AUTOMATED CCD SCANNING FOR NEAR EARTH ASTEROIDS

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ABSTRACT: The Spacewatch group at the University of Arizona's Lunar and Planetary Laboratory was probably the first (1984) to implement CCD-scanning in a major astronomical program. In the past three years, using a Tektronix 2048 x 2048 CCD, the program has discovered ~ 45% of the new Earth approaching asteroids, measured astrometric positions for over 50,000 main belt asteroids, discovered two of the three known Centaurs, and found evidence for an unheralded population of small (~ 10-m) objects in the inner solar system. This success is due to the automated Moving Object Detection Program (MODP) which searches successive scans over the same region for objects showing consistent motion. While visual examination of photographic plates may have a higher efficiency, an automated routine for detecting moving objects does not tire and is repeatable. Our recent work quantifies the efficiency of MODP as a function of the asteroid's magnitude, rate of motion, and orbital parameters. Other work suggests that the observational detection of faint, trailed, Fast Moving Objects may be improved by incorporating linear darkfield subtraction and flatfielding during scans.

1. INTRODUCTION

In 1981 Spacewatch began the first long term, CCD-based, discovery program for Near Earth Asteroids (NEA) utilizing the Steward Observatory's 0.91-m f/5 Newtonian at Kitt Peak. The RCA SID 53612 512 x 320 pixel CCD used at the outset lacked the areal coverage necessary for detection of the sparsely distributed and faint NEAs. In 1988 a thick, front-illuminated, Tektronix TK2048SP 2048 x 2048 pixel CCD was delivered and the software required for real-time analysis of the images was developed by D. L. Rabinowitz (1993a). The first automated discovery of an NEO (1989 UP) was on October 27th, 1989, and since that time Spacewatch has found over 75 NEAs, two Centaur class asteroids, two comets, and recorded astrometric positions for over 50,000 main belt asteroids. Yet another twofold improvement in the NEA discovery rate was achieved in 1991 with the delivery of a thinned, back-illuminated, Tektronix TK2048EB1 2048 x 2048 pixel CCD with twice the quantum efficiency of the earlier Tektronix device.

Until recently, there existed little quantitative understanding of the absolute efficiency of the detector and software systems even though this information is critical to a meaningful analysis of the data. Like photographic surveys for moving asteroids which are limited by the magnitude cutoff of the system for faint objects and by over-exposure for bright objects, a CCD search is similarly limited at faint magnitudes and by pixel saturation for bright objects. Asteroid detection is also affected by crowded star fields, seeing conditions, etc. An advantage to the use of an automated routine for locating the objects is that it does not tire and its results

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are repeatable. This study presents a determination of Spacewatch's asteroid detection efficiency using the set of numbered asteroids as a benchmark.

2. AUTOMATED DETECTION TECHNIQUE

Spacewatch operates the telescope and CCD in a *drift scan* mode where the telescope drive is turned off during an exposure. Instead of tracking the telescope with the stars, the charges generated on the CCD representing the star's image are transferred across the face of the CCD at the same rate as that of the star's image due to sidereal motion. When the star's image passes off the CCD the charge is read out and almost instantaneously displayed on a computer screen. An image of the sky is built up during a scan which has a fiducial extent of about 32' in declination and a practicable length of up to forty-five minutes in right ascension.

Each scan is repeated three times over the same section of sky. While the image is being read from the CCD and displayed on the computer screen, MODP searches through the image seeking out point sources and also streaks which may be consistent with an interpretation as nearby Fast Moving Objects (FMO). The streak detection mode is efficient for bright objects moving with angular rates of motion (ω) greater than about 2°/day. Streaks are identified in real-time within each of the three passes of a scan and their locations are highlighted in order to notify the observer who decides on the credibility of the object.

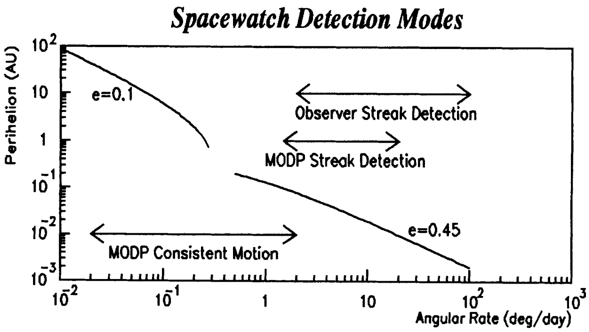

Fig. 1. Spacewatch NEA detection modes as a function of rate of motion and distance. Distances were calculated for the eccentricity specified on the figure and for objects at perihelion and opposition.

In the range 0°.02/day < ω < 2°/day MODP detects objects through their consistent motion from pass to pass. Point sources identified in the second pass are matched with sources in the first pass. Most of these are stars which align exactly with one another except for a small offset (normally less than about 10") in right ascension and declination. The offset is determined and corrected in software. When there is no direct match in the first pass for a source in the second pass, MODP searches (normally a radius of 120 pixels) for a second unmatched point source. When an unmatched point source is identified in both passes MODP assumes that they are the same object and predicts its location in the third pass assuming that it moves at a consistent rate. During the third pass MODP matches triplets of otherwise unmatched point sources with consistent motion and informs the observer of the location, brightness, and direction of motion of the new object.

A third mode of NEA detection relies entirely on the observer to identify faint and/or long trails missed by the automated streak detection. These Very Fast Moving Objects (VFMO) are typically within 0.2 AU of the Earth, are moving at $\omega > 2°$/day, and have signal to noise (S/N) in a single pixel between one and three. Their proximity to the Earth, small size, and extreme rate of motion make them exciting objects to follow during the few days in which they are visible.

Fig. 1 indicates the modes of NEA detection used by Spacewatch as a function of the range in rate of motion and distance to the object. The distance has been calculated for objects found at opposition and at perihelion. In the range $0.01 < \omega < 0.3$ (in °/day) the distance has been calculated for asteroids with $e = 0.1$ while for $0.5 < \omega < 100$ the eccentricity is set equal to the mean for the Spacewatch NEAs ($e = 0.45$). The limit at the lowest rate of motion is determined by the rate required for the object to move two pixels during the time interval between passes. The limit at the highest rate of motion is set by the ability to distinguish between meteors or faint satellites (which traverse the entire field of view in declination or about 2048 lines in right ascension) and VFMOs (which are required to begin and end within a single frame). At the highest rates of motion the system has been limited by the ability of the observer to identify the object and calculate its position at the middle of another scan though new software now automates this process as well.

3. AUTOMATED DETECTION EFFICIENCY

The principle of "blinking" images of the same piece of sky to detect objects which move against the background of stationary stars was established more than sixty years ago. Except for the introduction of the *blink comparator* this tradition continues essentially unaltered at observatories around the world. Two of the three contemporary NEA discovery programs (both of them utilizing the 18" Schmidt at Palomar) use a stereoscopic viewing device which makes moving objects appear to "float" above the background. When carefully implemented, the blinking technique can be very efficient in the range of magnitudes from where the photographic images are not overexposed to close to the limiting magnitude of the system. For example, the Palomar Leiden Survey of Faint Minor Planets (Van Houten et al. 1970) reported efficiencies of 100% in the range $14.0 < m < 19.5$ and 70% in their last bin where $19.5 < m < 20.0$.

The efficiency of the automated Spacewatch CCD system has been determined using the database of 5856 numbered asteroids as a benchmark. Scans are performed preferentially near opposition to take advantage of the opposition effect (where asteroid apparent magnitudes are at their brightest) and along the ecliptic. These two strategies also favor the recovery of known asteroids. Since each of the numbered asteroids has a well determined orbit it is possible to predict their apparent location to within a few arcseconds. Thus, a search was initiated through the Spacewatch archive of astrometric positions from the past two years for serendipitous observations of known objects. Every asteroid which should have appeared in a scan was recorded, as well the measured position, magnitude, rate of motion, etc., for those objects which were actually detected by MODP. Dividing the observed by the expected distribution determines the efficiency of the system.

Fig. 2a shows the detection efficiency across the CCD. The exceedingly low efficiency in the first bin is due to a "forest" of cosmetic defects in the first 220 columns of the CCD. All other efficiency plots in this paper represent only the CCD columns between 221 and 2048. The efficiency is consistent with being constant and equal to about 55% over the rest of the CCD.

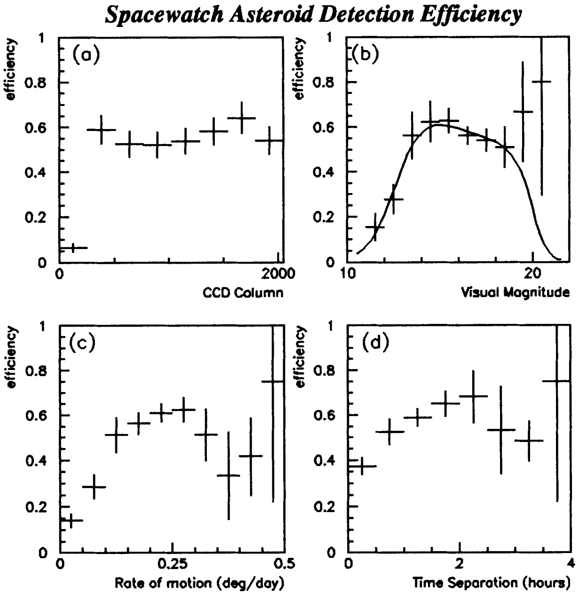

Fig. 2a. Spacewatch asteroid detection efficiency as a function of CCD column. b. efficiency vs. asteroid's rate of motion, c. efficiency vs. apparent magnitude, d. efficiency vs. time separation between observations.

Fig. 2b gives the efficiency as a function of the visual magnitude of the asteroid. A plateau is visible between magnitude 13.5 and 18.5 along with a steep drop for bright objects with the efficiency reaching about 10% of its maximum near magnitude 10.5. The apparently high efficiencies in the last two bins are significantly different from the efficiency determined by the method of Rabinowitz (1993b). His technique extrapolated the observed magnitude distribution of all asteroids detected by Spacewatch, from a range in which the detection efficiency was thought to be nearly constant, to the high magnitude limit. Dividing the actual by the extrapolated distribution gave an indication of the efficiency at faint magnitudes. The problem with his technique is that it assumes the efficiency is flat in some otherwise unknown range of magnitude, that the real distribution of asteroid magnitudes is represented accurately by a power law over the entire range, and that the choice of scanning regions has not biased the apparent magnitude distribution in an unusual manner. Unfortunately, at this time, it represents the only available measure of the efficiency near the magnitude cutoff of the Spacewatch system. The curve superposed on the efficiency vs. magnitude plot is a fit to a function of the form:

$$\epsilon(m) = N(sm + b)\left[\frac{1}{1+\exp(\frac{m-m_H}{w_H})} - \frac{1}{1+\exp(\frac{m-m_L}{w_L})}\right]$$

where N is an overall normalization, ($sm + B$) provides the sloping "plateau", and the last term provides a "smoothed box car" function spanning the range $m_L < m < m_H$). The efficiency falls off at the lower and upper edges over a range given by w_L and w_H respectively. In practice, m_H and w_H were fixed at values consistent with the shape of the efficiency curve obtained using the method of Rabinowitz. The values of the parameters are: $N = 0.95 \pm 0.51$, $s = -0.032 \pm 0.010$, $b = 1.1 \pm 0.3$, $m_L = 12.7 \pm 0.3$, $w_L = 0.73 \pm 0.22$, $m_H = 20.0$, $w_H = 0.4$.

The ill-defined cutoff at high magnitudes is due to the intrinsic limits of the Spacewatch camera and variability of local conditions. The drop at bright magnitudes is due to saturation of the point sources at visual magnitudes of about 12. The "plateau" is barely consistent with being flat and the maximum efficiency is about 62% at magnitude 15.

The efficiency as a function of the rate of motion of the asteroid is shown in Fig. 2c. Since numbered asteroids were used in this study it is no surprise that this range of rates is a good representation of typical main belt rates observed at opposition. The reduced efficiency for low rates of motion is due to the requirement that an object must move at least a couple pixels during the interval between passes in order to be detected as non-stationary. Since these plots represent an average over all scan intervals (which range between 10 and 90 minutes) the minimum detectable rate varies by about an order of magnitude and this is reflected in the gradual increase in efficiency to about 50% near 0.125°/day. The efficiency for detecting typical MB objects ($\omega \sim 0.2°$/day) is good. The apparent decrease in efficiency for faster rates may be due to the fact that when the time interval between scans is large, faster objects move outside the 120 pixel search radius. It is also possible that the decrease in efficiency is due to a problem in determining the centroid of slightly trailed objects. If the centroid is improperly determined, the link between scans, which depends upon an accurate measure of the rate of consistent motion, may be inefficient.

Finally, the last of the plots in Fig. 2 shows the efficiency as a function of the time separation between the first and third of the observations. The efficiency for MB asteroids increases to a maximum at about two hours because the slower moving asteroids are detected more often when there is sufficient time between the observations. The decrease in efficiency at greater times is due to the fixed search radius within MODP. It is difficult to have a variable search radius due to the fact that the number of false candidates increases as the square of the radius as does the computing time required for the search. Thus, the empirical setting of 120 pixels maximum search radius creates an effective variable limit on the maximum detectable asteroid rate which is inversely proportional to the time separation between scans.

Figs. 3a-c show the efficiency of the Spacewatch camera and software systems as a function of three orbital parameters for the numbered asteroids. If all the asteroids were on purely circular orbits there would be an exact correlation between their distance and rate of motion at opposition. Since the efficiency is rate dependent this would cause an apparent relationship between the detection probability and the orbit of an asteroid. In actuality, the spread in eccentricities of asteroids with a given semi-major axis within the main belt is wide enough to mask the rate dependent effect. In addition, if the software preferentially found objects moving in either right ascension or declination there would be a bias towards or away (respectively)

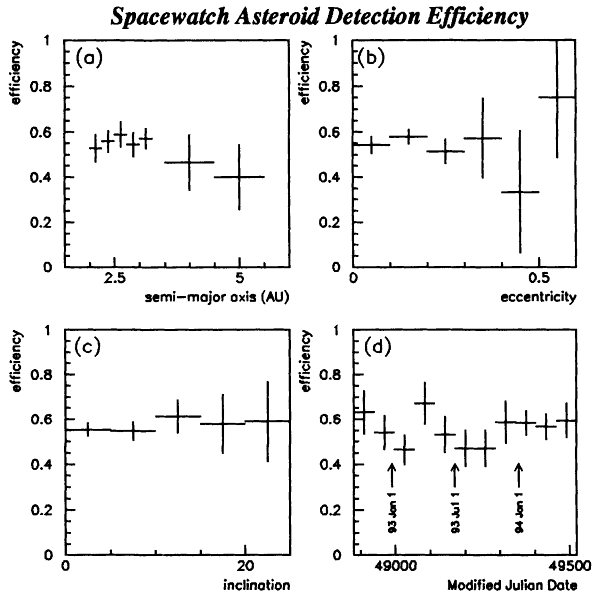

Fig. 3a. Spacewatch asteroid detection efficiency as a function the semi-major axis of an asteroid's orbit, b. efficiency vs. asteroid's orbital eccentricity, c. efficiency vs. asteroid's orbital inclination, d. efficiency vs. Modified Julian Date.

from objects of low orbital inclination. Fortunately, the efficiency is consistent with being constant in all three parameters of semi-major axis, eccentricity and inclination.

The first five data points in Fig. 3a are equally distributed through the main belt while the last two points correspond to the Hilda and Trojan mean semi-major axes respectively. Although the data are consistent with being constant, the fact that Trojan asteroids are almost twice as distant as the average main belt asteroid does result in their rate of motion being about one-half that of the main belt asteroids at opposition. Thus, short intervals between successive observations does bias against detection of the Trojan group of asteroids.

In the interest of successfully debiasing observations for detection efficiency it is desirable to have a system operating consistently over time. Fig. 3d shows the efficiency as a function of time and indicates that the efficiency has been more consistent since this study was performed in late 1993. Unavoidable temporal variations in the detection efficiency may continue to linger due to seasonal changes in weather/seeing and also in the density of stars per unit area. When seeing conditions are bad the stellar point spread function is spread out over more pixels which decreases the probability that an asteroid image will be detected by examining the individual pixel's signal-to-noise (S/N $\equiv \sigma$) ratio. The inverse relation between stellar image density (stars/area) and detection efficiency is due to two factors: (1) the opportunity for increased confusion between faint stars (which may appear in one image and not in the next due to seeing variations) and asteroid candidates and (2) the increased likelihood of at least one of the asteroid's images lying within the saturated area of a star's image.

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The plots in Figs. 2 and 3 represent the efficiency for the automated real-time detection of asteroids by MODP using the consistent motion technique. The technique is amenable to quantitative determinations of its absolute efficiency using the numbered main belt asteroids. However, the results are not strictly applicable to the majority of Spacewatch's NEAs since they are distinguished as such from the plethora of main belt objects by their characteristically high rates of motion - in the upper range of rates explored (and beyond) using the technique described here.

Many of the NEAs found by Spacewatch are close enough to the Earth that their images are trailed due to motion during a typical 150 second exposure. The efficiency of MODP's streak detection ability will be difficult to calculate as will the efficiency of the observer's ability to detect faint trailed asteroid images. Not only might there be differences in the ability of each observer to locate and identify these faint trails at the one and two σ level, there may be subtle variations in the mind's perception of faint trails in the vertical, horizontal and intermediate directions. Faint meteors, cosmic rays, strangely "linear" edge on spiral galaxies, subtle variations in the sky background, etc., may inadvertently pique the interest of an observer and, in dense regions of the sky, litter the CCD image with false FMO and VFMO candidates. All of these effects will introduce a bias into the observations which makes it difficult to interpret the data.

Many of the VFMOs detected by the observers have been trailed over hundreds of pixels with peak S/N in individual pixels along the trail of only one or two. Their detection relies on a good background subtraction before being displayed. At the present time, the correction is applied by removing the median background signal in bands 50 pixels high over the full 2048 column width of the CCD. Since the images are formed by drift scanning, every pixel in a CCD column contributes an equal share to the final image. In this way, pixel efficiency variations in the CCD row direction are averaged and, to first order for a good CCD, there is no need for flat-fielding. In the Spacewatch system, a remnant 1 - 2% difference in the CCD response is visible and should be applied as a one-dimensional column correction in order to flatfield the resulting image. Applying this correction will provide greater opportunity for discerning the faint VFMOs within the background noise at the 1 - 2 σ level. The detection of the NEAs through consistent motion is not affected by the column dependent flatfield because MODP does a local background subtraction around each possible source.

4. CONCLUSIONS

Any analysis of the Spacewatch data to determine a magnitude-frequency relationship must compensate for the efficiency of the detector system as a function of apparent magnitude. In addition, studies of the orbital element distributions require knowledge of the efficiency as a function of those observable parameters which depend upon the significant orbital elements. This study has presented a technique which is being used to determine the magnitude-frequency relation of the main belt asteroids and which will be equally applicable to any set of Spacewatch asteroids detected through consistent motion by MODP (NEAs, Trojans, etc.). Other techniques are being developed to better explore the efficiency in the faint magnitude limit.

The mean efficiency of about 57% in the range from visual magnitude 13.5 to 18.5 implies that the real-time detection system is missing about 1/3 of the available asteroids. The most likely culprit for the loss of these asteroids is the routine which searches for sources within the CCD image by comparing the signal within individual pixels to the background noise level. When MODP was written there was insufficient computing resources available for a more sophisticated search for point sources and an impression that the search must be performed in real-time. With the purchase of faster computers and the development of new software it may be possible to achieve a significantly higher detection efficiency.

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DISCUSSION

PHILIP: Is there any interest in your group in the stellar information contained in your scans? You should have much interesting information concerning some types of variable stars if you scan areas three times.

JEDICKE: There is a lot of interest in our group in all of the information contained in our scans - there is just not enough time to utilize it fully! We are always seeking useful collaborations.

GUSEVA: What is the precision of your positions and magnitudes? May be, the precision in magnitudes is worse due to the drift-scanning mode?

JEDICKE: Our astrometric positions are good to about 1/4" while our magnitudes are probably good to about 0.3 to 0.5 magnitudes. The drift scanning technique does not contribute to the error in the measured magnitudes.

IWERT: What would you call the ideal CCD for this program and of what kind of options in the CCD and the controller you could think to carry out this program even more effectively in the future?

JEDICKE: The ideal CCD and controller system is intricately linked to the telescope. In general, large scale or mosaic CCDs, with fast and flexible readout for both drift scan and stare modes of operation are desirable.

SCHILLING: What would be detection frequency of objects on a collision course? (based on current statistics)

JEDICKE: I believe that the detection frequency of objects which will actually collide with the Earth is very small at current rates. The smallest objects detected by spacewatch are amongst the largest meteors - about five - ten meters in diameter. These objects strike the Earth perhaps once a year. The probability of detecting one prior to impact is very low.

SZECSENYI-NAGY: What are the limitations of this program in sky coverage? I mean what is the declination zone you are able to "space watch" regularly?

JEDICKE: The declination scanning limit is set by the amount of "smearing" we accept in the CCD image due to the effect of differential rotation in declination across the 0.5 width of the CCD in declination. We try to scan only within 20° of the equator.

CRAWFORD: Does the observer see space debris streaks? Are they being logged?

JEDICKE: The space debris is being seen and logged but not followed up.

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