun-debris-observer angle will be 90°. If I_o is the solar irradiance over the bandwidth, X is the geometrical cross section, and R is altitude of the debris, then the flux is

$$I_x = \frac{0.034XI_o}{R^2}$$

The bandpass chosen includes 0.59 of the total solar irradiance (0.14 watts per cm^2), thus

$$I_x = 2.81 \cdot 10^{-3} \frac{X}{R^2}$$

Using the limiting flux value 6.76×10^{-19} w/cm^2, we find on solving for X/R^2 that

$$\frac{X}{R^2} = 2.4 \cdot 10^{-2}$$

where X is in cm^2, for convenience, R is in units of 100 kms (thus R would be 5 for an object 500 km above the Earth). The resulting cross sections and diameters for various altitudes are given in Table II.

TABLE II

Altitude	Pixels Illuminated	Cross Section	Dia.
800 km	10	cm^2	4.43 Cm
800	4	6.14	2.8
500	4	2.40	1.75
500	1	0.60	0.875
400	10	3.84	2.20
400	4	1.536	1.41

Assuming a 4 arc second image width, the relative number of images filling 1 pixel to all images (the case 500 km altitude) can be determined--it is 0.3. The same considerations for the "worst case" altitudes give for the ratio objects illuminating two pixels to all objects 0.3 also. As each object should appear in many frames, any particle debris with the limiting cross section will in a few frames illuminate the minimum number of pixels and, thus, be detectable. Such particles will appear to "blink" in and out through the slew. The available volume from the region 375 to 850 km is $3.15 \times 10^{+5}$ km^3. The span of inclinations available depends on the criteria for detection. In one frame the available number of inclinations comes from asking what portion of the population has a velocity along the scan direction sufficiently large to maintain a motion of .544 pixels. This is a 10% for

500 kms and rises to 0.16 for particles at a 375 kms. The number decreases slowly from 500 to 850 km. For an average value one might take 10%. Thus the number of events per scan assuming 10^{-7} particles per km^3 ($d \geq 1$ cm) average over the 375 to 850 km range is

$$3.15 \times 10^{+5} \times 0.1 \times 10^{-7} = 3.15 \times 10^{-3} \text{ Acquisition field}$$

The continued observation along the slew direction does little to alter this probability; to improve the acquisition rate one must slew many times (observe many fields). A continued observation along a slew direction does provide three advantages. First, the limiting signal to noise for objects at the design altitude and inclination can be markedly improved by addition of frames (by the square root of N, with N the number of frames); second, the identification for any faint object is more certain by virtue of observation over many frames; third, the inclination of the object can be determined. In theory data based on very long slews (90°) could be used to completely determine the orbital parameters of the debris. However, the determination would be based on only 2.2% of the orbit.

Assume that the system slews for periods of 13 seconds at a time at a rate of 0.813°/second producing an effective arc of 10.4° length centered on the zenith. Assume 2 seconds reverse time and the next slew in the opposite direction. There are then 4 slews a minute. Thus for a 45 minute observing period, the total probability of detection with N equal to 10^{-7} particles/km^3 is

$$4 \times 45 \times 3.15 \times 10^{-2} = 0.55 \text{ acquisitions/evening,}$$

The 45 minute period is based on observations at an equatorial site beginning when the sun is 6° below the local horizon. By simply adjusting the rate the system could be used there after maximized for successively larger altitudes. An observing plan so designed might expect to double the number of acquisitions. One should therefore expect

1.1 acquisition/Evening

One can of course, repeat these observations in the early morning hours using successively larger slew rates as morning comes.

One should note here that the capabilities of the video data system enter into the discussion above only for particle identification and determination of approximate orbital characteristics. The considerable gains possible in threshold detection from summation of frames have not been considered in the threshold calculation or in the acquisition rate determination.

STATIC OPERATIONS

Suppose that the instrument is pointed upward toward the local zenith and fixed. In one 0.04 sec exposure the image of an object at 400 km moves 9 pixels but the image of one at 1600 km moves only 3 pixels--the stars are effectively frozen moving only 1 pixel after 28/frames. The simplest criterion possible may be used for detection (one easily accomplished with modern video image proccessors); namely, whether an image "moves" from frame to frame. In addition, the debris images will be elongated. An object in a circular orbit at 400km altitude will cover at most 22 pixels (11x2), and in some frames, only 9; at 500km, this becomes 18, and in some frames 7; at 1600km, one finds 8, and in some frames 2. All possible inclinations are included.

The volume of space accessed in one exposure has the figure of a truncated pyramid whose bases are areas on the surface of a sphere bounded by four arcs of great circles with each arc of equal length. The spheres are centered on the observer and the radii are the limiting altitudes given above. A simple differential volume element of the observing volume is a section of a spherical shell of radius z and thickness dz bounded by 4 arcs of great circles each $\alpha_0$zkms in length where α_0 is the field of view in radians. The number of particles per unit time passing through the small volume element of thickness dz and length on a side of z is:

$$nV(\alpha_0 z)dz$$

where V is the "circular" velocity of the debris, r_0 the radius of the earth, the FOV in radians, z the height above the earth, and n the particle density per $(km)^3$.

In a time t the number of particles which enter the slab element is

$$nV \quad t \; (\alpha_0 z)dz$$

Note that V is just

$$V = V_0 \sqrt{\frac{r_0}{r_0+z}}$$

where V_0 is 7.91 km/s.

For all the particles observed then one has

$$N = n\, V_0\, \alpha_0\, T \sqrt{r_0} \int_{z_1}^{z_2} \frac{zdz}{r_0 + z}$$

Where T is the total observing time (taken to be 3600 seconds) with a change of variable to the distance from the center of the Earth to the region of integration (simply $r_0 + z$), one finds

$$N = n\, V_0 \alpha_0 T \sqrt{r_0} \left[\frac{2}{3} \left(h_u^{\frac{3}{2}} - h_l^{\frac{3}{2}} \right) + \frac{r_0}{2} \left(h_u^{\frac{1}{2}} - h_l^{\frac{1}{2}} \right) \right]$$

Over a region stretching from 6770 km to 7970 km this gives

$$N = 2.89 \times 10^{+9} n$$

For n equal to $10^{-9}/km^3$ this is

2.89

detections.

While the minimum detectable diameters in a single frame has been increased by a factor of 2.6 at 500km to 2.31 cm, it has not increased appreciably for larger altitudes. Further, more sophisticated multi-frame analysis techniques can be expected to recover much of the lost sensitivity. On the average, a particle in a circular orbit at 500 km will be imaged 56 times. Thus 4 or 5 marginal detections along a straight line may be sufficient for a positive identification.

One should note that meteor trails will be clearly unlike debris. A 20km/s meteor at 100 km would produce a 135 pixel trail on a single frame.

LIMITS OF OPTICAL DETECTION

An ideal optical system must:

1. Have sufficient collecting area and transmission to allow detection of the desired limit in one frame (here taken to be 0.04 seconds).
2. Be sufficiently fast to optimize the conflicting requirements of large field of view and effective pixel size when projected onto the sky.

3. Have a flat field over the field of view.

We shall for this discussion assume a detector which provides 20 pixels per mm and an average quantum efficiency of 10 percent. We shall further assume Lambertian scattering from a spherical particle of diameter d with albedo 0.5, distant R from the Earth's surface with a sun-object-observation angle of 90°. The sky background as before is 330 10th magnitude stars per square degree. The first condition above controls telescope diameter; the second, the f-number.

Under the assumptions above one finds that

$$I_{obs} + 2.171 \times 10^{-17} \left(\frac{d}{R}\right)^2 \quad \text{in } \frac{W}{cm^2}$$

where as before d is the diameter of the debris and R is altitude in units of 100 km. If one assumes that the product of collecting area as a percent of the geometrical collecting area, the instrument transmission, the sky transmission, and the quantum efficiency to be 0.0576, one has

$$\text{Flux producing photoelectrons} = 0.0452 D^2 I_{obs}$$

where D is the telescope diameter. Thus,

$$\frac{\text{Number of photoelectrons}}{\text{pixel and frame}} = \frac{0.1098\ d^2 D^2}{R^2}$$

For d = 1 cm and R - 10 (1000 km)

$$\frac{\text{Number of photoelectrons}}{\text{pixel and frame}} = 1.098 \times 10^{-3} D^2$$

One must now determine the minimum detectable signal in photoelectrons per pixel and frame. For purposes of argument let us set this number as 5 which should be valid for any detector system under consideration. Then,

$$D = 67.5 \text{ cm}$$

This result may be used as a scale factor for comparison to other systems. The practical limit to telescopic detection from the ground is about 2mm at 1000km altitude. To go to 1mm would require a collecting area slightly more than 6 meters in diameter. Two caveats are necessary. First, image processing of multiframe data could push down the detection limit by lowering the single frame signal required. Second, multimirror designs for large telescopes which give large effective collecting areas are under investigation by at least three groups in this country.

The background present in an individual detector element is controlled by the focal length. If we require that

$$\frac{S}{\sqrt{S + 2B}} = 1$$

where S is the signal, then B can be as large as 10 photoelectrons/pixel and frame. Using 4.32×10^{-14} watts per cm^2 per square degree and remembering that the sky subtended by one pixel is $8.208 \times 10^{-2}/(\text{f-number} \times D)^2$, we find that the minimum value is

$$\text{f-number} = 1.30$$

One should remember that a larger f-number improves the noise per pixel at the expense of field of view.

Instruments of half-meter diameter with f-number as small as 1.3 and acceptable curvature of field have been constructed. Astronomical instruments with 1 meter aperture are generally no faster than 1.8. For diameters beyond 1 meter an optical system with f-numbers as small as 1.8 and flat-focal plane of 40cm presents a significant technical problem. If the f-number requirement is relaxed to 2.5 to 3.5, however, a number of optical approaches are possible--Richey Chretrain systems, Schmitt optics with a curved focal plane of sufficient radius to be negligible over 40mn, and standard parabolic systmes at Newtonian or prime focus with field correctors. Systems using parabolic primaries and field correction should be examined in more detail.

POSSIBLE OBSERVING SITES

Maximum utilization of rapid slewing instruments over any one night requires that measurements continue as long as a portion of the observable sky volume is in sunlight. In short, one needs a site which has dark sky to horizons. Remarkably few developed observing sites in the continental United States meet this requirement. For example, the Kitt Peak and University of Arizona observatories both suffer from the growing problem of the Tucson light dome. Nor do there appear to be any developed sites in California which are dark to the horizon. There are developed sites in West Texas, New Mexico, and Wyoming with very dark skys, however all three suffer from the Western U.S. weather patterns which limit the number of usable nights per year. The best sites for this work available to U.S. observers are the obsevatories on Maui (USAF & UH) and on Hawaii (IRTF, UH).

FUTURE IMPROVEMENTS IN DETECTORS

The low light level television system is a mature technology. It would appear to be difficult to push these cameras to larger effective areas. Two developing detectors which could provide larger effective areas are charge coupled devices (CCD) and multi-anode microchannel arrays (MAMA). The largest commercially available CCD is an 800x800 array. However, there are ongoing efforts at GSFL to construct "mosaics" of the arrays to give very large detector areas. These devices have already been used both astronomical and military observations. The MAMA systems are now approaching 1024x1024 in the laboratory, and smaller arrays have been used in both astronomical, and military applications. At present these systems have approximately the same number of pixels per cm as the low light level cameras. Thus they offer the advantage of larger effective fields of view. The present indications are that the MAMA technology will produce the greatest sensitivity.