Near Earth Objects, our Celestial Neighbors: Opportunity and Risk
Proceedings IAU Symposium No. 236, 2006
A. Milani, G.B. Valsecchi & D. Vokrouhlický, eds.

doi:10.1017/S1743921307003407

Spacewatch preparations for the era of deep all-sky surveys

Robert S. McMillan[1] **and The Spacewatch Team**[1]

[1]Lunar and Planetary Laboratory and Steward Observatory, University of Arizona, Tucson, AZ 85721, USA
email: bob@lpl.arizona.edu

Abstract. The Spacewatch Project at the University of Arizona uses a 0.9-meter and a 1.8-meter telescope to search for new Near-Earth Objects (NEOs) and make astrometric followup measurements of known ones. Among the presently operational asteroid astrometry programs, Spacewatch is uniquely suited to support discoveries by the planned deep all-sky surveys. The Spacewatch 1.8-meter telescope is the largest in the world that is used exclusively for observations of asteroids and comets. Since 2003 January 1, Spacewatch has made ∼2400 separate-night detections (discoveries plus followup) of NEOs with absolute magnitude $H \leqslant 22$, including 117 fresh discoveries of NEOs with $H \leqslant 22$ and ∼900 separate-night detections of Potentially Hazardous Asteroids (PHAs). Objects have been recovered at $V=23$ and at elongations less than 60 degrees from the Sun. Spacewatch followup observations have contributed to the removal of 137 objects from JPL's impact risk website. Examples of notable recoveries by Spacewatch include the extension of orbital arcs from one month to multi-opposition orbits, and a successful targeted search for a large PHA (1990 SM) with 80 degrees of uncertainty. Spacewatch has been making as many observations of PHAs with $H \leqslant 22$ and $V > 21$ as all other followup stations combined. Followup of NEOs while they are not near Earth provides better leverage on orbital elements and will be well suited to follow up some of the discoveries by the larger-scale, deeper sky surveys: both ground- and space-based. Spacewatch is collaborating with the Panoramic Survey Telescope and Rapid Response System (PS) of the University of Hawaii's Institute for Astronomy. Each lunation, Spacewatch sends its listings of point sources detected in survey images for PS's moving object detection team to test their software. Spacewatch is also prepared to follow up objects of special interest, fast motion, or less than three nights of observations by PS itself. Spacewatch's current equipment is only a few years old, but there is still room to improve limiting magnitude & time efficiency.

Keywords. Telescopes; catalogs; survey; astrometry; discoveries

1. GOALS and CONTRIBUTIONS of SPACEWATCH

The goals of the Spacewatch Project are to discover and observe small bodies in the solar system and to analyze the distributions of their orbits and absolute magnitudes. Astrometric imaging observations are scheduled an average of 24 nights per lunation with the 0.9-meter and 1.8-meter Spacewatch Telescopes at Steward Observatory on Kitt Peak mountain in the Tohono O'odham Nation, Arizona. Spacewatch discoveries and detections provide information about the dynamical history of the solar system. Analyses of the Centaur (Jedicke & Herron 1997), Main-Belt (Jedicke & Metcalfe 1998), Trans-Neptunian (Larsen *et al.* 2001; Roe *et al.* 2005; Larsen *et al.* 2006a); and Near-Earth Object (NEO) populations (Rabinowitz 1991; Rabinowitz 1993; Jedicke 1996; Bottke *et al.* 2002; Morbidelli *et al.* 2002; McMillan, Block & Descour 2005; Larsen *et al.* 2005; Larsen *et al.* 2006b) have used Spacewatch observations. Spacewatch also finds and follows up potential targets for interplanetary spacecraft missions (McMillan 1999a; McMillan 1999b) and radar observations (Ostro *et al.* 2003), and finds and follows objects that might present a hazard to the Earth. Spacewatch provides hundreds of thousands of astrometric and photometric observations of asteroids annually, and recovers and does astrometry of high-priority comets and asteroids that are too faint for most other asteroid observing stations. This report is focused on the recent and future contributions of Spacewatch to campaigns to characterize the threat of impacts of asteroids on the Earth.

2. FACILITIES and METHODS

Site: Moving objects are discovered by imaging the sky with CCD detector arrays on a 0.9-meter telescope and a 1.8 meter telescope on Kitt Peak. This location has several advantages. Except in the summer when the ecliptic is unfavorably placed anyway, the climate rarely causes cloudy conditions for more than 2 or 3 days in a row. This helps the study of time dependent phenomena. The proximity to Tucson causes ∼0.5 mag loss of sensitivity on moonless nights, but it also makes excellent infrastructure possible. The relatively short commuting time from Tucson is favored by daytime technical support personnel.

Usage: The two Spacewatch telescopes complement each other, with the 0.9-m and its wider field of view operating in a systematic search pattern near opposition and the narrower-field 1.8-m concentrating on followup of specific targets. The wider field of the mosaic of CCDs on the 0.9-meter telescope has also recovered lost PHAs. The image scale on both telescopes is 1.0 arcsec per pixel, which samples the typical seeing at this site well. Three images, or “passes”, are made at short intervals to reveal moving objects.

Optics: R. A. Buchroeder designed the coma corrector/field flattener for the 1.8-meter f/2.7 paraboloidal primary mirror, based on a modified Klee prescription that prevents light reflected off the CCD from forming a ghost image of the telescope entrance pupil onto the CCD. Because the CCDs manufactured by Tektronix in the 1990s were not flat, but slightly convex, the optical prescription for the corrector at the 1.8-meter telescope accommodates the measured spherical component of the shape of the CCD surface. *This fact must be remembered if the detector at the 1.8-meter telescope is ever changed!* The lenses were fabricated by Tucson Optical Research Corporation. Buchroeder also designed the new (2002) f/3 optics for the 0.9-meter telescope, which includes a spin-cast primary mirror from Wangsness Optics of Tucson, AZ and a multi-element field lens fabricated by Cumberland Optics of Marlow Heights, MD. Unlike the 1.8-m mirror, which has a conventional coating of evaporated aluminum, the 0.9-m primary is silvered and protected by a red-optimized overcoating by Denton Vacuum of Moorestown, NJ. Rayleigh Optics of Baltimore, MD figured the 0.9-m mirror to a hyperboloidal surface.

Filtering: Both telescopes are filtered with Schott OG-515 filters that transmit from 515 nm to the long-wavelength cutoff of the CCDs. The effective wavelength on typical asteroids is ∼700 nm. However, Spacewatch photometry is still calibrated to the V bandpass for consistency with the absolute magnitude system used by the asteroid community. Reasons for the yellow-orange filter are primarily simplicity of optical prescription and ease of fabrication of the field correction lenses, allowing the use of flint glass for achromatism and all spherical surfaces in the lens designs. The filtering also provides cleaner images at high airmass without the need for atmospheric dispersion compensation, suppresses the mostly-blue twilight and scattered moonlight, and suppresses color equation between stars and asteroids in astrometric field modeling at high airmass. The filtering does not cost much light from asteroids shortward of 515 nm, especially when atmospheric dispersion of the shorter wavelength light is taken into account. Finally, glass colloidal filters are more stable and less expensive than interference filters, and are better suited to fast f/numbers.

Detectors: The back-illuminated, antireflection-coated 2048x2048 CCDs we used until 2002 with great success at the 0.9-m telescope and which we still use at the 1.8-m telescope were made by Tektronix (later Scientific Imaging Technologies, SITe®) of Beaverton, OR. They have high quantum efficiency, noise well below the sky background, and have never malfunctioned for us. For the 0.9-m telescope we now have six grade-one back-illuminated, antireflection-coated 4608x2048 CCDs from Marconi Applied Technologies (later EEV or E2V) of Chelmsford, Essex, UK, from which we selected the best four for our mosaic system.

0.9-meter Telescope:

In 1982 the Director of the Steward Observatory allocated the Observatory's 0.9-m telescope exclusively to the Spacewatch Project on a long-term basis, on the condition that technical support and maintenance of the telescope and dome be funded by grants obtained by and for the Spacewatch Project. Spacewatch personnel have rebuilt and upgraded many components and subsystems of this telescope over the years, making it a world-class tool for solar system research. In late 2002 the Spacewatch mosaic camera (McMillan *et al.* 2000) replaced our earlier drift-scan system (McMillan & Stoll 1982; McMillan *et al.* 1986; Gehrels *et al.* 1986; Gehrels 1991; Scotti 1994) on the same telescope and boosted our rate of detection of NEOs with that telescope by a factor of six. The mosaic of four CCDs on the 0.9-meter telescope covers a solid angle of 2.9 deg^2 (Figures 1 and 2). The history of hardware and software used on the 0.9-meter telescope is tabulated at http://spacewatch.lpl.arizona.edu/history.html .

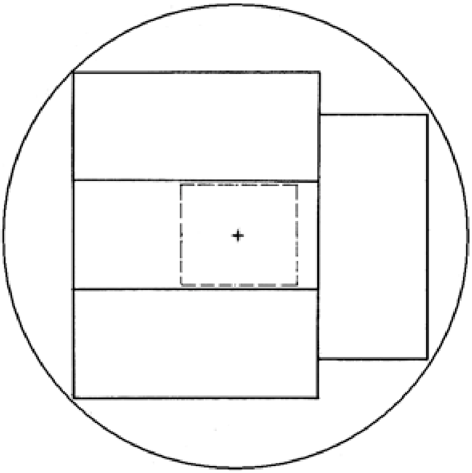

Figure 1. Comparison of the sizes and layouts of the CCDs on the 0.9-m and 1.8-m telescopes. The mosaic of four CCDs on the 0.9-m covers 2.9 square degrees, nine times larger than the area of the 2Kx2K CCD (small square) previously used on the 0.9-m and currently used on the 1.8-m.

Observations are made in the tracked "staring" mode because imagers this large are incompatible with drift scanning. The cycle goes as follows. We expose for two minutes on each position. Each exposure is followed by a 1.5-2 min interval to read the CCDs and slew and settle the telescope and dome to the next center. While the exposure time of 2 minutes may seem long for NEO work, it is the best compromise between sky coverage and open-shutter on-sky efficiency. Reading and slewing cannot be simultaneous owing

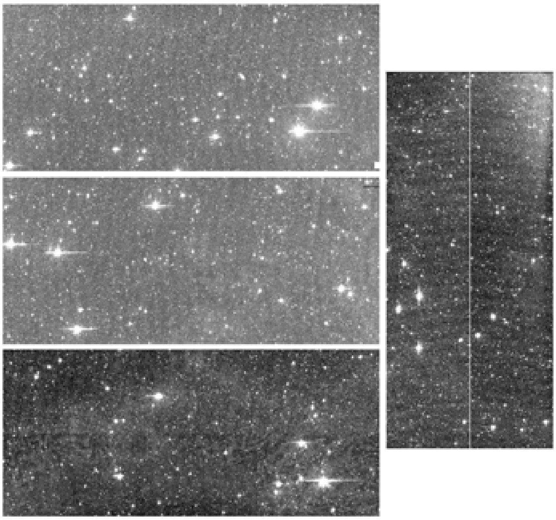

Figure 2. A star field imaged by the mosaic. The limiting V magnitude is 21.7.

to electronic noise from the telescope driving motors. With 2 minute exposures, the duty cycle of open-shutter on-sky time is 50%, as low as we choose to work. The period of the telescope's right ascension worm gear is also 2 minutes, so worm errors affect each 2-minute exposure the same way. Including overhead such as focusing, longer slews between regions, and other operations, we average a 4 min cycle per exposure. It takes ~0.4 hours to cycle once through seven such pointings. We return to each of the seven pointing centers in a region three times over ~1.3 hours. Thereby we search with a time baseline of about 0.9 hours for detecting motion, reaching V=21-22 mag on objects moving slower than ~1 arcsec per minute. The 0.9-m telescope and camera were completely automated in 2005, and early in 2006 we began operating both telescopes with one observer.

Software: Two programs written by J. A. Larsen run on a cluster of computers at the 0.9-m telescope site: MOSAF (MOSaic Astrometry Finder) and MOSSUR (MOSaic SURvey). The catalog-based search is fairly efficient in terms of execution time per candidate found. MOSAF performs all flat field, dark, bias, and fringe corrections, creates an object catalog of detections in a manner similar to Sextractor (Bertin & Arnouts 1996), and produces both raw and processed, astrometrically calibrated MEF FITS images using the CFITSIO libraries of Pence (1999), the WCSLIB libraries of Mink (2002) and the USNO-A2.0 astrometry catalog (Monet *et al.* 1998). (Conversion to USNO-B1.0 on both telescopes is pending in the winter of 2006-2007.) The catalogs of detected objects contain many image parameters such as the shape, position, flux, moments and the parameters of a simple fit to an ellipse. MOSAF is customized to the Spacewatch imaging system and is integrated into the image creation pipeline. MOSSUR uses the object catalogs created by MOSAF to search for moving objects and creates graphical displays for review and validation by the observer at the telescope. The catalogs are searched for motions with rates between 0.05 and 2.5 degrees per day. This system has been operational since early 2003 and will be described in a paper on the derived statistics of NEOs.

Mosaic Survey Pattern: Since 2003 April when it went into full operation, the mosaic of CCDs on the 0.9-m telescope has covered an average of 1400 deg^2 of sky each lunation. A survey pattern is usually concentrated near opposition, with three exceptions: in the times of the year when the ecliptic is most vertical in the evening and morning skies, in cases of targeted searches, and in the summer.

Figures 3(a), (b), and (c) illustrate the sky coverage with the mosaic of CCDs through May 2005. Since 2004 September we have been revisiting the same regions during each lunation to allow linking of main belt asteroids for statistical studies of that population. The overprinting of region symbols in Fig. 3(c) illustrates the effect. The region centers are actually moved between revisits to follow the motion of typical main belt asteroids. Simulations show that 4-8 day intervals of revisits are infrequent enough to refresh the content of NEOs in the images, although admittedly this practice makes sky coverage by Spacewatch look three times smaller on the Minor Planet Center's (MPC's) sky coverage plots than it really is.

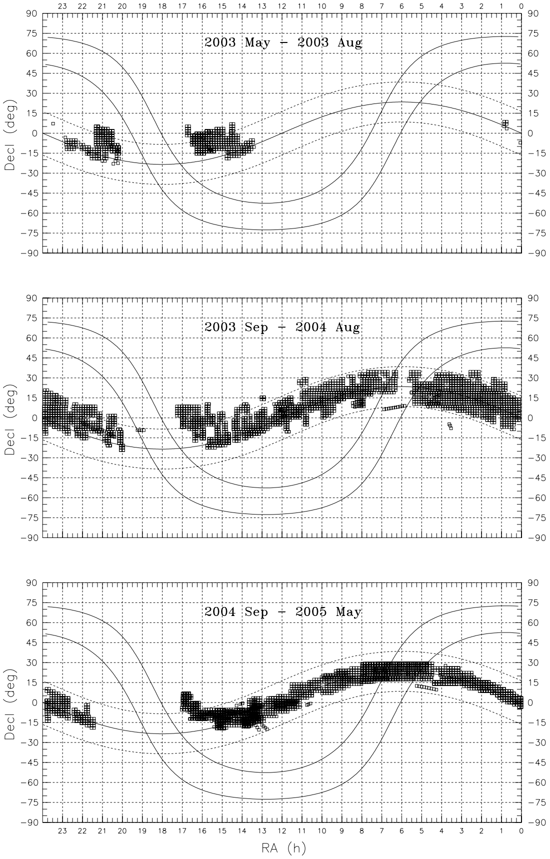

Figure 3. Regions observed with the Spacewatch mosaic of CCDs, 2003 March – 2005 May. The ecliptic and Milky Way are also shown. Coverage during the latest (2005 Sep – 2006 June) season looks similar to 3(c).

Spacewatch 1.8-meter Telescope: The 1.8-meter Spacewatch telescope is, as far we can tell, the largest telescope in the world dedicated exclusively to observations of comets and asteroids. It was built by and for Spacewatch (McMillan *et al.* 1998; McMillan *et al.* 2000; Perry *et al.* 1998). It has reached an apparent magnitude of V=23 for high priority recovery of asteroids. The field of view is 0.6 × 0.6 degrees on a 2K × 2K CCD. Routine operation of the telescope by solo observers began in 2001 October and improvements to the efficiency of its operation have continued steadily. The drift scanning technique (Gehrels *et al.* 1986) provides smooth background and flatfield response as well as straightforward astrometry. The exposure time for each pass with the 1.8-m telescope is 136s/cosδ. A typical scan to follow up an NEO covers from 0.3 to 1.0 deg^2. This telescope is dedicated to followup of faint NEOs, with emphasis on PHAs and objects on the MPC's NEO Confirmation Page and the JPL and NEODyS impact risk pages. About half of the followup targets are detected automatically and half are measured by hand, usually because they were too faint or too trailed for the software. The 1.8-m is also committed to lightcurves of Trans-Neptunian Objects (TNOs) under a grant to Jim Scotti from NASA's Planetary Astronomy Program.

3. RECENT RESULTS

Followup Observations: Spacewatch equipment and methods are best suited to followup observations nowadays. Followup of NEOs helps to consolidate their orbits as their brightness fades after discovery. Faint followup is also frequently required for recoveries of NEOs during later apparitions. We elaborate on recoveries in a later section.

About two-thirds of followup observations of PHAs by Spacewatch are deliberately targeted and one third occur incidentally during surveying. Discovery observations are counted here with the same weight as targeted and incidental followup observations. We quote most of our statistics for the last three years of operation in order to refer to the equipment we are presently using. We count one set of three observations of position as one "detection" by Spacewatch.

Figure 4 illustrates how Spacewatch's rate of detection of NEOs improved after the introduction of the 1.8-meter telescope in late 2001 and the mosaic of four CCDs and new optics of the 0.9-meter telescope in early 2003. Figure 5 shows a similar improvement for PHAs.

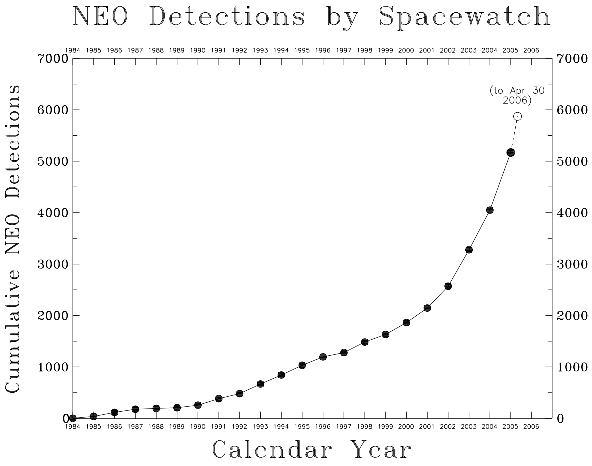

Figure 4. Cumulative count of detections of NEOs by Spacewatch vs. time. All discoveries, incidental detections, and targeted followup detections by either telescope are counted.

To show that Spacewatch samples a wide range of absolute magnitudes of NEOs, Figure 6 presents a histogram of the H values of NEOs detected with the 0.9-m telescope and mosaic. The results from the 1.8-m telescope are similar.

Spacewatch has recovered objects less than 60 degrees from the Sun. Figure 7 shows the distribution of pointings with the Spacewatch 1.8-m telescope during one lunation. Figure 8 shows the distribution of observations of PHAs with respect to opposition for both Spacewatch and the rest of the NEO community. The capability of ground-based telescopes to reach small elongations for special cases should not be overlooked.

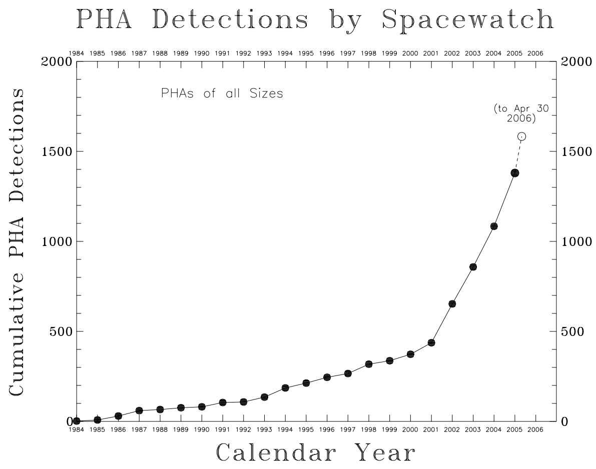

Figure 5. Cumulative count of detections of PHAs by Spacewatch vs. time.

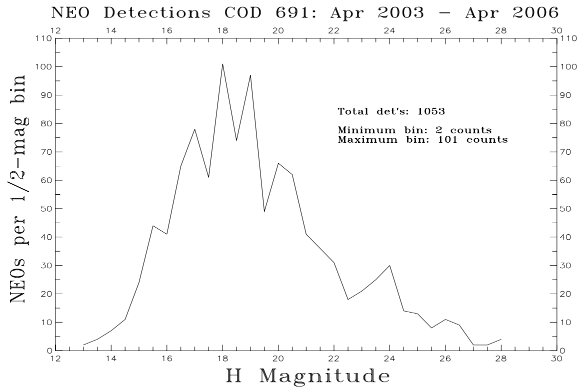

Figure 6. Histogram of absolute magnitudes H of NEOs detected by the Spacewatch 0.9-m telescope in the last three years.

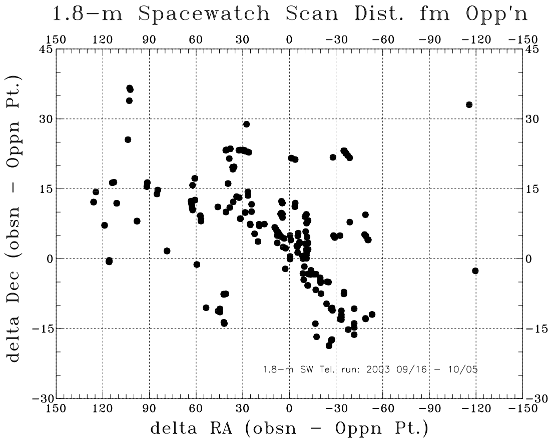

Figure 7. Distribution on the sky of observations made with the Spacewatch 1.8-m telescope during one lunation, illustrating how far from opposition we can observe.

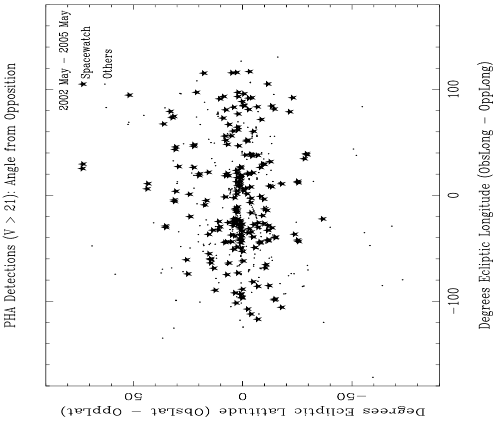

Figure 8. Distribution with respect to the opposition point of detections of PHAs by the asteroid followup community, with Spacewatch observations emphasized.

Another factor to consider is how our numbers of detections compare with those made by other stations. Some use four or five exposures instead of three, and sometimes an NEO might receive a long series to measure a lightcurve. Updating orbits is served better by distributing the observing effort over multiple objects and separate nights. For the statistics presented here, we count only one detection per object per station per night.

Figure 9 illustrates the substantial contribution of Spacewatch relative to the other stations that are active in followup of large PHAs when such objects are faint. Of course Spacewatch also follows up PHAs with absolute magnitudes down to the Minor Planet Center's (MPC's) defining limit of H=22; Figure 10 compares our contributions on those objects relative to the rest of the faint followup community. Spacewatch stands out similarly when the limiting magnitude is increased to V=21.5 and when numbers of different objects are counted instead of all detections on separate nights. Objects that appear on JPL's impact risk website are also priorities for Spacewatch followup. Spacewatch followup observations contributed to the removal of ∼80 objects from that list in the last 3 years.

Recovery Observations: PHAs with uncertain ephemerides are targeted by Spacewatch. Some objects become uncertain due to the infrequency of favorable apparitions and/or interference by the Moon or galactic plane. If the object is faint during a return apparition, which is usually the case, recovery is labor intensive and time critical. A. S. Descour and others developed software tools and an observing regimen to aid recoveries.

Table 1 lists some examples. Of particular note is the Spacewatch recovery of 1990 SM, a lost H=16 PHA that had not been seen since the discovery apparition, 15 years before. The object had had windows of opportunity for recovery nearly every year since discovery, more than six of which reached V brighter than 18, but they were very short and near the galactic plane, so the surveys had not recovered 1990 SM incidentally.

Image Data Archive: This archive has yielded arc extensions for more than a dozen virtual impactors, 2004 MN_4 being the most important example. Images have also been provided for other objects of interest. About 3 Terabytes (TB) of data from the old (1990-2002) configuration of the 0.9-m telescope covers a sky area of 30,000 deg^2 including revisits on separate nights. Imagery to date from the Spacewatch 1.8-m telescope amounts to approximately 1.5 TB. Data from the mosaic of CCDs have been accumulated since 2003 Mar 23 and now consist of >5 TB. About 40,000 deg^2 have

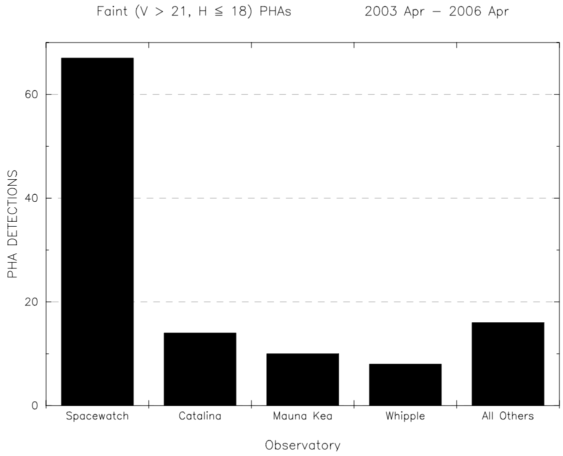

Figure 9. Numbers of detections of intrinsically bright PHAs while their apparent magnitudes were faint, sorted by observing station. “Catalina” combines station codes 703, G96, E12, and 413. NEAT (not shown separately) includes both 644 and 608, and Spacewatch includes both 691 and 291.

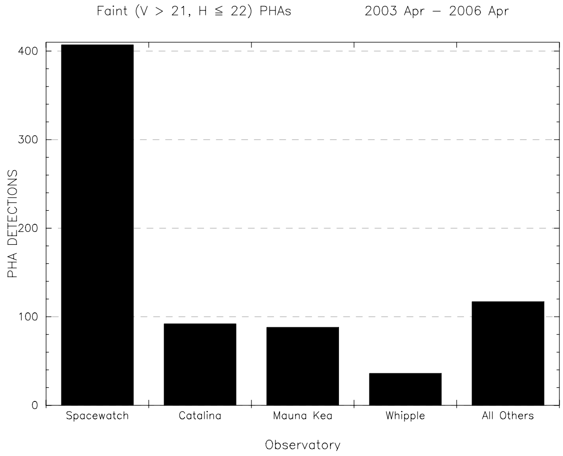

Figure 10. Numbers of detections of PHAs with absolute magnitude H $\leqslant$ 22 while their apparent magnitudes were faint, sorted by observing station.

been covered by three passes with the mosaic. The URL http://fmo.lpl.arizona.edu/cgi-bin/mosaic_archive/point_history.cgi accesses the database of pointing centers and our protocol for requests for imagery.

Incidental Astrometry (IA): In the last three years, Spacewatch has sent more than a million astrometric detections of asteroids (∼3 million astrometry records) to the MPC. More than half of those detections have been linked by the MPC to previously known asteroids or with each other. At our request, the MPC has recently agreed to release all of Spacewatch’s unlinked detections for the use of the asteroid community at large.

Precoveries: Observations made prior to discoveries can be found in archives of images as well as in previously reported incidental astrometry (IA). Here we give examples of both types of such “precoveries”. Spacewatch has precovered high priority NEOs such

Table 1. Notable Examples of Spacewatch Recoveries of Uncertain PHAs.

Object	Unc. (deg)	H mag	V mag	MPEC	Arc Before	Arc After	Net O-C arcsec
2002 TW$_{55}$	1	18.0	21.7	2005E54	52d	831d	237
1990 SM	80	16.2	21.2	2005C26	24d	5225d	23022
1999 VT$_{25}$	3	21.4	21.5	2004U47	26d	1786d	7556
2000 EV$^{*}_{70}$	3	20.5	20.9	2004E11	46d	1193d	214
2001 US$_{16}$	2	20.2	20.7	2004B68	31d	802d	485
1998 VS*	4	22.3	21.3	2003Y18	32d	1831d	1581
2000 UL$_{11}$	2	20.1	21.9	2003S71	28d	1039d	3320
2003 BH		20.7	22.7	2005-J56	51d	844d	45
1998 VF$_{32}$	2	21.2	21.2	2005-W43	14d	2555d	5581
2001 YP$_{3}$	2	22.0	21.4	2005-X55	109d	1453d	21
2004 JQ$_{1}$	1	20.1	21.8	2006-C02	31d	600d	210
2004 RY$_{109}$	0	19.1	22.6	2006-C19	94d	510d	22
2005 TR$^{*}_{50}$	1	20.2	21.5	2006-F24	2d	164d	3660

$*$ Asteroids 1998 VS and 2005 TR$_{50}$ lost their PHA status due to the recoveries' updates of their orbits. Catalina's station G96 recovered 2005 TR$_{50}$ on the same night that Spacewatch did.

as 2004 MN$_4$, a PHA whose estimated probability of impact on Earth rose to a record high value of a few percent in 2004 December before we found images in the Spacewatch archives. We increased 2004 MN$_4$'s arc from 190 days to 255 days, enough to reduce the estimate of probability of impact to a much less alarming value. 2004 MN$_4$ now has the permanent designation and name of (99942) Apophis. Other precoveries within the last 3 years total about 130 NEOs and 4 comets.

Examples of precoveries extracted by the MPC from our IA include 2001 WG$_2$ (an Apollo of high eccentricity and inclination), 2001 XN$_{254}$ (a PHA with H=17.5), periodic comet P/2002 BV, Amor 2003 HB$_6$, comet P/2004 A1, Amors 2003 OB$_4$ and 2003 MT, Apollo 2003 YO$_1$, and Apollo PHA 2003 YK$_{118}$. The latter was found among our observations in 1993, predating the discovery by more than a decade. 1994 UG was retired from JPL's impact risk page as a result of Larsen's new astrometry of old imagery. During the last three years, at least 122 NEOs, 6 comets, and 3 outer solar system objects were found by the MPC in our IA.

4. ASSISTANCE to Pan-STARRS

The next few years will see the beginning of the operation of the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) of the University of Hawaii's Institute for Astronomy (Kaiser *et al.* 2005; Jedicke *et al.* 2005a; Jedicke *et al.* 2005b). Pan-STARRS' (PS's) revisits of areas surveyed during a lunation will allow PS to determine preliminary orbits of asteroids spanning 4-16 days. Spacewatch has been providing PS with copies of catalogs of detected point sources on which they are testing their linking software.

Additional followup observations with other telescopes would help PS make such linkages in their archives. We assume that PS will detect ~50% of the NEOs with H$\leqslant$22 in 10 years of surveying (Jedicke 2006, personal communication). If there are ~50,000 NEOs with H$\leqslant$22 (Stuart 2001), PS will detect ~25,000 NEOs to V$\leqslant$24 with H$\leqslant$22 in 10 years. We suppose that ~10% of those might lack a third night due to picket fence and other incompleteness effects, and another ~10% might have poorly determined orbits (Jedicke 2006, personal communication). So PS may need followup of ~5,000 NEOs in 10 years or ~500 NEOs per year. About 200 of those should be accessible to Spacewatch with V⩽23 and our weather and declination constraints. With ~1000 hrs/yr of clear observing time with 2 telescopes, and a current annual average of ~1000 separate-night detections of NEOs per year, Spacewatch should be able to target and follow up ~200 NEOs per year at least once. Absorbing this burden into the existing target list is feasible because some of the targets Spacewatch currently follows are lower-priority non-hazardous NEOs, and the brighter (V⩽21.5) PS detections can be absorbed into the survey pattern covered by the automated 0.9-meter telescope. Furthermore, enhancements to software at the 1.8-meter telescope can probably gain us ~20% in telescope time efficiency and ~0.2 mag in sensitivity.

Acknowledgements

The Spacewatch Team members, past and present, and others who contributed their talents and fine work toward these results include L. Acedo, L. Barr, M. Block, T. H. Bressi, R. A. Buchroeder, K. C. Cochran, A. S. Descour, T. Gehrels, R. Jedicke, J. A. Larsen, B. W. Lawrie, J. L. Montani, M. L. Perry, M. T. Read, J. V. Scotti, A. F. Tubbiolo, W. T. Verts, J. T. Williams, and M. Williams.

Spacewatch is funded by grants from NASA's NEO Observation and Planetary Astronomy Programs, The Brinson Foundation, the estates of Richard S.Vail and Robert L.Waland, and other private individuals. At *http://spacewatch.lpl.arizona.edu* there is a description of Spacewatch, the present and former team members are listed, as well as past contributors of funds.

Extensive use of the subscription-supported on-line data services of the Minor Planet Center was made for this report.

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