CCD SYSTEMS FOR SEARCHING FOR NEAR-EARTH ASTEROIDS

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ABSTRACT Large format CCD systems arc superior to photographic systems in terms of quantum efficiency and that they yield digital output direct] y, which can be computer anal yzed to detect moving objects and to obtain ast rometric measurements. A disadvantage compared to photographic systems is that present CCDs arc not able to utilize the full field of view available in a Schmidt telescope of moderate size. We evaluate and compare three systems here: the Palomar 0.46 cm photographic Schmidt system, the *Spacewatch* camera on Kitt Peak (both of these systems presently operating), and a planned system using a large format CCD chip on a USAF 1 m short focus telescope. Telescopes of the latter type (using vidicon-type detectors) are presently in use for tracking Earth satellites. The evaluation presented here provides a recipe which can be used to compare the performance of other planned systems for detecting near-Earth asteroids.

INTRODUCTION

At the present time, there arc two fully dedicated systems in use to search for near-Earth asteroids (NEAs). One is an 18" (46 cm) Schmidt telescope, located on Palomar Mountain, which is used two teams headed by E. M. Shoemaker and Eleanor Helin, and uses photographic films in 8 inch diameter circular format, to cover 50 square degrees of sky area per exposure. They take two 6 minute exposures of each area of the sky. For a near-stationary object, this system is capable of reaching to visual magnitude 18. The other system, called the *Spacewatch Camera,* utilizes a 36" (91 cm), *f*/5 Newtonian reflector, located on Kitt Peak, with a large format CCD detector. The telescope is clamped down and the CCD clocked so that a strip image is read off continuously, covering 0°.69 in declination, scanning at sidereal rate, ~15° /hour at low declination. Scans arc typically 20 minutes long, and arc repeated three times. For near stationary objects, this system reaches a limit of visual magnitude 20.5. The Palomar system covers sky area much more rapidly, -150 sq. deg. per hour, compared to -3 sq. deg. pcr hour for *Spacewatch. The* fainter limiting magnitude of *Spacewatch* is nearl y compensated by the increased sky coverage of

Palomar, thus the two systems arc currcntly discovering NEAs at comparable rates of two or three per month. (Recently, *Spacewatch* has been upgraded to use a higher quantum efficiency CCD, so it is presently making about twice as many discoveries pcr month as the systcm wc have evaluated here.)

A third systcm is under design, using an existing 1 m, *f*/2.2 tclcscopc, which wc hope to employ with a large format CCD detector. Six of these tclcscopcs, known as the *Groundbased Electro-Optical Deep Space Surveillance* (GEODSS) systcm, arc currently in usc by the U. S. Air Force for tracking Earth satellites, but arc presently equipped with vidicon-style detectors. A CCD detector is under dcvclopmcnt by Lincoln Laboratories for these tclcscopcs, employing a single-chip, high quantum efficiency CCD with 1960 x 2560 exposed pixels, each 24 microns square. These detectors include shaded storage arrays, and hcncc can be read out almost instantancousl y. The charactcrist ics of the three systems which wc evaluate arc summarized in Table 1. For the Palomar photographic systcm, wc take for "pixel scale" the typical measured size of a point image on the film.

TABLE 1 Characteristics of Evaluated Systems

Characteristic	Symbol	18" Palomar	Spaccwatch	GEODSS
Effective aperture	D	0.35 m	0.73 m	0.70 m
Effcctivc focal length	*f*	0.91 m	4,6 m	2.2 m
Field of View		8° dia.	0°.69 x sidereal rate	°.22 x 1°59
Pixel scale	*d/f*	-3 arcscc	1.21 arcscc	I. 86 arcscc
Number of pixels to contain image	n_p	(1)	9	4
Area of a point image	*A*	*-10* arcscc^2	13,3 arcscc^2	13.8 arcscc^2
Exposure time	*t*	360 SCC	165 SCC	sclcctablc
Limiting magnitude	m,	18.0	20.5	20.2 (100 sec cxp)

In the following sections, wc derive the sensitivity of each system as a function of target rate-of-motion, and the rate of sky coverage. Combining these factors, along with an estimate of the number density of NEAs as a function of magnitudc in the sky and rate of motion, wc derive relative figures of merit for the two existing systcms and the planned new systcm.

DETECTION THRESHOLD

The detection threshold of a system is defined in terms of the limiting signal-to-noise ratio, $(S/N)_{lim}$, which can be discerned above the background level. For an unresolved, untrailed image, the signal intensity must be compared against the noise level in an area which contains the image, which may be limited by the pixel scale of the detector, the seeing, or the resolution of the telescope. For a short trailed image, one can still recover all of the signal, but the noise goes up as the area to contain the image increases, For a very long trail, it becomes difficult or impossible to correlate the entire signal, so the available signal for detection begins to fall off.

Stationary Unresolved Objects

The signal level has the following proportionality:

$$S \propto IQD^2 t, \tag{1}$$

where I is the intensity of the object imaged, Q is the quant um efficiency of the detector, D is the effective telescope aperture (allowing for transmission losses and obscurations), and t *is* the integration (exposure) time. The noise, N, is proportional to the square root of the background signal level:

$$N \propto \sqrt{AD^2 Qt}, \tag{2}$$

where A *is* the angular area on the detector required to contain the image. Thus the signai-to-noise ratio has the proportionality:

$$\left(\frac{S}{N}\right) \propto \frac{IQD^2 t}{D\sqrt{AQt}} = ID\sqrt{\frac{Qt}{A}} \tag{3}$$

. This can be rearranged in terms of the limiting intensity, I_{lim} which can be detected:

$$I_{lim} \propto \frac{(S/N)_{lim}}{D}\sqrt{\frac{A}{Qt}}, \tag{4}$$

or in magnitude units,

$$m_{lim} = m_0 + 1.25\log\frac{D^2 Qt}{A(S/N)^2_{lim}}, \tag{5}$$

where m. is a constant, which wc evaluate from demonstrated performance of a system of known characteristics. For the *Spacewatch camera* (Rabinowitz 1991), wc have D = 0,73 m, Q = 0.3, t = 165 *see*, A = 13.3 arcsec², $(S/N)_{lim}$ = 6, and the limiting magnitude is m_{lim} = 20.5. Substituting these values into Eqn. (5), we obtain for the constant, $m.$= 22.07. Thus for any CCD system,

$$m_{lim} = 22.07 + 1.25\log\frac{D^2 Qt}{A(S/N)^2_{lim}} \tag{6}$$

For a photographic system, Q and $(S/N)_{lim}$ arc hard to define. We can usc the constants for the Palomar photographic systcm, listed in Table I, to obtain:

$$m_{lim} \approx 17.2 + 1.25 \log \frac{D^2 t}{A}, \tag{7}$$

which should bc valid for another systcm using the same film. The main difference in the constant m_0 *is* duc to quantum efficiency, and implies that film has about 1 % of the efficiency of a CCD.

Short Trailed images

The linear size of an untrailed image is $\sim\sqrt{A}$. Thus an object moving at rater produces a trailed image if it is moving faster than $r_s = \sqrt{A}/t$ For the Spacewatch systcm, $\sqrt{A} \approx 3$ arcsec, and $t = 165$ seconds, thus $r_s \approx 3$ arcsec/165sec $\approx$ 0.5 deg/day. For the Palomar photographic system, $r_s \approx 0.2$ deg/day, mainly as a result of the longer exposure time. The area occupied by a trailed image is

$$A' \approx rt\sqrt{A} \tag{8}$$

Using A' instead of A *in* Eqns. 2-7, wc obtain the limiting magnitude for a moving object with a CCD system:

$$m_{lim} = 22.07 + 1.25 \log \frac{D^2 Q}{r\sqrt{A}\,(S/N)^2}, \tag{9}$$

or for a photographic system:

$$m_{lim} = 17.2 + 1.25 \log \frac{D^2}{r\sqrt{A}}. \tag{10}$$

Note that m_{lim} does not depend *on* exposure time, provided it is long enough to result in a trailed image. If m_1 *is* the limiting magnitude for a non-moving point source, then the limit for an object moving at rate $r > r_s$ is:

$$m_{lim} = m_1 - 1.25 \log \frac{r}{r_s}. \tag{11}$$

Long Trailed Images

At some point, a trailed image becomes so long that it is impossible to integrate the full length of the smeared image to improve detection. We define the maximum length which can bc integrated as the *correlation length*, l_c. If the rate of motion is greater than $r_c = l_c/t$, the useful area of the image is $A' = \sqrt{A}l_c$, and the useful signal is:

$$S \propto IQD^2 \frac{l_c}{r} \tag{12}$$

The noise which underlies A' continues to increase with added exposure:

$$N \propto \sqrt{A' D^2 Q t} = \sqrt{A^{1/2} l_c D^2 Q t}\,. \tag{13}$$

Thus the signal-to-noise ratio is

$$\left(\frac{S}{N}\right) \propto \frac{I Q D^2 (l_c / r)}{A^{1/4} D (l_c Q t)^{1/2}} = \frac{I Q^{1/2} D l_c^{1/2}}{A^{1/4} r Q^{1/2} t^{1/2}} \tag{14}$$

The limiting magnitude for a CCD system becomes:

$$m_{\text{lim}} = 22.07 + 1.25 \log \frac{D^2 Q}{\sqrt{A}\,(S/N)^2} \frac{l_c}{r^2 t}, \tag{15}$$

or for a photographic system,

$$m_{\text{lim}} = 17.2 + 1.25 \log \frac{D^2}{\sqrt{A}\, r^2 t} \tag{16}$$

Note that m_{lim} decreases with increasing exposure time, and also falls off even faster with increasing rate of motion. For a given exposure time, the limiting magnitude is:

$$m_{\text{lim}} = m_2 - 2.5 \log \frac{r}{r_c}, \tag{17}$$

where m_2 *is* the magnitude limit for an object moving at r_c, computed from Eqn, 11. Fig. 1 is a plot of limiting magnitude vs. rate of motion in the sky for the three systems considered here. The correlation length, l_c, *we* have taken to be 10 times the

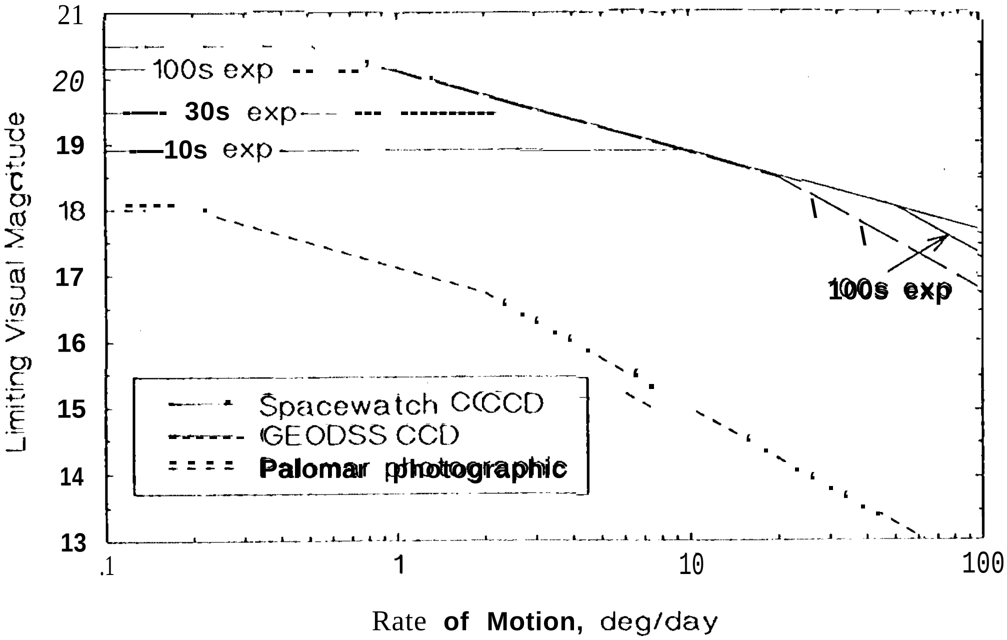


Fig. 1 Limiting magnitude vs. rate of motion in the sky for the three systems

trail width, or -30 arcsec, for the Palomar photographic system, and -100 pixels for the CCD systems. In principle, a trail can be correlated up to the full width of a CCD chip (-1000 pixels for thes ystems under consideration, allowing for images running off the edges), but carrying image correlations to such long images becomes rather computer intensive. It is clear from Fig.1 that the higher quantum efficiency of CCD detectors allows such systems to reach -2 magnitudes fainter than a comparable photographic system even for stationary targets. But of comparable importance is the fact that typical CCD systems retain sensitivity to much faster rates of motion, due to typically shorter exposures required, and hence gain even more over photographic systems for really fast **moving** NEAs.

RATE OF SKY COVERAGE

The Palomar photographic system requires -10 minutes cycle time for a 6 minute exposure. Thus it is capable of ~6 exposures per hour. Since each field is photographed twice, the rate of sky coverage is $R \approx 3$ x (5002/field) $\approx 150^{\circ 2}$/hr.

The *Spacewatch camera* is constrained to cover sky at sidereal rate, -1 50/hour near the equator, with a strip 0°.69 wide in declination, or - $10.35^{\circ 2}$/hr. Each strip is scanned three t imes. Allowing ~1 **5%** of the time for resetting, the net rate of sky coverage is $R \approx 3^{\circ 2}$/hr.

The GEODSS telescope with the planned CCD chip covers 1.96°* in a single exposure. It is planned to use it in a "stare" mode, tracking at sidereal rate. Thus the exposure time can be selected freely. The telescope is fully automatic and is capable of moving to a new field and settling on target in only -1 second. Assuming it takes three exposures of each field, like *Spacewatch*, then for exposures of 10, 30, or 100 seconds, R ≈ 200°2, 75°2, or 25°2 per hour, respectively.

Table II summarizes the derived characteristics of the three systems considered here. These parameters were used to construct Figure 1, and will be used in computing the relative figures of merit of the three systems in the following sections.

A system which is capable of a very high rate of sky coverage may run out of fresh sky to survey before new objects can move into place. The opposition region of the sky is "refreshed" when objects have had time to move -60° with respect **to the antisolar** position. Thus for objects nearly stationary with respect to the stars *(r* < 0.5 "/day), the seasonal change in the sky leads to a "refresh" time of -2 months.

TABLE 11 Derived characteristics for the systems considered

	Palomar 18"	Spacewatch 36"	GEODSS 1 m 10 Scc	30 sec	100 sec
m_1	18.0	20.5	18.9	19,5	20.2
r_s	0.2 ‘/day	0,5 °/day	10 “/day	3 °/day	1 “/day
l_c	10 “pixels”	100 pixels	100 pixels	100 pixels	100 pixels
m_2	16.8	18.5	16.8	17.4	18.0
r_c	2 “/day	20 °/day	500 °/day	150 °/day	50 ‘/day
$\mathcal{R}$	150°z/hr	$3^{\circ 2}$/hr	200 $^{\circ 2}$/hr	75 $^{\circ 2}$/hr	25 $^{\circ 2}$/hr

From experience with the Palomar systcm, a rate $\mathcal{R} \approx 150^{\circ 2}$/hr is capable of covering most of the useful sky area during a 14 night “dark run”. Thus for objects with $r \leq$ 0.50/day, the maximum *effective* rate of sky covcragc is $\mathcal{R}_{max} \approx 75\ ^{\circ 2}$/hr. For objects moving at r - 20/day, the opposition region of the sky is “refreshed” each dark run, so $\mathcal{R}_{max} \approx 150^{\circ 2}$/hr. For very fast moving objects, ncw objects can move into the field in a time short compared to the length of the “dark run”, so it can bc productive to cover the opposition region more than once during the run. To bc useful, the “refresh time" must bc less than -10 days, corresponding to $r >$ 60°/ 10 days = 60/day. Wc adopt values of $\mathcal{R}_{max}$ as listcd in Table 111.

Table 111. Maximum useful rate of sky covcragc *vs.* rate of object motion

r	$\mathcal{R}_{max}$
≤0.5°/day	75 $^{\circ 2}$/hr
1.0°/day	100 $^{\circ 2}$/hr
2.00/day	150°21hr
4.0°/day	$180^{\circ 2}$/hr
≥8.0 °/day	$(25r)^{\circ 2}$/hr

RELATIVE RATE OF DISCOVERY VS. RATE OF MOTION

The relative rate of discovci y of NEAs, $\mathfrak{R}$, is proportional to the volume of sky surveyed times the number of objects in the volume:

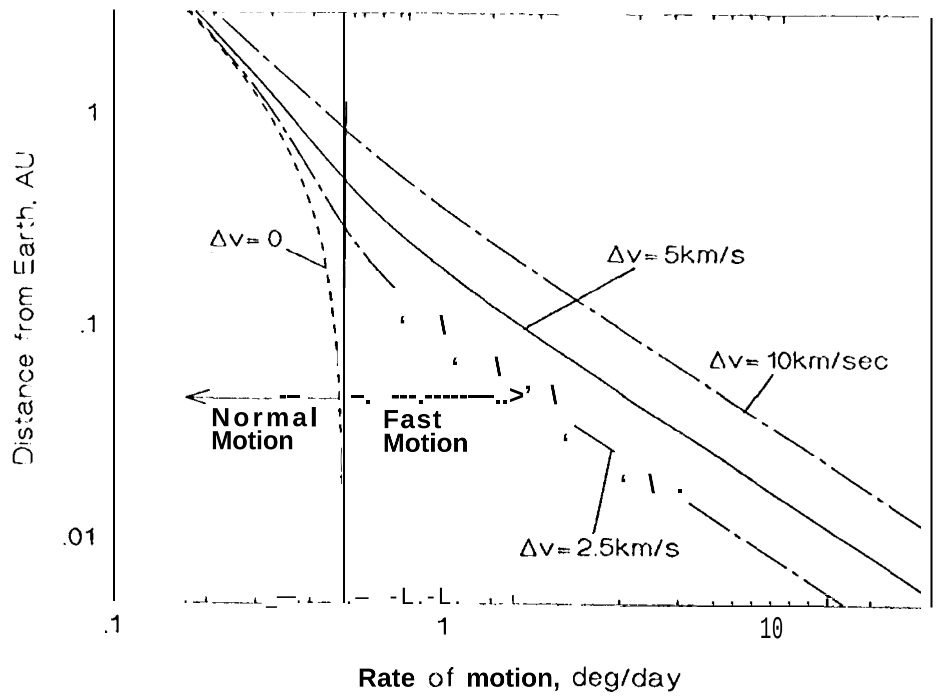
$$\Re = \Delta^3 R N(>D_{\lim}), \tag{18}$$

where A is the characteristic distance from the Earth, R is the square angle rate of surveying, and $N(>D_{\lim})$ is the population of NEAs $>D_{\lim}$. Since the above relation is actually only a proportionality, the numerical units of $\Re$ have no significance, but relative values are useful for comparing the expected rates of discovery between systems, or for rates of discovery of objects of different size for a single system. In order to evaluate the above, we need to relate the rate of motion in the sky, r, to a characteristic distance from the Earth, A:

$$r = \frac{\text{velocity relative to Earth}}{\text{distance from the Earth}} \approx \frac{\sqrt{v_{\text{Keplerian}}^2 + v_{\text{random}}^2}}{\Delta}, \tag{19}$$

where $v_{\text{Keplerian}}$ is the differential velocity between the Earth and an asteroid (radially outward a distance A from the sun) if both were in circular orbits, and v_{random} is the dispersion velocity of asteroids in their actual orbits, relative to circular orbits. For $v_{\text{random}} \approx 5$ km/sec:

$$r \approx \frac{\sqrt{\left[(1+\Delta)^{-1/2} - 1\right]^2 + 0.0278}}{\Delta} \text{ degrees/day} \tag{20}$$



Fig, 2 Expected rate of motion in the sky *vs.* distance from the Earth

For other values of v_{random}, the only change in the expression is the constant 0.0278, which is proportional to v^2_{random}. Hence for 2.5 and 10 km/sec, the constants arc 0.00694 and 0.1111, respectively. Figure 2 is a plot of average rate of motion in the sky vs. distance from the Earth, for values of v_{random} (labeled Av in the plot) of O, 2.5, 5, and 10 km/sec. 5 km/sec is average among main belt asteroids. $v_{random} \approx 10$ km/sec for NEAs. Thus the rate of motion in the sky generally constrains the probable distance of the NEA rather well.

For a given value of r, m_{lim} *is* defined for a given system. Knowing A, wc can find the corresponding diameter of asteroid, D_{lim} from:

$$m_{lim} = 18.0 + 5\log[\Delta(1 + A)] - 5\log(D_{lim}), \qquad (21)$$

where the constant 18,0 is appropriate for asteroids of moderate albedo (O. 10), typical of known NEAs. Having determined D_{lim}, we can determine $N(>D_{lim})$ from the estimated population of NEAs (e.g., Rabinowitz *et al.* 1994), which wc take to be the following:

$D > 2$ km	$N(>D) = 7310D^{-4\;\;19}$	
2 km> D > 0.1 km	$N(>D)$ = 1878D-223	(22)
$D < 0.1$ km	$N(>D) = 68311\text{-}^{2\,‘7}$	

Wc now have all the necessary parameters to evaluate Eqn. 18. Consider as an example the *Spacewatch* system, for objects with a motion in the sky $r = 20$/day. From Fig, 1, $m_{lim} = 19.747$. From Fig. 2, for $v_{random} = 5$ km/sec, wc estimate A = 0.0857. From Eqn. 21, for these values of m_{lim} and A, wc find D_{lim} = 0.04162 km. From Eqn. 22, we obtain $N(>D_{lim})$ = 3.326 x 10’. Thus wc obtain from Eqn. 18 the relative rate of discovery for this system for objects with sky rate of motion of 20/day:

$$\Re = (0.0857\ )^3(3^{\circ 2}/\text{hr})(3.326 \text{ x } 10’) = 6280 \qquad (23)$$

We have evaluated Eqn 18 for the three systems under consideration, including 10, 30 and 100 second exposures for GEODSS, for range bins of a factor of 2 in rate of motion in the sky. Fig. 3 is a plot of the results, with a different normalization for $\Re$. In Fig. 4 wc have plotted the same data, but using object diameter as the abscissa.

By integrating the curves in Fig. 3 or 4, one can arrive at the relative rate of all NEA discoveries for each of the systems considered, and median rate of motion and median diameter of discoveries for each system can be calculated. Table IV is a summary of those results. For the total rate of discovery, wc have renormalized the rates to equal 1.0 for Palomar, since the rate of discoveries from that system are well documented.

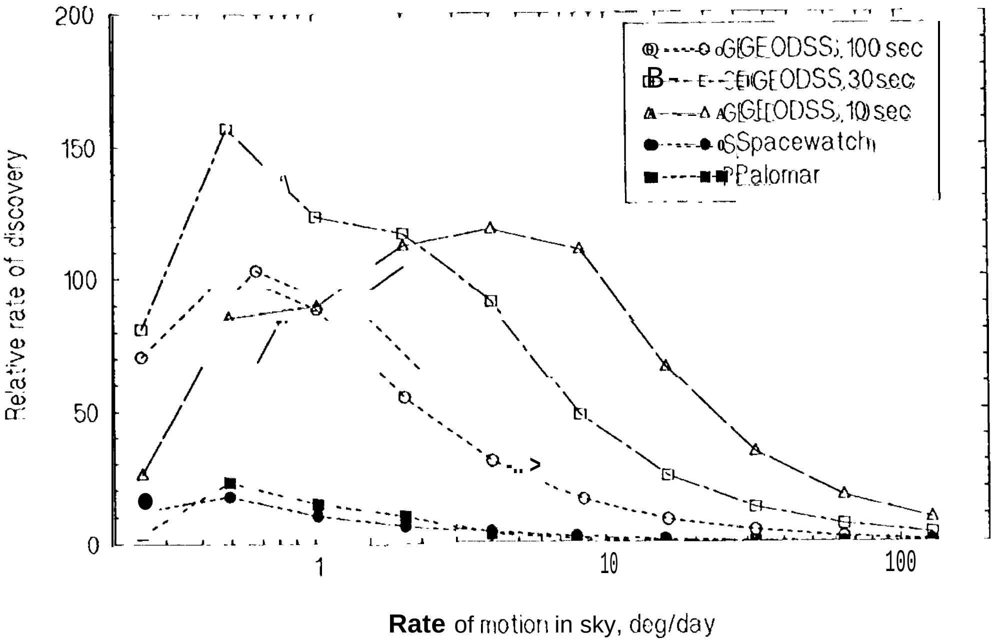


Fig. 3 The relative rate of discovery of NEAs for each of the systems evaluated *vs.* the rate of motion of detected objects in the sky.

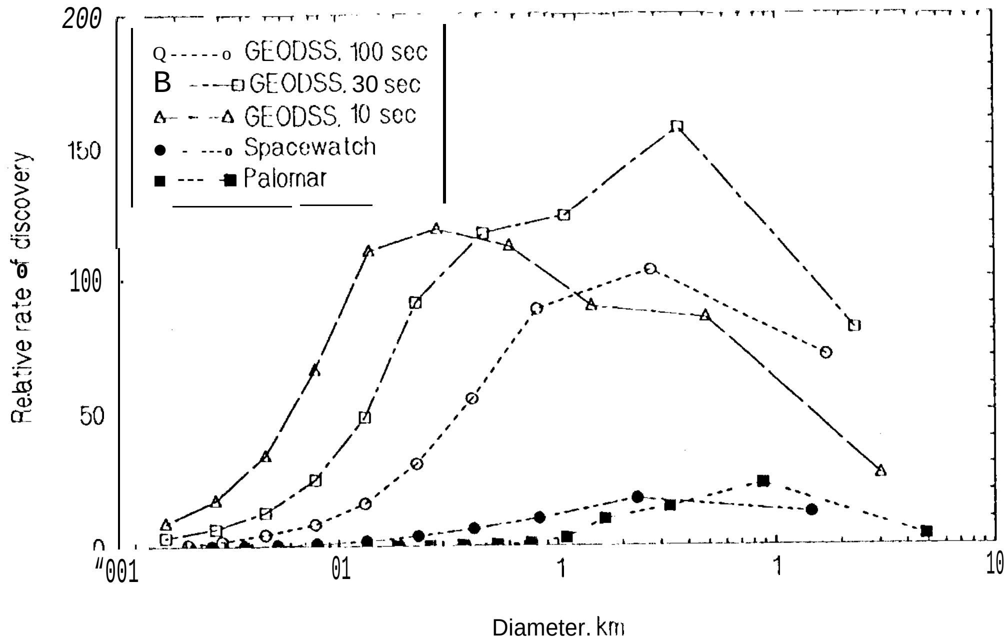


Fig. *4* The relative rate of discovery of NEAs for each of the systems evaluated vs. the diameter of objects detected.

TABLE IV Summary of rate and median characteristics of discoveries

	Relative rate of all discoveries	Median rate of motion	Median diameter
Palomar	1.0	0.8 "/day	0,5 km
Spacewatch	1.0	0.6 "/day	0.2 km
GEODSS 100s	7	0.8 °/day	0,1 km
GEODSS 30s	12	1.3 °/day	0.08 km
GEODSS 10s	12	3.0 °/day	0.04 km

SUMMARY AND CONCLUSION

Interestingly, *Spacewatch* and the Palomar photographic systems have very similar overall figures of merit, in terms of total rate of discoveries. We predict that a GEODSS telescope, configured with the CCD chip we have discussed, should be capable of discovering NEAs at approximately ten times the rate of either *Spacewatch* or Palomar, The systems differ substantially in the median sizes of objects discovered. The Palomar system discovers predominantly objects -0.5 km in diameter. The CCD systems, owing to their higher quantum efficiency and consequent shorter exposures, tend to discover faster moving, and hence smaller objects, typically of order 0.1 km in diameter. Because of this, *Spacewatch* and other C(D systems contemplated in the near future, are scientifically very interesting, as they are exploring a previously unsampled size range of the NEA population.

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