# OBSERVATION OF SMALL SOLAR SYSTEM OBJECTS WITH SPACEWATCH

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**Abstract.** Since beginning an automated full-time survey for Near-Earth objects in September 1990, the Spacewatch project has discovered 95 new Near-Earth asteroids (NEAs), 3 new comets, and 3 new Centaur asteroids. Spacewatch typically identifies about 2000 main-belt asteroids each lunation while covering about 150 square degrees to a limiting magnitude of $V_{lim} \sim 20.9$. We report automatically measured astrometric asteroid detections to the Minor Planet Center where known and multiply detected objects are identified. NEAs and other interesting objects are identified by their angular rates of motion near opposition at the time of discovery and are scheduled for astrometric follow-up on subsequent nights. Objects with exceptionally high rates of motion, called very fast moving objects, have been detected in near real-time by the observer and followed for several hours to several days. These objects are the smallest yet detected outside the Earth's atmosphere. Careful analysis of their discovery rates and orbits have indicated an enhancement of their magnitude-frequency distribution over that anticipated before the Spacewatch survey began – of about a factor of 40 for objects near absolute magnitude $H \sim 29$ (Rabinowitz, 1993; 1994). A subset of these small objects which have almost circular orbits and perihelia near the orbit of Earth have been recognized as having significantly different orbits from those of the previously known NEAs (Rabinowitz *et al.*, 1993). Their origin is still under debate, with possible sources including Earth or Lunar impact ejecta, Earth–Sun Trojans, or more complicated secular resonance interactions of NEA orbits with the giant planets combined with stochastic perturbational encounters with the inner planets (Bottke, 1994; N.W. Harris, 1995, personal communication). The large volume of asteroid detections allows magnitude–frequency studies of the detected main-belt asteroids and Jupiter Trojans. New discoveries

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of Comets and Centaur asteroids (whose orbits cross those of the outer planets) may allow studies of their magnitude–frequency distributions as well.

## 1. Introduction

The Spacewatch project has been developing the capability and techniques to detect solar system objects using electronic detectors since 1981. At that time, the decision was made to make use of longer focus telescopes and state-of-the-art electronic detectors rather than wide field Schmidt telescopes and photographic techniques for new object discovery. By 1984, an RCA 320 × 512 pixel CCD was being used at the $f/5$ Newtonian focus of the 0.91-meter Spacewatch Telescope to observe asteroids. The techniques of astrometry and asteroid detection were developed and improved between 1984 and 1988. The prototype for our present automated detection software was first implemented in January 1985 (McMillan *et al.*, 1986). The small format CCD, however, did not allow enough sky coverage to successfully discover NEAs.

A Tektronix TK 2048 CCD with 2048 × 2048 pixels was purchased in 1988 and first used at the telescope in 1989. This CCD suffered from low quantum efficiency and low charge transfer efficiency, but allowed enough sky coverage to faint enough limiting magnitudes to become an effective detector for discovery of NEAs. Our present detection software, called the "Moving Object Detection Program" or MODP, was first tested in early 1990 and has been used in an operational mode since September 1990. A thinned Tektronix TK 2048E CCD with higher quantum efficiency and improved charge transfer efficiency was installed in September 1992 and immediately doubled our discovery rates.

## 2. Observation and Data Reduction

A Tektronix TK2048E CCD is used at the $f/5$ Newtonian focus of the 0.91-m Spacewatch Telescope of the University of Arizona on Kitt Peak (Gehrels, 1991; Scotti *et al.*, 1992; Scotti, 1994). The CCD is operated in slow scanning mode in which the sky is made to drift across the focal plane, usually by turning off the diurnal tracking. The accumulating electronic charges in the CCD are transfered in sync with the drifting images and read out and transfered into our data processing computer. MODP recieves the data and is used to detect moving objects either by their consistent motion or their trailed appearance (Rabinowitz, 1991). Briefly summarizing the operation of MODP, the program provides a real–time observer interface while carrying out 3 modes of object detection. The first mode of detection is the automatic detection of slower moving objects in which three consecutive images of the same location on the sky are obtained usually at half-hour intervals. Each image in the three "passes" are identified and their location and brightnesses are measured. Their relative positions are compared as soon as the third image is available and objects are identified by their consistent motion. The images are flagged in the real–time display and their rates of motion are reported to the observer. The observer can then make use of the rates of motion to identify likely NEAs. The second, and least effective detection method, is automatic streak detection in which trails that are bright enough are identified by MODP. The third detection method is the visual identification of faint trailed images by the observer. The real–time display and online tools in MODP allow the observer to schedule follow–up for these objects in real–time.

MODP also identifies the locations of Hubble Space Telescope Guide Star Catalog (GSC) stars in the image data so that automated astrometric solutions can be computed off-line. Combined with automatically measured positions of confirmed moving objects, another program determines the astrometric solutions and calculates the positions for every confirmed asteroid detection.

## 3. Astrometry

The technique of drift scan astrometry was first tried and reported by Gehrels *et al.*, 1986. The process required manual measurement of bright (saturated) SAO and later AGK3 reference stars. The availability of the GSC with stars as faint as about $V = 16$ has allowed the process to be automated even though the catalog suffers serious uncertainties in the positions it gives for stars and does not include proper motion. Drift scanning improves the astrometric solutions by sampling a long strip of sky typically about 7 degrees long in Right Ascension and 0.5 degrees wide in Declination so that we sample through the boundaries of the original plates used in the generation of the GSC. The scan to scan consistency of the residuals of a given GSC star is better than 0.2 arcseconds while the typical standard deviation of the full set of several hundred GSC stars in a single scan is typically about 0.7 arcseconds, indicating that our ability to provide astrometric positions is catalog limited. Improved catalogs are still difficult to use with CCDs since the exposures required to obtain images of faint asteroids or comets results in saturation of the much brighter reference stars.

Comparison of the residuals of automatically derived astrometric measurements of asteroids with orbits determined from the automatic measurements and from measurements at other observatories confirms the relative consistency of observations on a given night and the larger night–to–night differences of the measurements. Table I from Scotti (1994) demonstrates this point by reproducing two examples from the Minor Planet Circulars.

## 4. Magnitude-Frequency Studies

Studies of the magnitude-frequency relationship of any population of asteroids detected by Spacewatch requires understanding the photometric accuracy and detection efficiency of the system.

The agreement between the magnitudes reported by Spacewatch and that expected from measurements of the same object obtained elsewhere have been surprisingly good since there has been relatively little effort to ensure that our magnitudes are calibrated. A comparison of the calculated magnitude for the same object in the three passes over the same section of sky indicates that we are accurate to better than 0.5 magnitudes. This measurement is complicated by the fact that an asteroid's brightness may change markedly during the 1.5 hour observation time due to its rotation. There is also a small tail of observations with very large differences between the brightest and faintest magnitude reported for the same object. These instances are understood as being due to the effect of cirrus and the chance that an asteroid may appear on or near a brighter star which the automated photometry routine mistakenly measures as the asteroid itself.

Knowledge of the detection efficiency and scanning history of the system is essential in order to debias both frequency and orbital distributions. Two important considerations are the efficiency as a function of asteroid magnitude and rate of motion. These two parameters are not independent since the faster an asteroid moves the smaller the signal will be in the peak pixel which is used for object identification. Complicating matters even further, it is not simple to measure the detection efficiency in a consistent and unbiased manner.

Several methods have been tested for determining the efficiency yet it appears that the best technique is to predict the location of known asteroids with good orbits in the scans and ask if the software detects the object. Twenty-two lunation's of data were searched for numbered asteroids yielding 1328 objects which should have appeared in the scans and 668 were detected by the system. Figures 1a and 1b show the detection efficiency as a function of magnitude and rate of motion respectively. The number of asteroids found in this study does not justify a two-dimensional determination of the efficiency in both parameters. Since most of the numbered asteroids are in the main belt, the efficiency in magnitude is dominated by these objects which have characteristic rates of motion near 0.2deg/day.

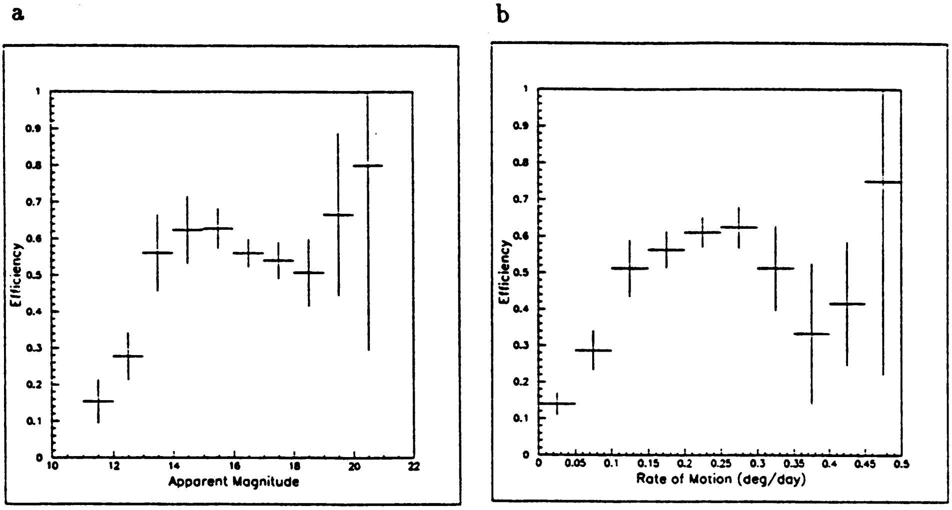

**Figure 1.** Figure 1a on the left shows the detection efficiency of MODP as a function of object magnitude. Figure 1b on the right shows the detection efficiency of MODP as a function of object motion

The efficiency is low for bright objects because they are saturated in the CCD image which makes centroiding difficult. Where the asteroid images are not saturated the efficiency appears to be almost constant. One of the problems with this technique is that the number of known objects which are very faint in our scans is quite small - this explains the large errors in the efficiency determination near the system's detection threshold. The efficiency is rate dependent due to the combined requirement that an asteroid must move at least a certain distance between scans in order to be detected and must not have moved too far in the same time. Spacewatch observers are now using scans of a fixed length (about 30 minutes and chosen to maximize the discovery rate of NEAs) in order to minimize changes in the detection efficiency due to this factor. Figure 1b shows that the efficiency is low for fast and slow objects and at a maximum for objects moving with main belt rates.

If the detection efficiency were independent of rate or magnitude it would be possible to measure the magnitude-frequency or orbital distribution of the detected objects in a relative sense. Since the rates of motion and the orbital characteristics of objects are well correlated near opposition a study of the orbit distribution of Spacewatch objects must take into account the detection efficiency as a function of their rate of motion.

Work is continuing on measuring our efficiency and it is hoped that by including 16 extra months of data, and un-numbered asteroids with good orbits, we can significantly reduce the errors on the measurement. This will allow a determination of the magnitude-frequency (or limits thereon) and orbital distributions of various classes of asteroids discovered by Spacewatch.

## 5. Near-Earth asteroid discoveries

The rate of discovery of NEAs by Spacewatch has been steadily improved since our first automated detection of an NEA in 1990 September. Our early rate of discovery of about 12 per year was doubled at the end of 1992 when we upgraded our CCD detector from a thick Tektronix CCD to a thinned Tektronix CCD with about twice the detective quantum efficiency. Figure 2 shows the number of NEAs discovered per year by all observers and by Spacewatch. Spacewatch presently is discovering about 2/3 of the NEAs found worldwide. Of the 95 new NEAs detected through 1995 June 6, 23 are brighter than $H = 18.3$ ($\sim$ 1 km diameter), 39 have $18.3 < H < 23.3$ (between 1 and 0.1 km diameter), and 33 have $23.3 < H$ (smaller than about 0.1 km diameter). NEAs are discriminated from the rest of the detected asteroids by their rates of motion. Near the opposition point where the search is concentrated, the angular ecliptic rates of motion are diagnostic of the source orbit and distance of the object (Bowell *et al.*, 1990; Scotti *et al.*, 1992; Scotti 1994). Jedicke (1995) has developed a technique which provides the probability that an object is a NEA based upon its rates of motion and location with respect to opposition. This measure will be incorporated into our discrimination criteria in the future.

The dynamical and physical characteristics of the smallest NEAs discovered by Spacewatch have been studied by Rabinowitz *et al.* (1993) and by Rabinowitz (1994). These investigations have found that there is an overabundance of objects smaller than about 50 meters diameter which increases to about a factor of 40 at a diameter of about 5–10 meters ($H{\sim}29$) when compared to a power law extapolation of the numbers of larger NEAs discovered by Spacewatch and elsewhere. A possibly significant number of objects with nearly circular orbits and perihelia near the orbit of the Earth has also been recognized. Several of these small NEAs have been observed spectrophotometrically when the opportunity has arrisen of having an object discovered before its closest approach to Earth. Although the data are individually of low signal-to-noise, taken as a whole, their colors can be compared with those of the main-belt asteroids. Collectively they are significantly different in color from the main-belt asteroids.

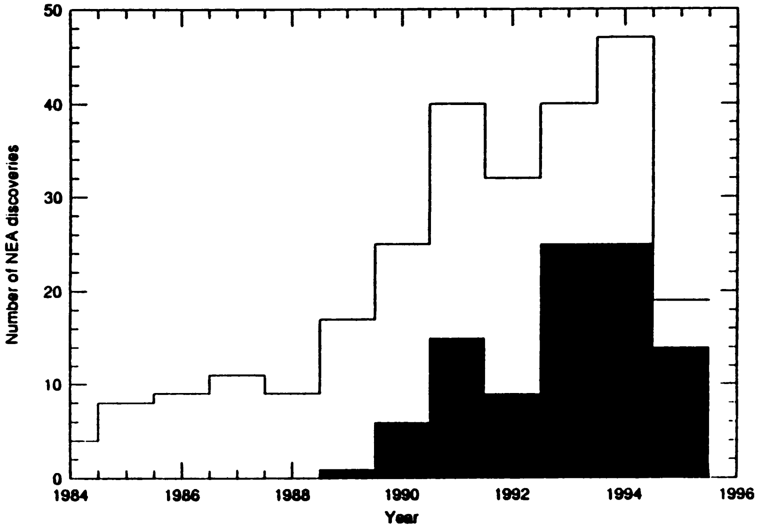

*Figure 2.* **The number of NEA discoveries per year between 1984 and 1995. This histogram shows the number of Spacewatch NEAs as black.**

## 6. Main-belt asteroid discoveries

A byproduct of the search for NEAs with Spacewatch is the discovery of several thousand Main-belt asteroids each lunation. These objects are not followed for a better orbit determination but we report automatically generated astrometric positions for each of the detections. They are regularly employed by the Minor Planet Center to update the orbits of known asteroids reported in our "incidental astrometry" as well as identifying objects which we have accidentally detected on more than one occasion, sometimes during different lunations or even during different oppositions.

The availability of these observations allows study of their magnitude-frequency relationships. In the past two and a half years we have obtained positions, motion vectors, and magnitudes for about 50,000 mainbelt asteroids. We are exploring the possiblity of using circular orbits in order to estimate the distance to each asteroid and thereby determine its absolute magnitude. The error in the apparent magnitude and the distance to the object (by assuming it is on a circular orbit) combine to give an error on the absolute magnitude of about 0.75 - we believe that this is sufficient for a statistical treatment of the magnitude-frequency of the main belt asteroids. Since Spacewatch can detect 1 km diameter objects at the inner edge of the belt, this measurement will have useful application to many main belt evolutionary studies.

A side affect of any future large scale survey for NEAs conducted using techniques similar to those employed by Spacewatch will include a similar (but correspondingly larger) collection of main-belt asteroid detections and ultimately will provide a survey of the main-belt complete to near the limiting magnitude used in the NEA survey. New families and possibly new orbit types amongst the smaller and more complete sample of asteroids may become known.

## 7. Centaur Asteroid Studies

There now exist over two dozen detected Kuiper Belt Objects yet only six known Centaurs – this is presumably due to their relatively short dynamical lifetime. Three of the Centaurs were discovered by Spacewatch and a fourth was accidentally re-discovered by Spacewatch. We are currently working on converting our observations into a limit on their number. This study depends critically on the efficiency of the system as a function of both magnitude and rates of motion as described above.

The efficiency for detecting Centaurs was determined using a reasonable model population to represent their orbit distribution. With only six known members it is impossible to draw any conclusions about the actual orbit distribution. A series of similar studies will be performed to determine the systematic effect of assuming a specific orbit distribution. In this preliminary study, the generated distribution in semi-major axis was flat in the range $10 \leq a \leq 29$ AU in order to span the range of the known Centaurs. Since their orbits are chaotic and characterized by high eccentricity the distribution in $e$ was generated normally with a mean of 0.4 and width of 0.3. Even though the work of Holman & Wisdom (1993) suggests that circular orbits are not stable between the gas giants, low eccentricity orbits were included in this preliminary study and the effect of excluding them and altering the distribution will be studied in detail in the future. Finally, the inclination distribution was motivated by that of the main belt asteroids and was generated according to a probability distribution of the form $P(i) \propto e^{62 \cos i}$. The distribution in the other three orbital elements and the absolute magnitude were flat in the range $(0, 2\pi)$ and $(5, 10)$ respectively.

Simulations such as this one must use *generated* orbit and magnitude distributions which mimic the actual population as closely as possible in order to properly interpret the results. In this particular case, since only the magnitude-frequency relation is being studied, the generated distribution in absolute magnitude may have any shape since the efficiency is being determined as a function of this parameter.

The model Centaur population of $10^5$ objects was subjected to the Spacewatch set of scans, and the efficiency as a function of rate and magnitude as determined above was used to determine if we might have discovered the object. For this particular orbit distribution, the efficiency for detecting simulated Centaurs drops from about 9% to 2% in the range $H = 5 - 10$.

The implied 90% confidence limit on the total number of Centaurs with orbits similar to the generated distribution and brighter than $H = 10$ is about 250. The number of Centaurs is clearly much less than the number of main belt or Kuiper Belt objects.

## 8. Comet discoveries

Spacewatch has discovered 3 new comets and re-discovered one long-lost comet. Several other comets have been accidentally re-discovered during the survey, however, based on the rate of discovery reported by Gehrels (1981) during the course of a photographic Schmidt survey for faint comets, we would have expected to find approximately 6 new comets each year! This discrepancy is at first surprising. Several factors are apparently conspiring against our finding faint comets. First, the faint comets we should see may not be active enough to show an obvious coma. Second, since we have observed during our first 5 years of our survey with an un-coma-corrected $f/5$ Newtonian, a marginally diffuse object might be masked by the substantial coma present in the images. Third, a recent estimate suggests that about 80% of the comets that we would detect will have rates of motion similar to the main-belt asteroids which are also detected. Fourth, MODP has been designed to minimize false detections as much as possible and it detects many fictitious objects around bright stars with large regions of scattered light, as well as comets with substantial coma and tails. A software filter was installed in the software to specifically guard against the numerous false alarms caused by bright stars, and has the undesireable side affect of removing active comets. Presumably, the observer will notice the comet – if it looks like a comet – and flag the object manually, but for fainter diffuse comets, or those which do not have a distinctive cometary appearance, this may not happen. We have recently installed a coma corrector on the Spacewatch Telescope and a coma corrector is to be part of the design of the 1.8-meter telescope which is under construction, so that the second point regarding badly comatic images should be eliminated. Another possibility which might explain our lack of comet discoveries would be a cutoff in the size distribution of small comets. Alternatively, small comets may not be active enough to be detected or may disintegrate more rapidly than the larger comets.

## 9. Conclusions and Future Research

Spacewatch has demonstrated the automated discovery and astrometry of small bodies in the Solar System and particularly of the population of NEAs. We are presently constructing a 1.8-meter telescope which will continue to improve our ability to discover and follow-up comets and asteroids.

Continued improvements in our equipment and techniques allow us to study the different populations in the solar system and their interrelationships.

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