

DETECTION OF EARTH-APPROACHING ASTEROIDS IN NEAR REAL TIME

D. L. RABINOWITZ

Lunar and Planetary Laboratory, The University of Arizona, Tucson, Arizona 85721

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ABSTRACT

This paper describes a computer program which is detecting Earth-approaching asteroids in near real time. The detection software runs on a Solbourne workstation computer at the site of the 0.91 m Spacewatch Telescope of the Steward Observatory on Kitt Peak. During the dark half of the month a Tektronix TK2048 CCD is mounted at one of the two Newtonian ports and operated in drift-scanning mode. Asteroids are detected by making three successive scans of the same field of view. During the first and second passes, the software can recognize fast moving objects by the trails they leave in the image. During the third pass, a moving object is detected by the displacement of its position in the first two passes relative to its position in the third. During 2 months of trial observing with this system (19 nights in May and June of 1990, covering 150 square degrees) 304 asteroids were detected down to a limiting apparent magnitude for untrailed images of $V = 20.5$. A comparison of the observed angular rates of motion with predicted rates for known orbit types shows that these are mostly main-belt asteroids, but also include some Hungarias, Phocaeas, Hildas, and one probable Mars crosser. The system also detected Earth approachers 1990 HA and 1990 MF. A study of the Earth-approaching asteroid distribution shows that this CCD system will be able to detect these objects and identify them based on their rate of motion before they approach the Earth, when they are moving less than $0.4^\circ/\text{d}$. The analysis also shows that the discovery rate of the fast-moving Earth approachers can be enhanced by moving the telescope rapidly across the sky. An ~ 2 m telescope designed for this purpose might discover Earth approachers at a rate 10 times greater than conventional techniques.

1. INTRODUCTION

The discovery of 1989 UP with the Spacewatch Telescope of the Steward Observatory on Kitt Peak (IAU Circular No. 4887) was the first near real-time detection with a charge-coupled device (CCD) of a member of the Aten, Apollo, or Amor groups of asteroids. To be a member of one of these groups, hereafter referred to as Earth approachers, an object must have a perihelion distance no larger than 1.30 AU. Such objects are usually discovered when they near the Earth and appear with a relative angular rate much higher than that of the more distant asteroids. They are then recognized by the signature trails they leave in a photographic image (Helin & Shoemaker 1979). 1989 UP was recognized by the trailed image with which it appeared on a video monitor as soon as the signal was shifted off the CCD for display. Using on-line software, the object's position and angular rates were readily determined, and mailed electronically to the Minor Planet Center in Cambridge, Massachusetts. This lead to further observations only 4 hr later by R. H. McNaught at Siding Spring Observatory, Australia (IAU Circular No. 4887). The only other Earth approachers that have been detected in near real time and reported in this way are 1983 TB and 1983 VA from the *IRAS* search for fast-moving objects (Green *et al.* 1985). Because most discoveries are made by visually examining photographic plates, there is usually a considerable delay (a few hours to a few days) between the time a plate is exposed and the time the object is discovered. More time is then required to make an accurate measurement of the position and rate of motion. Since prompt follow-up observations and their immediate reporting can be critical to continued observation of the fastest Earth approachers, near real-time detection techniques, as evidenced by the discovery of 1989 UP, are especially suited to this purpose.

In Secs. 2 and 3, this paper describes a computer routine

called the Moving Object Detection Program (MODP) which detects Earth-approaching asteroids in near real time. The software runs on a workstation computer which is linked to the output of the drift-scanning CCD camera of the Spacewatch Telescope. MODP recognizes trailed images, detects motion, and accurately determines angular positions and rates of motion for moving objects in the scan images. The results are obtained a few seconds after the image signals are shifted out of the CCD. In May and June of 1990, MODP was put into trial operation for a total of 19 nights, covering an area of 150 square degrees. Over 300 slow moving objects were detected, and the system also detected two fast-moving Earth approachers that had been discovered elsewhere. A comparison of the observed angular rates of motion for the slower objects with predicted rates for known asteroid orbits types shows that these were mostly main-belt asteroids, but also included Hungarias, Phocaeas, Hildas, and at least one probable Mars crosser.

Although no new Earth approachers were discovered during these trial runs, Secs. 4 and 5 of this paper will show that they can be detected and identified with the CCD system before they approach the Earth, when they are moving too slowly to leave a trailed image. They are distinguished from the other asteroids by the magnitude and direction of their angular motion. This is a capability not shared by conventional photographic methods which do not have a limiting magnitude faint enough to detect these slowly moving Earth approachers. The analysis also shows, however, that the detection of Earth approachers when they are near the Earth and fast moving can be improved by driving the telescope rapidly across the sky at an optimized rate. Although this degrades the limiting magnitude of the CCD system, it increases the area coverage and thus increases the rate of discovery for both fast and slowly moving Earth approachers. The scanning CCD system described here, with the incorpo-

ration of a near real-time detection program, is thus an improvement over conventional observing methods for the detection of Earth approachers when they are distant from the Earth. By driving the telescope rapidly across the sky, it can also be competitive for the detection of the nearby, fast-moving objects.

2. THE SCANNING CCD SYSTEM

The Tektronix TK2048 CCD mounted at the south Newtonian port of the Spacewatch Telescope and the drift-scan mode of CCD operation have been described elsewhere (Gehrels *et al.* 1985; McMillan *et al.* 1986; Gehrels *et al.* 1990; Rabinowitz *et al.* 1990). As described in those papers, the telescope drive is turned off and a microcomputer with an Intel 80386 microprocessor is used to read out the CCD so that signal charges move across the CCD at the same rate as the sky image. A Solbourne series 5/600 workstation computer with three 62-bit processors (scalable architecture "SPARC" chips), 32 megabytes of memory, and an 8-bit grey-scale monitor with 1152×900 pixels has been linked to the microcomputer by a 16-bit parallel bus. This workstation supports the Sun Unix operating system and the Sunview mouse-controlled, windowed interface. MODP appears as a window in this display environment. As each line of the CCD image is clocked into the serial shift register, it is read out by the microcomputer and passed on to the workstation. There the data are displayed, recorded on magnetic tape (an Exabyte 8 mm tape drive), and searched for moving objects. As each moving object is discovered, its image is copied to a separate "gallery" window for verification by the observer. The user can interact with MODP via keyboard and mouse commands while a scan is in progress. For example, changes may be made to the criteria for object detection and the grey-scale levels of the image. Portions of the image may be selected and stored on disk as "snapshots" for later review. These interactions are described in detail in Sec. 3.3, below.

3. METHODS FOR OBJECT DETECTION

Asteroids are detected by making three successive scans of the same field of view. Typically, each scan is 30 min long, which is the equivalent of about 22 000 line transfers for scans made at 0° declination. During the first and second passes, MODP recognizes fast moving objects by the trails they leave in the image. On the third pass, a moving object is detected by the displacement of its position in the first two passes relative to its position in the third pass. We refer to these two modes of object recognition as "streak detection" and "motion detection," respectively. A third operation, which must be performed by both the observer and the software, is "error rejection." Because of random noise in the image, MODP may fail to detect an object which is moving ("detection failure"), or may mistakenly report a stationary object as a moving one ("erroneous detection"). Unfortunately, the rates at which these two errors are made cannot both be minimized at the same time. Since the discovery of an Earth approacher is a rare occurrence and it is the purpose of MODP to detect them, the program is adjusted so that the rate of failed detections is as small as possible. An attempt is also made to keep the erroneous detection rate small, but not by increasing the rate of failed detections. The observer is therefore counted upon to visually examine each candidate object reported by MODP and reject the erroneous ones. The interactive interface that MODP offers the observer was designed for this purpose.

3.1 Streak Detection

The method used by MODP to detect streaks is similar to digital methods used to classify and count galaxies on Schmidt plates (Jarvis & Tyson 1980). Each object in the digitized image of a plate is first identified. Then a set of classifiers, or quantitative object properties, are evaluated for each object. These classifiers are used to discriminate galaxies from stars and other objects in the image. If their values are within the ranges expected for galaxies, the object is so classified. In the present case, a set of classifiers have been adopted which discriminate trailed images from galaxies, stars, double stars, cosmic ray tracks, diffraction spikes, noise spikes, and other stationary objects that may appear in the scanned images. If the value of any given classifier is outside the range expected for trailed images, the object is not reported. The classifiers used are: *size*—the length of the minor axis of an ellipse fit to the moments of an object's image intensity profile (Stobie 1980; Sebok 1980); *aspect ratio*—the ratio of an object's major axis length to its minor axis length; *uniformity*—the rms ("root-mean-square") deviation of an object's intensity profile along its major axis, normalized to the expected deviation for a streak with the same length and same mean intensity; *asymmetry*—the rms fractional change in an object's intensity profile when reflected through its minor axis; *goodness of fit*—the rms deviation of the object intensity profile from a template trail of the same size, orientation, and peak intensity, normalized to the peak intensity of the object.

An acceptable streak must have a size greater than or equal to the size of a faint star at the limit of detection (~ 2.0 arcsec) and its aspect ratio must be greater than 2. Since the image scale for the CCD at the Spacewatch Telescope is 1.21 arcsec/pixel, this sets a lower bound of 2 pixels for an object's size. No upper bound is set for this parameter, nor is one set for the aspect ratio. The acceptable ranges for uniformity, asymmetry, and goodness of fit start at zero. Their upper bounds extend to values that are heuristically determined. The program is trained on prerecorded scans of the sky in which the trailed images of Earth approachers are present (e.g., 1989 UP). Artificial trails, modeled from the image profiles of stars, are also added. The full range of stationary objects MODP is expected to ignore are already present in these scans. MODP is then repeatedly tested, adjusting the classifier ranges by trial and error, until the error rates meet the criteria discussed above.

3.2 Motion Detection

The motion detection method used by MODP is based on an earlier program written by J. V. Scotti (McMillan *et al.* 1986), but adapted for real-time operation and a larger format CCD. In essence, the method requires that every object in three successive scan images of the same region of sky be identified. A list is created for each scan which describes the position and brightness of each object. Each list is then examined for position entries that appear in neither of the other two lists. These unmatched positions correspond to objects that either changed position from one scan to the next or appeared in only one scan. The latter are noise events, while the former may be the moving objects of interest. Fortunately, the two are distinguishable because only a moving object appears as an unmatched position in all three lists and generates a position which changes linearly with time of observation (i.e., a constant angular velocity). The moving objects

are therefore found by comparing the three lists a second time. Sets of three unmatched positions that form a linear, constant-velocity trajectory, and for which the brightness of the observed object is approximately constant, are recognized as moving object positions. Because the observed brightness of an object may change between scans, owing to clouds or variations in the object's own intrinsic brightness, changes of 50% or less are tolerated. Also, the measured trajectory must have a constant velocity only to within the precision of the position measurements (about ± 1 pixel).

This method of motion detection requires one additional operation. Because of telescope pointing error and atmospheric refraction, consecutive scans will not cover precisely the same region of sky. A stationary object will not appear at precisely the same position in any two scans. However, this change in position is the same for each stationary object in the same scan. Once the offset has been determined, it can easily be subtracted whenever the entries from two position lists are compared. MODP determines this offset by generating binary images of each position list. These are images which have the same angular resolution as the CCD image, but consist of two intensity values only. Wherever an object was found, the value is one. Everywhere else the value is zero. These binary images are then cross correlated, yielding correlation strength as a function of the position offset between the two images. The offset that maximizes this correlation function is the pointing error offset.

As has been described, the motion detection method used by MODP requires three consecutive scan images. Only those objects that have a constant velocity across all three scans are recognized. The same method would work, however, on two scan images if this constraint of constant velocity were relaxed. In that case, only two position lists would be generated. Any pair of unmatched positions, one from each list, for which the corresponding object brightness was nearly constant would indicate a moving object. Unfortunately, when the number of noise sources is high, the chance associations between their corresponding unmatched positions are frequent. Thus, the constraint of constant velocity is necessary to keep the rate of erroneous detections low. In fact, the constraint is so effective that it is not necessary to recognize and reject noise sources when the position lists are constructed. Each local maximum in a scan image is accepted, with the exception of noise spikes which are no wider than a single pixel. Because these spikes do not have a "seeing" profile, they are clearly part of the noise in the image. Also, it is computationally inexpensive for the software to recognize and reject them. Although a system of classifiers could be used to reject other noise sources, such as cosmic ray trails and diffraction spikes, and thereby reduce the erroneous detection rate, it would also increase the rate of failed detections. Since the number of objects in each scan image is large, it would also be expensive, computationally, to apply such a filter. MODP therefore relies on three passes to identify objects by motion.

3.3 Error Rejection

The rate of erroneous detections reported by MODP depends on the noise in the image, the atmospheric conditions, and the part of the sky being observed. When a scan is made near the galactic plane, the number of apparent double stars that are incorrectly reported as streaked objects will increase. If the "seeing" at the site is poor, a bright star will

appear as a cluster of many local intensity maxima. The algorithm for motion detection will therefore find many erroneous trajectories with constant velocity through this cluster. Fortunately, an experienced observer who understands the limitations of the detection methods used by MODP can easily distinguish the false detections from the real ones by visually examining the object images. MODP has a variety of interactive features and image display formats that were designed to make the job manageable in real time. As shown in Fig. 1 [Plate 92], MODP presents the observer with a large window which is subdivided into the following special purpose panels:

Status—The wide, horizontal panel at the top of the window reports the status of various program variables such as the number of CCD lines read, the number of objects identified, and the peak and half-width ("background" and "noise" levels) of the distribution of image intensities.

Control—The vertical panel at the left is used to start and stop the scan, adjust the acceptable ranges for the streak detection classifiers, and to choose among different modes of displaying the scan image. These operations are initiated by selecting the appropriate button with the mouse control.

Scan display—The largest panel in the middle of the MODP window is where the scan image is shown. As new CCD lines are read, the contents of the panel are automatically scrolled upwards, and the new lines are displayed at the bottom. This occurs every 4 or 5 s, which is the equivalent of approximately 50 lines. The grey scale of the image may be adjusted during the scan to cover any desired range of pixel intensities. Also, as each new candidate is detected, a white box is drawn around its location in the image. On the third scan pass, additional white boxes are drawn to show the position the moving object had in the previous two passes. Because more image data are stored in memory than are displayed on the screen, the observer can redisplay data that have already been scrolled out of the panel by scrolling the image back downwards by as many as 1024 lines. The display may also be temporarily frozen for careful inspection while MODP continues to read new CCD lines into memory.

Object gallery—Below the scan image is a wide, horizontal panel that serves as an object "gallery." As each candidate object is discovered, a small image region centered on the object (50×50 pixels) is added to the gallery. At any point during or after a scan, the observer can use this panel to visually review all the objects that have so far been detected. The button to the left of the gallery labeled "add" allows the observer to manually select object images for inclusion in the gallery. The observer can also remove an image from the gallery by first selecting it with the mouse control and then selecting the "clear" button. The button labeled "snap" is used to record a "snapshot" of a selected object, as discussed below.

Snapshots—Partially blocking the lower right corner of the scan display is shown an example of a "snapshot." When a candidate object is detected, the observer may choose to save an area around its image larger than a gallery image. The snapshot window displays image areas of 256×256 pixels centered on the detected objects, or areas manually selected by the user. As with gallery images, all snapshots can be reviewed at any point during or after a scan. The window may be repositioned or hidden so that it does not continue to block part of the scan display.

Information—Just above the gallery window is a space

where the position and brightness of each candidate are reported. If the object was detected as a streak during scan pass 1 or 2, then its size, aspect ratio, and orientation are also reported. If it was detected by motion in scan pass 3 then its angular rate and three observed brightness values are reported instead. This information appears when an object is first detected, or when its gallery image is selected with the mouse control.

In addition to these panel features, the observer can center a cross-hair cursor on any given pixel in the scan display. The position and intensity value of that pixel are then displayed in the status panel.

There are several ways in which this interface helps the observer to review detected objects. If the detection rate is low, the observer can simply watch the screen and examine the contents of the white boxes which are drawn around detected objects. If the intensity profile of the object is not clear because it is outside of the range of the grey scale, this range may be readjusted. If there is a burst of detections and no time to examine each one before they scroll out of the display, the display may be frozen. Alternatively, the observer can examine the detected objects in the gallery while the scan display continues to update. If the validity of a detected streak cannot be decided immediately from visual inspection, a snapshot may be taken of the region around it. A test for motion can then be made on the next pass by comparing the position of the object in the scan display to its position recorded in the snapshot. When the observer does decide that an interesting object has been discovered, its position and brightness are immediately obtained by selecting its image in the gallery window and reading the information line. Alternatively, the observer may position the cross-hair cursor over the center of the object, and read its position and peak intensity value from the status panel.

4. OBSERVED DISTRIBUTIONS OF ANGULAR RATE

MODP was initially tested in April 1990. These nights were used to iron out major bugs in the system and also to train the observing team (T. Gehrels, J. V. Scotti, and myself) in its operation. In May and June, we put the system into trial operation. Table I shows the date, starting position (in of date equatorial and ecliptic coordinates), area coverage, and longitudinal separation of the starting position from opposition ($\Delta\lambda$) for each of the regions we scanned. All observations were made during the dark half of the month, between last and first quarter phase of the moon. Because the opposition point was near its most southern position in the sky, and because the Milky way covered the area 1–3 hr east of opposition, we made most of the scans northwest of the opposition point or 3–4 hr to the east. Each region was searched in three passes, using streak detection in the first two, and motion detection in the last. Also, we set a brightness threshold for both streak and motion detection; only objects with a peak intensity greater than the local background intensity by an amount four times larger than the noise level of the background were searched. By measuring images of standard stars recorded with the CCD system, this threshold was found to be the equivalent of an apparent magnitude limit of $V = 20.5$. It was also found to be the equivalent of a 6σ threshold in the object intensity integrated over its area in the image.

As a result of these efforts, 304 moving objects were detected, excluding erroneous detections. All detections were double checked after the run by visually reviewing the data

from each of the three passes that had been recorded on tape. Figures 2 and 3 show the angular rates of these objects at the time of discovery in May and June, respectively. The rates of motion in right ascension and declination reported by MODP have been transformed to ecliptic coordinates and the size of the boxes representing each object are proportional to the logarithm of their observed intensity. The few objects with positive rates in longitude were all observed 3–4 hr east of opposition. All the remaining objects were observed west of opposition ($\Delta\lambda \cong -15^\circ$ in May, $\Delta\lambda \cong -20^\circ$ in June). No fast-moving objects were discovered and no new objects were detected as streaks. However, fast moving objects 1990 HA and 1990 MF were successfully detected as streaks when scans were intentionally made at their positions in the sky. Follow-up observations were made for a few of the discoveries, and positions have been recorded under the designations 1990 KL1 and 1990 KN1 (Hungarias) and 1990 KM1 (a Phocaea) in the Minor Planet Circulars (hereafter referred to as MPC) numbers 16528 and 16529.

5. DISCUSSION

5.1 Expected Rate Distributions

For objects that follow nearly circular orbits and are observed within a few degrees of opposition, their angular rates in longitude, $\dot{\lambda}$, and latitude, $\dot{\beta}$, can be simply expressed in terms of their orbital elements and heliocentric distance, r (Bowell *et al.* 1989). Here we consider objects separated in longitude from opposition by angle $\Delta\lambda$, but restricted to motion in the ecliptic plane. It follows that $\dot{\lambda}$ is given by

$$\dot{\lambda} = k(r^{-3/2} - u)/(1 - u),$$

where $k = 0.986^\circ/\text{d}$, r is in AU, and u is given by

$$u = [1 + (r^2 - 1)/\cos^2 \Delta\lambda]^{-1/2}.$$

For an object at $r = 2.8$ AU, near the mean aphelion distance of the main-belt asteroids, this gives $\dot{\lambda} = -0.20^\circ/\text{d}$ for May (at $\Delta\lambda = 15^\circ$) and $\dot{\lambda} = -0.19^\circ/\text{d}$ for June (at $\Delta\lambda = 20^\circ$). As can be seen from Fig. 2, the rates in longitude for objects detected in May cluster near $-0.20^\circ/\text{d}$, in good agreement with this prediction. However, in June the rates cluster near $-0.16^\circ/\text{d}$, more positive than expected by $0.03^\circ/\text{d}$. This discrepancy is not a surprise, however, because the June objects were detected about 10° farther north from the ecliptic than the May objects. Their orbits are too far out of the ecliptic for this simple calculation to hold. Also, the orbital eccentricity of the objects with higher inclination may not be negligible.

In order to obtain a better understanding of the observed distributions of angular rates, a computer program was written to model them more accurately. Given an arbitrary source distribution of asteroid orbital elements and an arbitrary viewing position in the sky, this program calculates the point along each orbit at which the angular separation from the specified viewing position is minimized. The angular rate an object would have at that point is also determined. Given a circular field of view of specified angular radius, the program thus determines what rates to expect for orbits whose minimum angular separation from the given viewing position brings them into the field of view. In the absence of other selection effects, the distribution of these expected rates should represent what is observed as long as the assumed distribution of orbital elements represents the asteroid population in the solar system. Of course there are other selection effects, such as the limiting magnitude of the observations. A more realistic model would estimate the brightness of the

TABLE 1. Starting position, area coverage, and angular separation along the elliptic from opposition ($\Delta\text{Lon.}$) for CCD scans made in May and June of 1990.

Date (U.T.)	equatorial R.A.(h m s)	coords. Dec.($^{\circ}$ ' ")	ecliptic coords. Lon. ($^{\circ}$)	Lat. ($^{\circ}$)	area (deg ²)	$\Delta\text{Lon.}$ ($^{\circ}$)
May 23	15 13 00	-11 23 00	222.95	+06.31	3.11	-12.67
May 23	15 13 00	-11 58 00	229.10	+05.74	3.11	-12.51
May 23	15 13 00	-12 33 00	222.26	+05.18	3.12	-12.36
May 23	15 58 00	-11 58 00	239.88	+08.34	1.80	-01.74
May 25	15 21 00	-09 38 00	230.40	+08.51	3.09	-13.14
May 25	20 00 00	-10 00 00	300.04	+10.37	3.09	+56.50
May 26	15 44 33	-15 41 57	237.47	+04.00	3.17	-07.03
May 29	14 48 00	+00 48 00	219.30	+16.20	3.89	-28.07
May 29	15 30 00	+00 52 00	229.86	+19.23	3.89	-17.52
May 30	15 11 23	-08 28 00	227.77	+09.01	3.93	-20.57
May 30	15 11 23	-09 03 00	227.93	+08.45	3.94	-20.41
May 31	15 15 28	-07 53 00	228.60	+09.84	3.93	-20.70
May 31	16 15 28	-07 53 00	243.38	+13.17	3.93	-05.92
May 31	15 30 36	-17 01 30	234.52	+01.93	1.84	-14.78
May 31	17 15 28	-07 53 00	258.57	+15.12	3.93	+09.28
June 1	53 30 27	-17 00 00	234.48	+01.95	4.09	-15.78
June 14	15 20 21	-13 35 30	231.27	+04.64	1.81	-31.43
June 14	16 00 20	-02 10 00	238.39	+18.05	3.89	-24.31
June 15	15 59 25	-01 27 00	237.99	+18.70	3.89	-25.66
June 15	15 59 32	+00 52 00	237.89	+19.28	3.89	-25.76
June 15	15 59 27	+00 17 00	237.74	+19.85	3.89	-25.91
June 16	16 00 00	-02 28 30	238.37	+17.73	3.89	-26.24
June 16	16 00 00	-03 03 30	238.50	+17.16	3.90	-26.11
June 17	15 59 30	-04 05 00	238.59	+16.13	3.90	-26.97
June 17	20 50 45	+02 43 30	315.97	+19.61	3.72	+50.41
June 18	15 58 40	+00 43 00	237.31	+20.78	3.89	-29.21
June 18	15 58 40	+01 18 00	237.17	+21.35	3.89	-29.34
June 18	20 55 00	+03 44 00	317.36	+20.27	3.04	+50.84
June 20	15 57 20	+02 07 30	236.63	+22.08	3.89	-31.79
June 20	15 57 20	+02 42 30	236.49	+22.65	3.90	-31.93
June 21	16 29 20	+00 30 00	245.61	+21.04	1.96	-23.76
June 21	21 08 20	+07 25 00	321.96	+22.77	2.02	+52.58
June 22	21 08 20	+06 50 00	321.76	+22.22	3.06	+51.43
June 22	21 13 20	+07 53 00	323.40	+22.82	3.06	+53.07
June 23	15 55 20	-05 49 30	237.92	+14.21	3.91	-33.37
June 23	15 55 20	-05 14 30	237.79	+14.78	4.34	-33.49
June 23	21 17 20	+08 54 00	324.77	+23.46	2.52	+53.49
June 24	16 09 05	+03 42 00	239.39	+24.24	3.04	-32.58
June 25	16 08 20	-06 43 00	241.37	+13.99	4.35	-31.83
June 25	16 08 20	-06 08 00	241.25	+14.56	4.35	-31.94
June 26	16 07 36	+05 01 00	238.69	+25.45	4.34	-35.46
June 26	21 46 20	+03 14 00	329.95	+15.69	4.32	+55.81

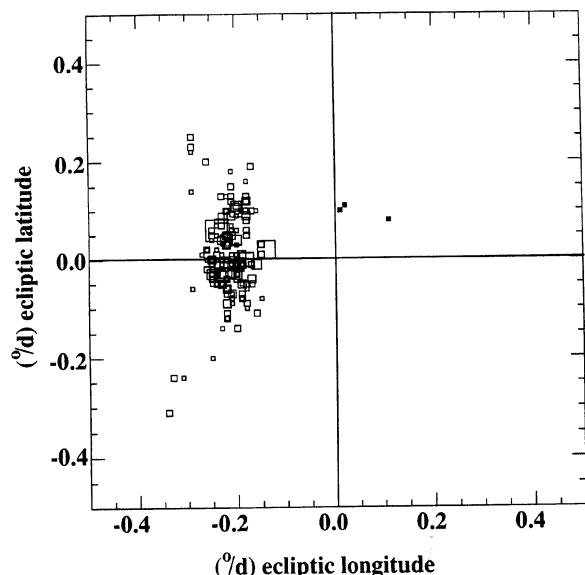


FIG. 2. Angular rates for moving objects detected in May 1990. Each detection is represented by a box with dimensions proportional to the apparent magnitude of the object. All prograde objects (solid boxes) were observed 3–4 hr east of opposition. All retrograde objects (open boxes) were observed within 20° of opposition.

asteroid associated with each orbit. Only those orbits for which the brightness was above the detection limit would be accepted into the distribution. Also, the representation of each orbit should be weighted differently, depending upon the likelihood of finding the asteroid within the field of view. Objects near perihelion would be given less weight than objects near aphelion, because they spend less time on that part of their orbit. These effects will be addressed later in this paper. The purpose here, however, is not to have the com-

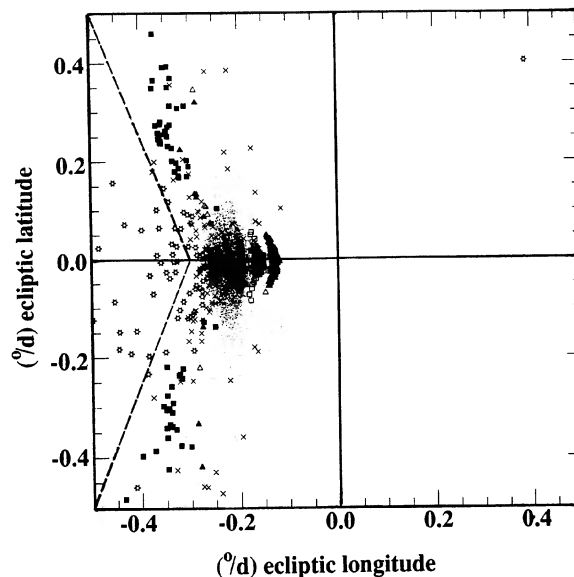


FIG. 4. Expected angular rates for objects visible in the regions of the sky scanned in May 1990. The dashed lines bound an area occupied uniquely by Earth approachers, which are represented by (*). Other asteroid groups represented are Trojans (Δ), Hildas ($\square$), main belts ($\cdot$), Phocaeas ($\blacktriangle$), Hungarias ($\blacksquare$), and Mars crossers ($\times$). The asteroid population represented here is the known solar system population multiplied by an expansion factor of 30 (see text for details).

puter reproduce the observed rate distributions in detail, but merely to capture their general features.

With these shortcomings in mind, the rate distributions expected for May and June were calculated, as shown in Figs. 4 and 5. Each point is represented by a symbol indicat-

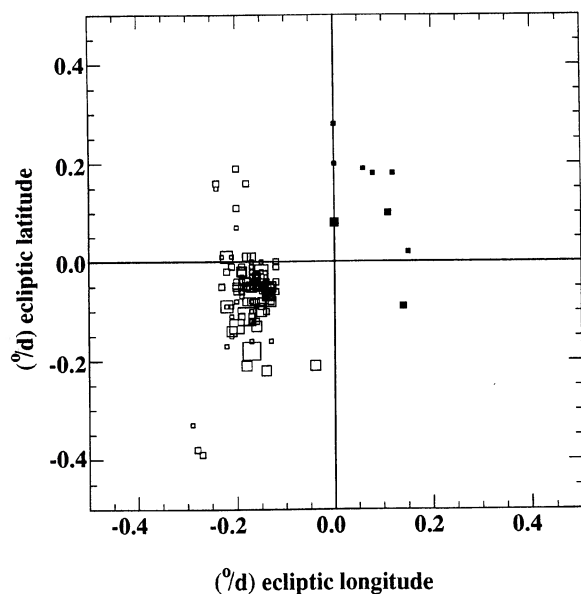


FIG. 3. Angular rates for moving objects detected in June 1990. See Fig. 2 for details.

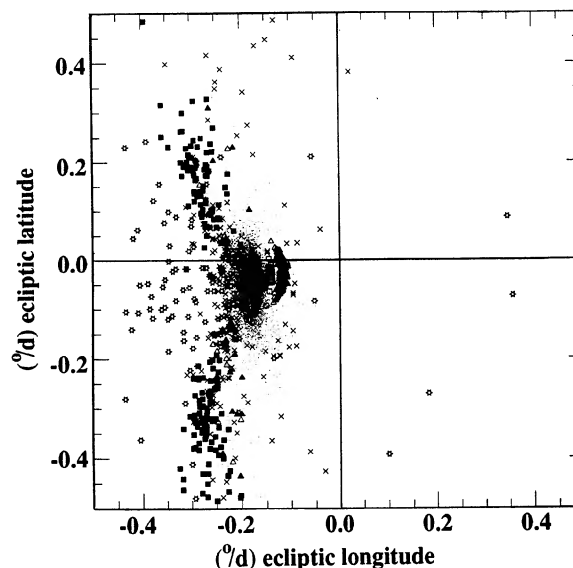


FIG. 5. Expected angular rates for objects visible in the regions of the sky scanned in June 1990. See Fig. 4 for symbol explanations. The asteroid population has been expanded by a factor of 80 (see text for details).

ing the orbit type according to the element zones of Zellner *et al.* 1985. The source distribution used for these calculations was the set of orbital elements for all the numbered asteroids in the MPCs up to 4549 (supplied by D. Tholen, University of Hawaii). In order to obtain a larger sample size, however, this set was artificially increased by choosing many random orientations for the ascending node and argument of perihelion of each orbit. These random values were uniformly distributed from 0° to 360° . For the May distribution, 30 random orientations were generated for each numbered asteroid. For June, 80 random orientations were generated. Also, in order to simplify the calculation, the assumed viewing positions and opposition points for these calculations were not those of the actual observations. Instead, the opposition point was fixed at 0° longitude, 0° latitude. The viewing positions were then fixed so that they had the same position relative to opposition that they had for the observations (-9° ecliptic longitude, $+11^\circ$ ecliptic latitude for Fig. 4 and -20° longitude, $+20^\circ$ latitude for Fig. 5). The only significant distortion introduced by these changes was the overrepresentation of Hildas and Trojans, owing to the correlation of their orbits with the orbit of Jupiter. For both months, the assumed field of view was 10° in diameter.

Comparing the expected distributions in Figs. 4 and 5 to the observations in Figs. 2 and 3, it is clear that the shape and location of the observed rate distributions have been properly modeled by the calculation. In particular, the displacement of the center of the observed distribution from $-0.20^\circ/\text{d}$ longitude, $0.0^\circ/\text{d}$ latitude in May to $-0.16^\circ/\text{d}$ longitude, $-0.05^\circ/\text{d}$ latitude in June is well predicted. Also, both predicted and observed distributions are wider in the direction of latitude than they are in the direction of longitude. Finally, both distributions have "tails" that bend towards increasingly negative rates in longitude as they trail in the direction of increasingly positive and negative rates in latitude. It thus appears that the observations made in May and June are what should be expected, given the orbits of the known asteroid population and the viewing geometry of the telescope.

5.2 Asteroid Orbit Type

In addition to explaining the observed rate distributions, the calculated distributions show that an object's angular rate is a good indicator of its orbit type. For example, Fig. 4 shows that any object detected in May with a longitudinal rate in the range $-0.18^\circ/\text{d}$ to $-0.26^\circ/\text{d}$, and between $\pm 0.10^\circ/\text{d}$ in latitude, is almost certainly a main-belt object. The contribution of any other asteroid group to that region of the distribution is relatively negligible. Objects in the "tails" of the rate distributions (near $-0.35^\circ/\text{d}$ in longitude, $\pm 0.30^\circ/\text{d}$ in latitude in May) are most likely Hungarias. However, there still is a small chance they could be Phocaeas, main belt, or Mars crossers, owing to the small presence of these groups in that part of the distribution. Comparing Figs. 4 and 5 to Figs. 2 and 3, it is thus apparent that a few Hungarias (3 to 5) were detected in both May and June, in addition to the numerous main-belt observations. One or two of the objects could also have been a Phocaea or Mars crosser. An object with a rate of $-0.04^\circ/\text{d}$ in longitude and $-0.20^\circ/\text{d}$ in latitude was detected in June, clearly outside of both the main belt and Hungaria regions. This object is very likely a Mars crosser. The object was observed on two separate nights, with positions consistent with this classification.

Examination of Figs. 4 and 5 shows that the Hilda and Trojan asteroids also occupy unique regions of the rate distributions (closer to $0.0^\circ/\text{d}$ in longitude than the main belts, and between $\pm 0.05^\circ/\text{d}$ in latitude). Recall, however, that these asteroids are overrepresented in the model source distribution, as discussed earlier. It is therefore difficult to estimate the likelihood of membership in one of these groups based on the measured angular rate of any one object. However, since they occupy only a very small area in the expected rate distribution, and because more than 10 objects were detected in May and June with rates inside the Hilda region, it is likely that at least a few Hildas were observed. The brightest of these candidates, detected in May and moving $-0.14^\circ/\text{d}$ in longitude, and $0.03^\circ/\text{d}$ in latitude, turned out to be (334) Chicago, a known Hilda. A few of the objects detected in June also had rates consistent with Trojan orbits ($-0.12^\circ/\text{d}$ in longitude, $0.0^\circ/\text{d}$ in latitude). However, given the small number of detections, any assignment to this orbit type cannot be justified. Also, the Jupiter-Sun L4 and L5 points were more than 4 hr away from the regions of the sky scanned in May and June.

As with the Hildas and the Trojans, the population of Earth-approaching asteroids is overrepresented in the calculated rate distributions. The reason for this is not because of their misrepresentation in the source distribution, however. Instead, it is because the limiting magnitude of the observations has not been taken into account in the model. The Earth approachers have such small diameters that they are normally visible only when their distance from the Earth is less than 0.5 AU. Their rates are nonetheless represented in Figs. 4 and 5, without consideration of that distance limit. It can still be concluded, however, that the likelihood an Earth approacher was observed in May or June is small. In the regions where the calculated and observed rate distributions overlap (i.e., among the Hungarias, main-belt objects, and Hildas), even the overestimated population of Earth approachers is small compared with other asteroid groups. For an object to be identified as an Earth approacher, its place in the expected rate distribution must be distinctly separated from the regions of any of the other asteroid types.

5.3 Detection of Slow-Moving Earth Approachers

Although Figs. 2 and 3 show that no Earth approachers were detected in May and June, Figs. 4 and 5 show that these objects, when observed within 30° of opposition, do not require high angular rates in order to be identified. For slow prograde objects, this is clearly true because only objects that approach the Earth can have prograde motion near opposition. However, the conclusion also holds for retrograde Earth approachers. There is an area in each rate distribution extending in longitude motion from $-0.30^\circ/\text{d}$ to more negative values which is uniquely occupied by Earth approachers. It is bounded on the right by the Hungaria and main-belt populations, and is unbounded to the left. In Fig. 4 this area is delineated by dashed lines. A retrograde object moving along the ecliptic at $-0.35^\circ/\text{d}$, less than the rate of a typical Hungaria, could have been safely identified as an Earth approacher in May or June because its rate would have fallen to the left of these boundaries. Taking into account this area populated uniquely by Earth approachers, it is thus possible to use MODP to identify retrograde Earth approachers which move too slowly for streak detection.

Unfortunately, the advantage this method of object identi-

fication brings to the discovery of Earth approachers is partially offset by the fact that those that move slowest are also the most distant, and therefore fainter than the faster-moving asteroids of the same size. As explained in the previous section, many of the Earth approachers represented in Figs. 4 and 5 would not be bright enough for detection by the CCD scanning system. In order to quantify this cutoff, the calculation of the rate distribution was therefore repeated. This time the expected apparent magnitude was determined for each asteroid in the source distribution, in addition to the expected angular rate. In terms of geocentric distance Δ , heliocentric distance r , angular rate ω ($^{\circ}/d$), and absolute visual magnitude H (as tabulated for the numbered asteroids by Tedesco 1989), the apparent magnitude at opposition, V , was evaluated using the following expression:

$$V = H + 5 \log r\Delta + 2.5 \log q(\omega),$$

where

$$q(\omega) = \begin{cases} 1 & \omega < 0.3 \\ 1 + 5(\omega - 0.3) & 0.3 \leq \omega < 0.5 \\ 4\omega & \omega \geq 0.5. \end{cases}$$

In this expression, $q(\omega)$ approximates the assumed variation of object brightness per unit length along a trail. Thus, for any trailed object, V corresponds to the apparent magnitude of any portion of the trail with the same length and width as the "seeing" profile. For example, an object with $\omega = 0.5^{\circ}/d$ leaves a trail about 4 pixels long. This is twice the width of the "seeing" profile, so $q(\omega) = 2.0$. When $\omega < 0.3$, there is no significant trailing and $q(\omega) = 1.0$. For $\omega \geq 0.5$, trail length is proportional to ω , so $q(\omega)$ increases linearly with ω . By restricting the assumed viewing position to the opposition point, no phase correction is required.

The results of this calculation are presented in Fig. 6, which shows the expected apparent magnitude, as defined above, as a function of expected angular rate, for Earth approachers only. The source distribution consisted of all reported Earth approachers in the MPCs, both numbered and unnumbered (135 orbits altogether). As in the preceding calculation, the sample size was expanded by choosing multiple random orientations for each orbit. For this case, the expansion factor was 100. The assumed diameter for the field of view was once again 10° . Note that three different symbols are used to represent the resulting distribution. If the motion is prograde, or the calculated rate is greater than $0.5^{\circ}/d$, or if the rate of motion falls within the area unique to Earth approachers outlined in Fig. 4, then the object could be identified as such on the basis of its angular motion. These asteroids are represented by solid boxes (retrograde motion) and crosses (prograde motion). All other members of the distribution could not be unambiguously identified in this way and are therefore represented by points. Also shown in Fig. 6 are the detection limits achieved by photographic methods and by the scanning CCD system. Region "a" defines the limits achieved by the Palomar Planet Crossing Asteroid Survey (PCAS) in 1985 by visually searching Schmidt plates for streaked images (Helin & Shoemaker 1979; Shoemaker 1985). Recently, this has been extended to include region "b" (Helin & Roman 1989). The Spacewatch CCD system extends these limits to include region "c."

Several conclusions can be drawn from Fig. 6. First, it is apparent that nearly all of the objects with absolute rates of motion greater than $0.3^{\circ}/d$ could be identified as Earth approachers based on their place in the figure. This is consis-

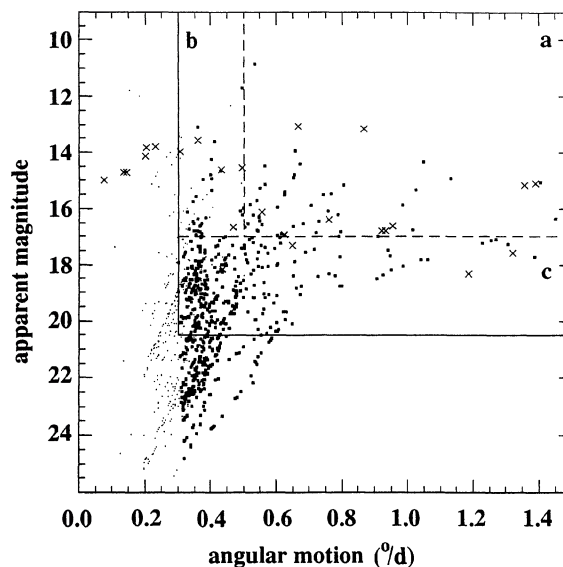


FIG. 6. Apparent magnitude vs angular rate expected at opposition for Earth-approaching asteroids. Objects which can be identified as Earth approachers based on their motion are indicated by (■) for retrograde motion, and (×) for prograde motion. All other objects are represented by (·). Regions a, b, and c correspond to the limits of detection achievable by different observing methods (see text for details). Note that regions a and c are unbounded on the right, extending without limit to higher angular rates. They therefore include points that are not shown and correspond to objects moving faster than $1.5^{\circ}/d$.

tent with Fig. 4, which shows that most of the Earth approachers are located within the area unique to Earth approachers. Second, very few Earth approachers have prograde motion at opposition. They contribute only a few percent to the population brighter than apparent magnitude 18, and a negligible fraction to the fainter objects. This is because the fainter objects are detected too far from the Earth to have prograde motion. Finally, there is a significant increase in the number of objects that can be detected at opposition and identified as Earth approachers as the minimum observable rate approaches $0.3^{\circ}/d$ and the minimum brightness decreases. Of all of the identifiable Earth approachers represented in Fig. 6, 10% are within region "a," 16% are within region "a" + "b," and 66% are within region "a" + "b" + "c." It is thus clear that the best system for detecting and identifying Earth-approaching asteroids is one that can best detect slowly moving, faint objects and accurately measure both angular rate and direction of motion.

This conclusion is strengthened when the biases inherent in the calculation of Fig. 6 are considered, the strongest of which is a bias against faint objects. This occurs because the source distribution used in the derivation is not the true distribution of Earth approachers. It is the distribution represented by the known Earth approachers only. Since most of these asteroids have been discovered by PCAS with a limiting magnitude of $V = 17$, there is a fainter and presumably larger population which is not represented. Another bias exists against those Earth approachers that have the largest perihelion distances, the Amors. This is because PCAS has depended primarily on streak detection, at least up until

1985, to find them. Those Earth approachers that have the largest perihelion distances have therefore been undercounted (Helin & Shoemaker 1979). Finally, a third bias exists in Fig. 6 because each point is given equal weight, even though objects on eccentric orbits are less likely to be observed near perihelion than near aphelion, where they spend more time. Figure 6 thus overrepresents objects where they are fast moving and bright. Correcting any one of these biases would increase the relative number of detectable Earth approachers inside region "a" + "b" + "c" compared to region "a" or "a" + "b."

Based on these considerations alone, the scanning system discussed here is an excellent complement to the photographic methods. These other methods cannot detect the slowly moving, faint objects. Instead, they are primarily used to detect fast-moving objects leaving trailed images or objects having prograde motion. Of all the Earth approachers discovered photographically between 1981 and 1989 and reported in the IAU Circulars (1981 CW to 1989 UR, 80 objects in total), only two were retrograde objects with angular rates less than $0.5^\circ/\text{d}$. Of course, the photographic methods make up for this deficiency in faint object sensitivity by using Schmidt telescopes with large fields of view. In 1985, the area covered by PCAS averaged 30 000 square degrees per year (Shoemaker 1985) whereas the yearly area coverage that may be achieved by the present CCD system is ~ 1640 square degrees. Taking into account this difference, and also the differences in limiting magnitude and angular rate thresholds, an estimate for the ratio of the detection rate of Earth approachers by the CCD system to the detection rate by PCAS in 1985 is given by $(1640/30\,000) \times (16/10) \times 2.5^{3.5} = 2.2$. Here, the factor $(16/10)$ is the relative number of points inside region "a" + "b" compared to region "a" in Fig. 6. It accounts for the increasing number of detectable Earth approachers with decreasing angular rate. The factor $2.5^{3.5}$ accounts for the increase of this population with fainter limiting magnitude, assuming the same magnitude-frequency relation for Earth approachers as for the main-belt asteroids (Van Houten *et al.* 1970). Alternatively, if Fig. 6 were corrected for its bias against faint objects, the combined factor $(16/10) \times 2.5^{3.5}$ would be replaced with the number of points in region "a" + "b" + "c" relative to region "a." Although this correction has not been attempted, calculations have been performed which correct for the overrepresentation by Fig. 6 of objects near perihelion. This correction yields a $\sim 20\%$ increase in the number of points inside region "a" + "b" compared to region "a." Taking this adjustment as the error in the prediction, and given the detection rate of ~ 6 Earth approachers per year reported by PCAS in 1985 (Shoemaker 1985), the discovery rate for the CCD system should be 13 ± 3 .

5.4 Detection of Fast-Moving Earth Approachers

Although MODP is capable of detecting fast-moving Earth approachers by recognizing their trailed images, this is not the most efficient way to detect the fast-movers with a scanning CCD. With the Spacewatch Telescope held fixed at 0° declination, the time taken for star images to drift across the field of view (the "drift time") is the field width (2474 arcsec) divided by the sidereal angular rate (15 arcsec/s), or 165 s. An object with the relative angular rate of $1.0^\circ/\text{d}$ then leaves a trail 6 pixels long. Alternatively, if the telescope

were driven rapidly across the sky so that the drift time were only 28 s, the same object would leave an untrailed image. Also, the brightness per unit length of this untrailed image would be the same as the trailed one. MODP could therefore detect this object most quickly (84 s) with three rapid passes using motion detection, rather than one slow pass at the sidereal drift rate using streak detection. The time gained could then be used to scan other areas of the sky and increase the area coverage of the search. The detection of fast moving asteroids by the Spacewatch Telescope would thus be improved by driving the telescope rapidly across the sky, and matching the drift time to the time taken for fast movers to move the angular equivalent of one CCD pixel.

Although the present CCD system is not configured for scanning at the rate that would be optimum for asteroids moving $1^\circ/\text{d}$, it would be possible to modify the controlling software for this capability. It is therefore instructive to estimate the numbers of fast-moving and slow-moving Earth approachers per year such an improved system would find and compare the results to the discovery rates currently expected for the Spacewatch Telescope, scanning at the sidereal rate. The latter can be estimated by reexamination of Fig. 6. Of all the detectable Earth approachers within region "a" + "b," 24% have angular motion greater than $1.0^\circ/\text{d}$. Since the formula presented earlier to estimate a detection rate of 13 Earth approachers per year scales as the number of points in this region, the current CCD system should find $0.24 \times 13 = 3.1$ of these fast movers per year. If the Spacewatch Telescope were optimized to find objects moving $1.0^\circ/\text{d}$, the drift time would be 28 s and the yearly area coverage would be $165/28$ times greater. The yearly discovery rate for objects moving greater than $1.0^\circ/\text{d}$ would then be about 18. Although the limiting magnitude would also degrade to 19.5 for stationary objects (see Appendix A), recalculation of the discovery rate for all Earth approachers moving faster than $0.3^\circ/\text{d}$ shows that this number would increase to 31 per year.¹ Thus, by driving the Spacewatch Telescope at the optimum speed for detection of $1.0^\circ/\text{d}$ objects, the discovery rate of the fast movers would increase by a factor of $18/3.1 = 5.8$ while the rate of discovery for all Earth approachers, including the fast movers, would increase by the factor $31/13 = 2.4$.

Given these improvements which rapid driving brings to the discovery rates of the Spacewatch Telescope, Table 2 shows the capabilities to be expected for a hypothetical telescope specifically designed for rapid scanning: a "Scanner-scope." The aperture size of 1.82 m envisioned for the Scanner-scope is only an example, but such a telescope would fit inside the dome of the Spacewatch Telescope. The pixel scale is then calculated assuming an f ratio of 2.2 and a CCD which is the same as the one presently used with the Spacewatch Telescope. Listed in Table 2 for both the Spacewatch Telescope and the Scanner-scope are the drift time, limiting magnitude, area coverage per year, and estimated discovery rate. For each telescope, two cases are considered: telescope drive off, and telescope moving for optimum discovery of $1.0^\circ/\text{d}$ objects. For the Scanner-scope, a third case is considered in which the telescope is moved for

¹ For objects moving $1.0^\circ/\text{d}$, the limiting magnitude improves when the exposure time is shortened to 28 s because the noise contribution from the sky background is reduced. However, a more thorough calculation of the discovery rate for objects moving greater than $1.0^\circ/\text{d}$ does not significantly change the prediction presented.

TABLE 2. Performance characteristics and estimated discovery rates of Earth approachers for the Spacewatch Telescope and the Scannerscope.^a

	Spacewatch Telescope		Scannerscope (1.82m)		
	stationary	moving ^b	stationary	moving ^b	moving ^c
f-ratio	5.0	5.0	2.2	2.2	2.2
pixel scale (arcsec)	1.21	1.21	1.39	1.39	1.39
drift time (s)	165	28	202	33.2	8.3
Lim. Mag.	20.5	19.5	21.7	20.7	19.9
area coverage (deg. ² / yr.)	1640	9670	1885	11469	45920
fast mover discovery rate ^d (objects/yr.)	3.1 (0.5)	18 (1.1)	10 (1.5)	61 (3.9)	< 46 (35)
Earth approacher discovery rate (objects/yr.)	13	31	41	110	< 190

Notes to Table 2

^aAll estimated rates are uncertain by 20%^boptimized for objects moving 1.0°/d .^coptimized for objects moving 4.0°/d .^dfor objects moving greater than 1.0°/d (4.0°/d).

optimum discovery of 4.0°/d objects. Each of the entries in this table is calculated for the Scannerscope in the same manner it was calculated for the Spacewatch Telescope, as discussed above. The yearly area coverages for the Scannerscope are scaled from the area coverage of the Spacewatch Telescope by the fractional increase in pixel scale.

It can be concluded from Table 2 that doubling the mirror diameter from 0.91 m for the Spacewatch Telescope to 1.82 m for the Scannerscope does more to improve the discovery rate of Earth approachers than optimizing the motion for 1°/d objects. For the stationary Scannerscope, the gain is $41/13 = 3.2$, whereas the gain is 2.4 by moving the Spacewatch Telescope. However, nearly twice as many fast movers ($> 1°/d$) would be discovered by optimizing the motion rather than doubling the mirror size. When these two improvements are combined by optimizing the motion of the Scannerscope for 1°/d objects, the expected discovery rate increases to 110 Earth approachers per year, a gain of 8.5. The expected gain in the fast-mover discoveries is $61/3.1 = 20$. The last column in Table 2, for which the Scannerscope is moving optimally for 4.0°/d objects, is an extreme example of motion optimization. The CCDs currently available for astronomical measurements cannot be readout at the rate that would be required for such a system (250 lines/s). Also, it would be impossible to scan the 45 920 square degrees of sky per year that would be required to

achieve the estimated yield of 190 Earth approachers without scanning the same area of the sky more than once. A realistic estimate for the discovery rate by such a system would have to take into account double coverage of the sky area and the rate at which the detected Earth approachers leave the field of view. However, assuming an astronomical CCD becomes available that can be read out at the required rate, it is safe to conclude that the rate for discovery of objects moving faster than 4.0°/d would be larger than the rate expected when driving slower, for 1.0°/d objects. The expected rate is therefore between 3.9 and 46 per year. This is greater than the total number of these objects reported in the IAU Circulars in the last 10 yr (3 objects: 1989 DA, 1989 VB, and 1989 UP). The discovery rate expected for the Spacewatch Telescope (stationary) is only 0.5 per year. It is therefore clear from these comparisons that the Scannerscope would be at least an order of magnitude improvement over any of the techniques used today for detecting the fast-moving Earth approachers.

6. SUMMARY

The Spacewatch Telescope is successfully detecting moving objects in near real time with a scanning CCD. A powerful workstation computer has been programmed to recognize Earth-approaching asteroids by the trailed images they

leave in a single scan, or by their motion in three successive scans. The position and brightness of each object, in addition to its angular rate if detected by motion, are reported as soon as the image signals are shifted out of the CCD. The interaction of the observer with the program has also been facilitated so that each object can be visually examined while the scan progresses. This allows the observer to share with the program the responsibility of rejecting erroneous detections. The methods used by the program to detect moving objects can therefore be adjusted to minimize the rate of failed detections.

The results from 2 months of trial observation with this system have been compared with a numerical model which shows that the observed distribution of angular rates is well described by the known distribution of asteroid orbits. Of the 304 objects detected, most are main-belt asteroids, several are Hungarias or Phocaeas, a few are Hildas, and at least one is a Mars crosser. Although no new Earth approachers were identified, this analysis has shown that only 1 ± 1 object was expected. Two known objects of this class were successfully detected as streaks when scans were intentionally made at their positions in the sky. Further analysis shows that retrograde Earth approachers moving too slowly to leave a trailed image can be detected by the CCD system and identified by their angular rate. Based on these results, it is predicted that the CCD system will continue to make near real-time discoveries of Mars crossers and the more distant asteroid groups, and be able to identify them by their rate of motion. This will extend the known populations of Hungarias and Phocaeas which have suffered from biased observing in the past (Helin & Roman 1989). Also included in these discoveries will be the Earth approachers which are moving too slowly, and are too faint to be detected by photographic surveys.

The observations to be made in the coming months will bear out these capabilities of the CCD detection system. This paper has indicated the direction, however, for future improvements in the existing configuration. By rapidly driving the Spacewatch Telescope across the sky at a rate optimized for the detection of fast movers, a higher discovery rate would be achieved. Although the limiting magnitude of the detection system would be degraded and the most distant objects could not be observed, the increased area coverage would more than compensate for this loss. Slow-movers would continue to be detected, and at a higher rate. Looking farther into the future, a new scanning telescope, specifically designed for driving at high rates and configured with a mirror twice the size of the mirror for the Spacewatch Telescope, would discover Earth approachers at a rate much higher than can be achieved by the Spacewatch Telescope or any other technique in current use. It is anticipated that such a telescope would help bring to completion our understanding of the distribution of the minor planets.

Note added in proof. In the first 6 months of regular operation with the CCD scanning system, beginning September 1990, 10 Earth-approaching asteroids have been discovered: 1990 SS, TG1, UN, UO, UP, VA, and 1991 AM, BA, BN, and CB1. One of these is an Aten object (1990 VA), 2 are Amors (1990 UP and 1991 CB1), and the remaining 7 are Apollos. 1991 BA is an exceptional asteroid, being the smallest (~ 5 –10 m) and nearest (0.0033 AU) ever observed outside the Earth's atmosphere.

I wish to extend heartfelt thanks to Tom Gehrels. The work reported in this paper is the result of his groundbreaking efforts in the field and is inspired by his passion for the

project. Thanks also go to R. S. McMillan, J. V. Scotti, and M. L. Perry who complete the team for CCD scanning at the Spacewatch Telescope and without whom this work would not have been possible. In particular, I thank J. V. Scotti for his help in writing MODP and analyzing the observations. Finally, thanks go to Joe Gotobed for programming advice, Dave Tholen at the University of Hawaii for putting together the asteroid data base, and Leonard Drucker at Solbourne for computer system support. This work was supported by the National Aeronautics and Space Administration (NAGW-887), the Air Force Office of Scientific Research (AFOSR 89-0170, 89-0027), and the Space Engineering Research Center of the University of Arizona under NASA Contract No. NAGW-1332.

APPENDIX A

The purpose of this appendix is to determine "working" limiting magnitudes, V_{limit} , as a function of pixel scale, mirror size, and drift time, t , for the Spacewatch Telescope and the Scannerscope listed in Table 2. This limit is defined to be the apparent magnitude an object would have if its intensity, integrated over the area of the object image, were six times the noise in the image, integrated over the same area. Here, we assume that the average signal in the background has been subtracted and define the area of the object image to be the set of connected pixels for which the object signal is above the noise level. Although a significant part of the light from a faint star may extend beyond this area, we use this definition because it is consistent with the integration limits used by MODP to analyze streaked objects. We will assume that all the light from a star is contained within this area, and correct for this and any other systematic errors by "calibrating" the calculated values of V_{limit} with the value $V_{\text{limit}} = 20.5$, which has been determined empirically for the stationary Spacewatch Telescope ($t = 165$ s) from measurements of standard stars. The difference between this empirical determination and the calculated value will be added to each of the other values of V_{limit} calculated for Table 2 to arrive at the listed values.

From McMillan and Stoll 1982, the noise in the difference between two exposures, one with a star and one without, is given by

$$\text{noise}^2 = R_* t + 2(R_s + R_d)t + 2N_r^2 + e_p^2 [(R_s + R_* + R_d)^2 + (R_s + R_d)^2] t^2, \quad (\text{A1})$$

where R_* = star count rate in ehp/pixel/s; R_s = sky background rate in ehp/pixel/s; R_d = dark count rate in ehp/pixel/s; N_r = CCD readout noise in ehp/pixel; and e_p = flatfield nonuniformity in ehp/pixel. This is the noise per pixel assuming all the light from the star is imaged onto an area less than the size of a single pixel. For the case where the star image covers more than one pixel, we must consider the integrated object signal, ΣR_* , where ΣR_* is the sum of R_* over all the pixels in the image. Assuming R_d and e_p to be negligible, the noise is given by

$$\text{noise}^2 = \Sigma R_* t + 2(R_s p t + p N_r^2), \quad (\text{A2})$$

and the signal to noise ratio, S_n , is given by

$$S_n = \Sigma R_* t / [\Sigma R_* t + 2(R_s p t + p N_r^2)]^{1/2}, \quad (\text{A3})$$

where p = the number of pixels covered by the object image. Solving Eq. (A3) for ΣR_* in terms of S_n yields

We can determine R_s and ΣR_* for a G2V star with apparent magnitude $V = 17.5$ by using the following table:

λ	%QE	N_*	N_s	T_e	%QE $\times N_* \times T_e$	%QE $\times N_s$
400	3	272	8	0.745	6	0.24
450	8	436	11	0.831	29	0.88
500	19	499	10	0.875	83	1.9
550	19	534	19	0.890	90	3.6
600	29	554	20	0.900	145	5.8
650	22	538	18	0.933	110	4.0
700	23	525	18	0.957	116	4.2
750	35	501	25	0.971	170	8.8
800	28	479	32	0.977	131	9.0
850	20	447	48	0.981	88	9.6
900	12	425	55	0.984	51	6.6
950	8	405	57	0.986	32	4.6
1000	2	377	170	0.988	7.5	3.4

$$\Sigma R_* = (S_n^2/2t) \{1 + [1 + (8p/S_n^2) \times (R_s t + N_r^2)]^{1/2}\}. \quad (\text{A4})$$

where λ = wavelength in nm; %QE = CCD quantum efficiency; N_* = photons $\text{m}^{-2} \text{s}^{-1}$ in the given wavelength bandpass (50 nm) from a G2V star with apparent magnitude $V = 17.5$; N_s = photons $\text{m}^{-2} \text{s}^{-1}$ from the night sky at zenith with a 3 day moon; and T_e = transmissivity of the Earth's atmosphere at zenith. Values for N_* , N_s , and T_e are taken from McMillan & Stoll 1982. Values for %QE are taken from Epperson *et al.* 1987, who measured them for a TK512M-011 CCD, a frontside-illuminated CCD with the same construction as the TK2048 CCD, and therefore expected to have a similar spectral response. The mirror area of the primary minus the area of the secondary for the Spacewatch Telescope is 0.58 m^2 , their combined reflectivity is 0.72, and the area of one pixel is 1.46 arcsec^2 , so that for the Spacewatch Telescope we find

$$\Sigma R_{*17.5} = [\Sigma_\lambda (\%QE \times N_* \times T_e)] \times 0.58 \times 0.72 = 442 \text{ ehp/s},$$

and

$$R_s = [\Sigma_\lambda (\%QE \times N_s)] \times 0.58 \times 0.72 \times 1.46 = 38.2 \text{ ehp/s/pixel},$$

where $\Sigma R_{*17.5}$ is the integrated image signal for the G2V star of magnitude $V = 17.5$ and Σ_λ indicates a sum over λ . Now taking $S_n = 6\sigma$, $t = 165 \text{ s}$, $N_r = 15$ electrons, $p = 9$, and using the value for R_s determined above, the integrated signal from an object at the 6σ threshold for the Spacewatch Telescope is given by

$$\Sigma R_{*6\sigma} = 12.6 \text{ ehp/s}.$$

We use $p = 9$ in this calculation because this is the number of pixels over which the signal from a 6σ star is above background under average "seeing" conditions. The streak detection algorithm used by MODP assumes a threshold size of 2 pixels because that is the lower limit for exceptional "seeing" conditions. Values for $\Sigma R_{*6\sigma}$ and $\Sigma R_{*17.5}$ are calculated in a similar way assuming $t = 28 \text{ s}$ for the Spacewatch Telescope and $t = 202, 33.2$, and 8.3 s for the Scannerscope, taking into account the different mirror size and pixel scale for the Scannerscope. Finally, for each telescope and each value of t , V_{limit} is determined from $\Sigma R_{*6\sigma}$ and $\Sigma R_{*17.5}$ by

$$V_{\text{limit}} = 17.5 - 2.5 \log(\Sigma R_{*6\sigma} / \Sigma R_{*17.5}), \quad (\text{A5})$$

with the result that the "uncalibrated" limiting magnitudes for the Spacewatch Telescope are $V_{\text{limit}} = 21.3$ and 20.3 for $t = 165 \text{ s}$ and 28 s , respectively. For the Scannerscope they are $V_{\text{limit}} = 22.5, 21.5$, and 20.7 for $t = 202, 33.2$, and 8.3 s . The difference between the empirical and calculated limit for the stationary Spacewatch Telescope is therefore $20.5 - 21.3$ or -0.8 mag . For a 6σ star this is a reasonable offset, given that $\sim 50\%$ of the light may fall outside the area of the object image, as defined above. Adding this offset to each of the calculated values yields the limits listed in Table 2.

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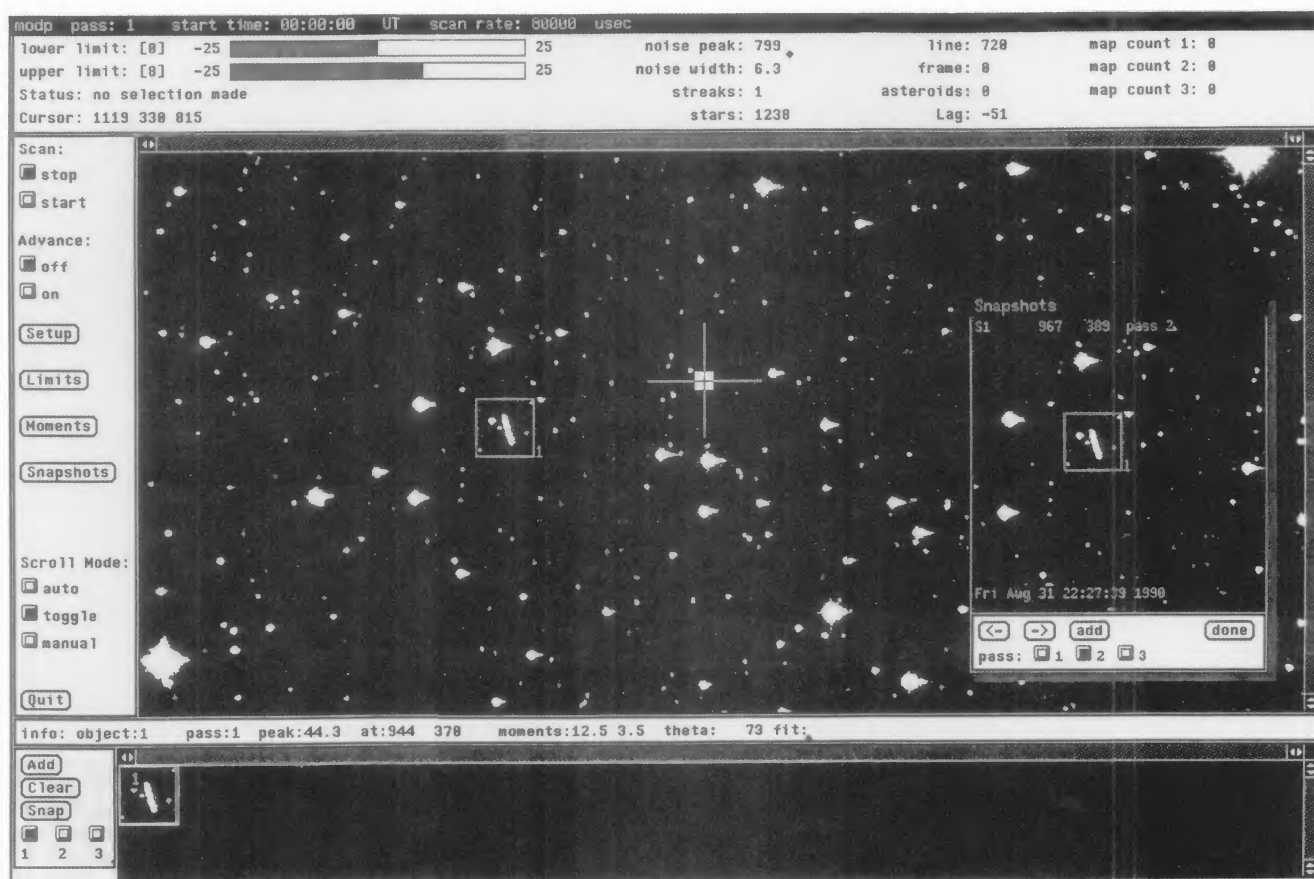


FIG. 1. The user interface for the near real-time software for the detection of moving objects (MODP). The streaked object shown in the white box is an image of 1989 UP as recorded by the CCD system near the time of discovery (box scale is 50×50 pixels, or 60×60 arcsec). The software has measured a peak brightness for this object of 44.3 standard deviations above background, a length and width of 12.5 and 3.5 pixels, respectively, and an orientation rotated 73° from horizontal.

D. L. Rabinowitz (see page 1520)