REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-06-0041

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing i
the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any c
reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis
Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE 26 January 2006	3. REPORT TYPE AND DATES COVERED Final; 1 December 2002 - 30 November 2005

4. TITLE AND SUBTITLE

Spacewatch Survey for Asteroids and Comets

5. FUNDING NUMBERS

AFOSR Grant F49620- 03-1-0107

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8. PERFORMING ORGANIZATION REPORT NUMBER

FRS 330820

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U. S. Air Force: AFOSR/NM
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10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

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12a. DISTRIBUTION / AVAILABILITY STATEMENT

UNCLASSIFIED, UNRESTRICTED

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 Words)***

Low-light-level telescopic imaging observations of the night sky were made with the 0.9-meter and 1.8-meter Spacewatch Telescopes on Kitt Peak mountain in the Tohono O'odham Nation, Arizona. Small bodies in the solar system were discovered and followed to improve knowledge of their orbits and analyze the distribution of their absolute magnitudes. During this grant interval, a total of 6,620 positional measurements of 1,352 Earth-approaching Asteroids (EAs) were made, 200 of which were objects newly discovered by this project. The other EAs were observed to improve their orbits. Spacewatch also discovered 5 Centaurs or Scattered Disk Objects, 3 Trans-Neptunian Objects (TNOs), and 12 comets during this report interval. The 0.9-meter telescope was automated during this grant interval, allowing unattended operation. The number of detections of EAs and the area of sky covered allowed a new determination of the number of EAs with absolute magnitudes ≥22 and their distribution with absolute magnitude to be made. New collaborations were formed between Spacewatch and the USAF-funded Pan-STARRS project in Hawaii and the NASA-funded WISE spacecraft mission. Updates on loose associations with a program of asteroid photometry in NW Australia, and astronomers in Mongolia are also given. Spacewatch is described at http://spacewatch.lpl.arizona.edu.

14. SUBJECT TERMS

Asteroids. Space. Surveillance. Telescope. Camera. Survey. Orbit. Astronomy

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED, UNRESTRICTED	UNCLASSIFIED, UNRESTRICTED	UNCLASSIFIED, UNRESTRICTED	NONE

FRS 330820

FINAL REPORT for GRANT
F49620-03-1-0107
to the
University of Arizona
Steward Observatory
from the
U. S. Air Force Office of Scientific Research

Title: **Spacewatch Survey for Asteroids and Comets**

Duration of Grant: 1 December 2002 - 30 November 2005

Dates Reported on: 1 December 2002 - 30 November 2005

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ABSTRACT of Original Proposal in May 2002:

Overview: The Spacewatch Project, begun at The University of Arizona in 1980, is an exploration of the various populations of small objects throughout the solar system, from the orbit of the Earth to beyond the orbit of Neptune. Spacewatch provides information on the distributions of asteroids as functions of orbital parameters and absolute magnitude, finds interesting targets for space missions, and finds objects that might present a hazard to the comfortable environment we enjoy on Earth. Spacewatch is described at http://www.lpl.arizona.edu/spacewatch/index.html, where a list of publications can also be found. This proposed grant will cover about one fifth of Spacewatch's salary and operating expenses for three years.

Relevance to the AFOSR Mission: This proposal is addressed to AFOSR's involvement in "...advancing deep space surveillance techniques to observe and track Near Earth Objects....", as stated on page 29 of the October 2001 issue of Research Interests of the AFOSR and Broad Agency Announcement 2002-1. AFOSR's interest in asteroid surveying and astrometry was also stated on pp31-32 of the June 2001 issue of AFRL Technology Horizons magazine.

Discovery: Spacewatch will expand and accelerate its search for new members of all classes of asteroids and comets throughout the solar system. The new, larger (1.8-meter) telescope now provides access to more of the intriguing very small Earth-approaching asteroids, as well as Trans-Neptunian Objects (TNOs). By the time this grant begins, the 0.9-m telescope will have been fitted with a mosaic of CCDs, allowing Spacewatch to detect Earth-approaching Asteroids (EAs) six times faster than it has been doing, up to 300 (new plus old) per year. These will include many EAs larger than 1 km in diameter.

Recoveries: EAs tend to be fainter (dimmer) on their return apparitions years after their epoch of discovery because close approaches to Earth are rare. The Spacewatch Project will recover and do astrometry on EAs that are too faint for other observatories.

Interpretation: Integration of the size distribution of EAs, combined with corrections for the incompleteness of our survey, will yield a new estimate for the total number of EAs that are large enough to endanger the Earth with their impacts. Their distribution with orbital elements can also help determine the relative contributions from the various dynamical mechanisms replenishing the population of EAs. Finding large (bright) TNOs will provide clues to the extent of accretion of bodies in the outer solar system.

Overseas Collaborations: Spacewatch will continue to provide advice and guidance via email on asteroid astrometry and photometry to the Research Center of Astronomy and Geophysics (RCAG) of the Mongolian Academy of Sciences, which operates the Khureltegoot Observatory near the capital city of Ulaanbaatar, and to astronomers at the Learmonth Observatory in Western Australia.

STATEMENT OF WORK in Original Proposal, May 2002:

This grant from AFOSR will fund only about one-fifth of the payroll and operating costs of Spacewatch. Therefore, meeting the obligations enumerated here is subject to Spacewatch receiving the rest of its funding from other sources.

! The search for asteroids will be continued with the Steward Observatory 0.9-m telescope and the Spacewatch 1.8-m telescope.

! Spacewatch will recover known EAs that are in need of updated orbits and are too faint for other observatories. The smaller telescope, with its wider field of view, will be used to recover asteroids with large positional uncertainties. The larger telescope will be used to recover asteroids that are too faint for smaller telescopes. Priority will be given to PHAs, virtual impactors, and objects discovered by Spacewatch.

! We will continue to mine our 1990-1999 data archive for moving objects that were missed by old software.

! All discoveries and astrometric positions will be reported promptly to the International Astronomical Union's Minor Planet Center in Cambridge, Massachusetts.

! Studies of the statistics of the various populations of asteroids will be conducted to analyze their distributions with absolute magnitude and orbital parameters.

! Spacewatch will continue to provide advice and guidance, exclusively via email, on asteroid astrometry and photometry to the Khureltegoot Observatory in Mongolia and to the Learmonth Solar Observatory in NW Australia.

EXPECTED RESULTS in Original Proposal, May 2002:

! Hundreds of detections of EAs (new plus old) should be made by Spacewatch in the course of routine surveying in the next 3 years. This assumes both telescopes will be in heavy use and the mosaic of CCDs will be operational soon after this grant begins on 2002 November 1. Most of the EAs with H#18 detected by Spacewatch will have been too faint at those times for the LINEAR survey (Stokes et al. 2000) to detect in its large-area short-exposure mode of observing.

! The statistical properties of these detections will be presented as constraints on the numbers of EAs with H#22, their distribution with absolute magnitude, the number of PHAs, and on the evolution of EA orbits.

! Some of the recoveries by Spacewatch of EAs with large uncertainties in position and/or faint magnitudes will be unique and will prevent loss of the objects.
! Approximately 80,000 objects, including 12-24 EAs, are expected to be measured for the first time in each year of data prior to 1999 October by reanalysis with new software. All new detections will be sent to the MPC and the pixel data will be converted into a searchable database.

SUMMARY OF GRANT EFFORT, 1 DEC 2002 - 30 NOV 2005

The goals of the Spacewatch Project are to discover small bodies in the solar system and to analyze the distributions of their orbits and absolute magnitudes. Astrometric imaging observations are scheduled on an average of 3 weeks per month with the 0.9-meter and 1.8-meter Spacewatch Telescopes on Kitt Peak mountain in the Tohono O'odham Nation, Arizona. Our discoveries support studies of the Trans-Neptunian, Centaur, Trojan, main belt asteroid, and Earth-approaching (EA) asteroid populations. These studies provide information about the evolution of these objects and their orbits. Spacewatch also observes potential targets for space missions and radar, finds objects that might present a hazard of impact on the Earth, provides accurate astrometry of tens of thousands of asteroids annually, and recovers and does astrometry of high-priority comets and asteroids that are too faint for most other asteroid observing stations.

The 1.8-meter Spacewatch telescope is the largest telescope in the world dedicated exclusively to discovery and astrometry of comets and asteroids. It has a limiting magnitude of V=23, 4 mags fainter than the LINEAR survey (Stokes et al. 2000). With this telescope, Spacewatch contributed as many observations of faint Potentially Hazardous Asteroids (PHAs) during this report interval as all other observing stations combined.

Since it went into operation, the mosaic of CCDs on the 0.9-m telescope covered in each lunation an average of 1400 square degrees of the most important regions of the sky for EA discovery. Thus Spacewatch's fainter magnitude limits and sensitivity to slower motions permitted comprehensive discovery and followup of EAs at relatively large distances from Earth, thereby helping to complete the survey for hazardous asteroids.

During this grant interval, we made a total of 6,620 positional measurements (2,206 detections) of 1,352 EAs, 200 of which were objects newly discovered by us. We observed the other EAs to improve their orbits. Spacewatch also discovered 5 Centaurs or Scattered Disk Objects, 3 Trans-Neptunian Objects (TNOs), and 12 comets during this report interval.

The 0.9-meter telescope and camera were completely automated during this grant interval, allowing the entire system including the dome to operate unattended all night under computer control.

Newly formed collaborations between Spacewatch and the USAF-funded Pan-STARRS project in Hawaii and the NASA-funded WISE spacecraft mission reflect the usefulness of Spacewatch

for years to come. Updates on loose associations with a program of asteroid photometry in NW Australia, and astronomers in Mongolia are also given.
Spacewatch is described at the URL http://spacewatch.lpl.arizona.edu.

BACKGROUND

This grant covered about one fifth of Spacewatch's salary and operating expenses during this report interval. As the AFOSR has elected not to continue funding Spacewatch after 30 Nov 2005, this grant is the last of a series of grants from AFOSR that funded Spacewatch continuously since 1984. Spacewatch continues with funding from NASA and the Chicago-based Brinson Foundation.

History: Asteroid surveying with charge-coupled device (CCD) detectors was developed by Spacewatch in the early 1980s. Spacewatch was the first to use CCDs to survey the sky for comets and asteroids, first to do astrometry on an asteroid with a CCD (1984 JZ on 1984 Apr. 28; numbered (3325) after our observation), first to do targeted astrometry of an Earth-approacher (EA) with a CCD (1983 TB, now known as (3200) Phaethon, on 1984 Sep. 22), first to discover asteroids with a CCD, first to use a CCD to discover an asteroid that received a permanent number (the Trojan (3801) Thrasymedes), first to discover an EA with a CCD (1989 UP), first to discover an EA with software (1990 SS; now (11885)), and first to discover a comet with a CCD (125P/1991 R2). Later accomplishments are described below. Spacewatch is also a conscientious and authoritative interface to the media and general public on this discipline and on the issue of the hazard from impacts by asteroids and comets.

Technique: 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. The principles of Spacewatch observing have been described by McMillan and Stoll (1982), Gehrels et al. (1986), McMillan et al. (1986), Gehrels (1991), Rabinowitz (1991), Scotti (1994), Jedicke (1996), Perry et al. (1998), McMillan (1999a,b), McMillan et al. (2000), and McMillan et al. (2005). The two telescopes complement each other, with the 0.9-m and its wider field of view operating in a systematic search pattern near the ecliptic and the narrower-field 1.8-m concentrating on followup of specific targets. Both telescopes= CCDs are filtered to a bandpass of 515-950 nm, with an effective wavelength on typical asteroids of 700 nm. (Spacewatch photometry is still calibrated to the V bandpass for historical reasons.) The image scale on both telescopes is 1.0 arcsec per pixel. Three passes or images are made at short intervals to reveal the motions of objects.

FACILITIES and EQUIPMENT

Detectors: The back-illuminated 2048x2048 CCDs we used with great success at the 0.9-m telescope and which we still use at the 1.8-m telescope were made by Tektronix7 (now Scientific Imaging Technologies, SITe7) 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, AR-coated 4608x2048 CCDs from Marconi Applied Technologies, from which we selected the best four for our mosaic system.

0.9-meter Telescope: The Director of the Steward Observatory has 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 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. The mosaic of four 2Kx4K thinned, back-illuminated EEV CCDs on the 0.9-meter telescope covers a solid angle of 2.9 square degrees. Observations are made in the Astaring@ mode. The observing cycle goes as follows. We expose for 120 sec on each position. Each 120 sec exposure is followed by a 97 sec interval to read the CCDs and slew and settle the telescope and dome to the next pointing center. Including overhead such as focusing, longer slews between regions, and other operations, this makes a 4 min cycle per exposure. It takes 26 minutes to cycle once through seven such pointings. We return to each of the seven pointing centers in a Aregion@ three times over 78 minutes. Thereby we search with a time baseline of about 0.9 hours for detecting motion. An area of about 1400 deg^2 near the ecliptic centered on the opposition point is surveyed during each lunation, reaching V=21-22 mag depending on conditions.

1.8-meter Telescope: This was built by and for Spacewatch, largely at the expense of AFOSR. The field of view is 0.6x0.6 degrees and the image scale is 1.0 arcsec/pixel on a 2048x2048 CCD. This is the largest telescope known to us that is dedicated exclusively to surveying and astrometry of asteroids and comets. Routine operation of the telescope by solo observers began on 2001 October 16 and improvements to the efficiency of its operation have continued steadily. On 2003 June 18 the 1.8-m primary mirror was realuminized for the first time in 4 years. In early July 2003 the cooling system of the CCD was boosted with greater heat pumping capacity to deal with the hot summers here. In 2004 June, new quieter electronics to read the CCD were installed along with some upgrades to suppress electronic noise from our other equipment, yielding a 0.4 mag improvement in limiting magnitude. Improvements to the hardware & software of the telescope drive systems made during this grant interval enhanced pointing and tracking.

The exposure time for each pass with the 1.8-m telescope is 136^s/cos(declination). A typical scan with the 1.8-meter to follow up an EA covers from 0.3 to1.0 deg^2. The 1.8-m has reached V=23.3. This telescope is dedicated to followup of faint EAs, with emphasis on PHAs and objects on the MPC=s NEO Confirmation Page and the JPL and NEODyS impact risk pages. The 1.8-m is also committed to doing lightcurves of Trans-Neptunian Objects (TNOs) in support of a grant from the NASA Planetary Astronomy Program to Scotti.

Computers: We are nicely equipped with a multitude of PCs on Kitt Peak and at LPL being used as scientific workstations running Xwindows under Linux. At the telescopes, PCs with various operating systems are used for realtime control of telescopes and CCDs. PCs we use for critical applications are frequently upgraded and replaced as technology improves.

Image Data Archive: The Spacewatch archive of observed regions and objects, so essential for our precovery work, now has a streamlined, public interface for displaying the Spacewatch pointing history. Without the expense of placing the imagery online, this is a way for interested parties to find out what data are available. This archive has yielded arc extensions for more than a dozen virtual impactors, 2004 MN4 being the most important example. Images have also been provided for other objects of interest. About 1 Terabyte (TB) of data from the old (1990 Apr 30 - 2002 Apr 22) configuration of the 0.9-meter telescope covers a sky area of 30,000 deg^2 including repetitions. Imagery to date from the Spacewatch 1.8-meter telescope amount to approximately 1.5 TB. Data from the mosaic of CCDs have been accumulated since 2003 Mar 23 and now consist of 4 TB. About 28,000 deg^2 were covered by three passes with the mosaic.

Spacewatch Laboratory Equipment: We maintain an extensive collection of state-of-the-art electronic design, fabrication, and test equipment, computer spare parts, electronic components, machine tools, mechanical parts, stock aluminum, and hand tools to support our observing operations and instrument maintenance.

Steward Observatory Facilities: In addition to the 0.9-m telescope, Steward Observatory provides electricity, plumbing, and custodial services on Kitt Peak as well as internet connectivity and the use of the dormitory rooms for our observers. We have to pay for our use of the internet.

Lunar and Planetary Lab (LPL) Facilities: Our research is conducted in the Kuiper Space Sciences Building, which provides ample office and laboratory space for our work and ethernet connectivity to all offices. LPL also supports mechanical design and fabrication, charged to projects by the hour. The quality of work done for this project has always been excellent. A small but carefully stocked library supports research with reference books, a journal archive, and current subscriptions to relevant journals. The LPL computing facilities feature servers with high-bandwidth Internet connectivity, numerous workstations and remote-mountable peripherals for general use, and software such as C, C++, Fortran, perl, tcl/tk, Pgplot, IDL, IRAF, LaTeX, etc.

University Facilities: The University Research Instrumentation Center (URIC) includes an electronics shop, a machine tool and welding shop, a cryogenic liquids facility, a printed circuit laboratory, extensive metal stock, equipment for rent, and a "Rent-a-Tech" program for temporary skilled labor. The URIC built most of the 1.8-meter Spacewatch telescope. The University Center for Computing and Information Technology provides high-bandwidth Internet connectivity to the outside world, including the Spacewatch Telescope data processing systems on Kitt Peak. The University Science and Engineering Library has a large collection of books and journals, indexes of which can be accessed via the Internet.

Kitt Peak National Observatory (KPNO) Facilities: KPNO sells high speed internet access, liquid nitrogen, and meals to us. They also provide maintenance of the grounds, snow plowing, backup electrical power, a cafeteria, and emergency medical and fire services in return for a AJoint Use Fee@ paid by all tenants such as the University of Arizona.

ACTIVITY REPORT

Discoveries: Between 1 Dec 2002 and 30 Nov 2005 inclusive, Spacewatch discovered 200 EAs. That total includes 13 Potentially Hazardous Asteroids (PHAs) with absolute magnitude H#22 and 41 objects that appear or have appeared in the past on the NASA JPL impact risk web site (http://neo.jpl.nasa.gov/risk/). A recent notable example is 140-meter-diameter Apollo asteroid 2005 NX55, discovered by Spacewatch on 2005 July 11 and which is listed by NASA/JPL with 85 possible encounters with Earth between the years 2011 and 2102. The Italian NEODyS website at http://newton.dm.unipi.it/cgi-bin/neodys/neoibo?riskpage:0;main actually lists 2008 as the next possible close approach of this asteroid. Spacewatch also discovered 12 comets and 8 other objects in the outer solar system during the report period.

Followup Observations:

Followup of EAs helps to consolidate their orbits as their brightness fades after discovery. Faint followup is also frequently required for recoveries of EAs on subsequent apparitions. We elaborate on recoveries in a later section. Some followup observations by Spacewatch are deliberately targeted and some occur incidentally during surveying. Figure 1 illustrates how Spacewatch=s rate of detection of priority EAs improved after the introduction of the 1.8-meter telescope and the replacement of the optics and detector at the 0.9-m telescope.

Between 1 Dec 2002 and 30 Nov 2005, Spacewatch observed and reported 6,620 positions of 1,352 EAs (including 1,774 observations of 415 PHAs with H<=22) and 696 positions of comets.

Figure 2 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 3 compares our contributions relative to the rest of the faint followup community.

Objects that appear on JPL=s impact risk website are also priorities for Spacewatch followup. Between 1 Dec 2002 and 30 Nov 2005, Spacewatch follow-up observations contributed to the removal of 71 objects from that list. No Spacewatch discovery with H#22 has ever been lost while appearing on that list. In March of 2005, Don Yeomans, Director of the JPL NEO Office, privately asked Spacewatch to follow up an object that had an impact solution for 2005 September 23 with a probability of $2x10^{-6}$. 2005 EM30 with H=18.5 was discovered on 2005 March 7 by LINEAR. Its apparition was closing, hence the urgent request for followup before such an early impact date had to be publicized, with all the attendant implications. Spacewatch contributed to the followup campaign, which resulted in the impact probability first decreasing by 3 orders of magnitude and then the object being removed from the risk page.

Recovery Observations:

PHAs with uncertain ephemerides are the main focus of targeted Spacewatch recovery work. 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. To streamline the effort, Spacewatch developed a suite of organizational software tools and an observing regimen to assure recovery of a needed PHA even if the window of opportunity is very short.

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

Object	Unc.(deg)	H	V	DOU/MPEC	Arc before search	Arc After	Net O-C
2002 TW55	1	18.0	21.7	MPEC 2005-E54	52d	831d	237"
1990 SM	80	16.2	21.2	DOU 2005-C26	24d	5225d	23022"
1999 VT25	3	21.4	21.5	DOU 2004-U47	26d	1786d	7556"
2000 EV70*	3	20.5	20.9	MPEC 2004-E11	46d	1193d	214"
2001 US16	2	20.2	20.7	MPEC 2004-B68	31d	802d	485"
1998 VS**	4	22.3	21.3	MPEC 2003-Y18	32d	1831d	1581"
2000 UL11	2	20.1	21.9	MPEC 2003-S71	28d	1039d	3320"

*Trailed, so deliberately done through FMO Project.
**Lost PHA status due to our recovery; H now > 22.

Of particular note is the Spacewatch recovery of 1990 SM, a very lost H = 16.2 PHA that had not been seen since the discovery apparition, 15 years before. The object had windows of opportunity viewable to recovery telescopes nearly every year since discovery, and had more than half a dozen windows reaching brighter than 18 V, viewable by the large surveys, but the windows were very short and occurred when the object was near the galactic plane, so the large surveys had not rediscovered 1990 SM accidentally. Encouraged by earlier Spacewatch successes with less uncertain PHAs (under 5 degrees), Spacewatch developed a plan to recover 1990 SM despite its 80 degree 3-sigma uncertainty. To handle the large uncertainty, Spacewatch developed software to analyze how the magnitude and rate change along lines of variation in order to target areas of an uncertainty ellipse where an object is visible to Spacewatch telescopes. For 1990 SM this meant searching half of the ellipse during one lunation (while the other half was too faint) and the second half during the next lunation. After Spacewatch's initial rediscovery was submitted to the MPC, the MPC immediately posted 1990 SM on the NEO Confirmation Page with an updated ephemeris, allowing another telescope to target it the next day.

Because of our focus on uncertain PHAs rather than just any PHA for which the MPC wants measurements, Spacewatch tends to view a PHA only once or twice, in contrast to other stations that might recover the same object many nights in succession. Therefore we based our plots on

counts of distinct PHAs rather than individual measurements. In addition, there has been some discussion as to the reliability of magnitudes in the asteroid survey community. To minimize the effect of observational errors on scoring our performance, we use ephemeris magnitudes for object classifications in all the tables and figures in this proposal.
All of the objects listed in Table 1 were deliberate recoveries. Many asteroids have short, faint viewing windows making them unsuitable for incidental survey recovery and most of the PHAs in Table 1 fall into this category. We targeted many uncertain PHAs, but in most cases, uncertain objects are not found that far from the expected position. This is evidenced by the fact that, despite Spacewatch's targeting of uncertain PHAs and dominance in recovering V > 21 PHAs (q.v., Figs. 2 & 3), only six faint (V > 21) PHAs have been found more than 1500" from their nominal positions, four of which were found by Spacewatch.

Image Data Archive: The Spacewatch archive of observed regions and objects, so essential for our precovery work, now has a streamlined, public interface for displaying the Spacewatch pointing history. Without the expense of placing the imagery online, this is a way for interested parties to find out what data are available. This archive has yielded arc extensions for more than a dozen virtual impactors, 2004 MN4 being the most important example. Images have also been provided for other objects of interest. About 1 Terabyte (TB) of data from the old (1990 Apr 30 - 2002 Apr 22) configuration of the 0.9-meter telescope covers a sky area of 30,000 deg^2 including repetitions. Imagery to date from the Spacewatch 1.8-meter telescope amount to approximately 1.5 TB. Data from the mosaic of CCDs have been accumulated since 2003 Mar 23 and now consist of 4 TB. About 28,000 deg^2 were covered by three passes with the mosaic.

Precoveries, 31 July 2004 - 2 August 2005: Spacewatch has contributed prediscovery observations of high priority EAs such as 2004 MN4, 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 prediscovery observations in the Spacewatch image archives. We increased 2004 MN4's arc of observations from 190 days to 255 days, enough to reduce the estimate of probability of impact to a much less alarming value. 2004 MN4 now has the permanent designation and name of (99942) Apophis. Other precoveries within the last 3 years total 121 EAs and 3 comets. Twenty-one of the EAs were precovered deliberately by inspecting our image archive and the rest were precovered by the MPC=s use of their archive of Spacewatch=s incidental astrometry.

Incidental Astrometry (IA):

Between 1 Dec 2002 and 30 Nov 2005, Spacewatch sent 1,584,347 astrometric detections of asteroids to the Cambridge, MA-based Minor Planet Center (MPC) of the International Astronomical Union (IAU). (One "detection" by Spacewatch usually equals three observations of
position.) Provisional designations for 58,857 asteroids resulting from those observations have been credited by the MPC to Spacewatch. Most of those are in the main belt, but a few examples of incidental precoveries of interesting objects 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, Mars crosser 2002 YK_{29}, Amor 2003 HB_6, comet P/2004 A1, Amor asteroids 2003 OB_4 and 2003 MT, and Apollo asteroid 2003 YO_1. The MPC also found that Apollo PHA 2003 YK_{118} was included among our reprocessed results from the year 1993, predating the discovery by more than a decade. 1994 UG was retired from JPL's impact risk page as a result of additional observations found by the MPC among this new astrometry. During this report period, a total of 39 EA s, 6 comets, and 3 outer solar system objects were found by the MPC in our IA. An additional 83 EA s were in the IA we submitted after reprocessing old (1990-1999) Spacewatch imagery with our new, more sensitive software.

Figures 4(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 slowly-moving distant EAs to reveal their presence; the overprinting of region symbols in Fig. 4(c) illustrates the effect. Spacewatch has sent more than a million astrometric detections of asteroids to the MPC as a result of surveying. Spacewatch IA on file at the MPC will remain a permanent asset to the asteroid science community.

Orbital Linkage Software, 31 July 2004 - 2 August 2005:

We worked toward taking better advantage of Spacewatch's deep limiting magnitude to find new, large EAs while they are far from Earth, near their aphelia. These EAs include those whose orbits will prevent their discovery by brighter-limited surveys between now and the deadline of 2008. A prototypical orbit of this type would be that of minor planet (719) Albert, whose eccentricity and sidereal/synodic periods make it detectable by brighter-limited surveys only once every 30 years.

Spacewatch, like the upcoming deep surveys, has the limiting magnitude to detect large and distant EAs, but the distance means their sky plane rates "hide them in plain sight" amongst the main belt. We have detected many large distant EAs which were not recognized until the MPC later linked them after a close approach (for example: 2003 MU, 2003 HB6, 2004 AE9, 2004 HM1=1995 SP4, and 2004 JW6). The current shallow surveys depend critically on close approaches: by the time an EA brightens sufficiently, it is also moving with an easily recognizable rate. Because of the rate-brightness relation, Spacewatch and the new surveys like Pan-STARRS and LSST will not discover many additional large EAs without a linking analysis. Any experience gained by Spacewatch will apply to the next generation of surveys. (See below for a description of our plan to assist the Air-Force-funded Pan-STARRS group in Hawaii.)

The MPC does not routinely check the incidental astrometry (IA) of the big surveys for such linkages promptly enough for targeted followup. Spacewatch has developed an effective brute force exploratory linking technique working on three or more visits during a single lunation. The astrometric data, subject only to a comparison of net motion with that of the main belt, are exhaustively tested in all combinations which search for consistent circular, Väisälä, or Gaussian orbits with non-systematic residuals. A postprocessing step combines multiple realizations of the same orbit from the repeated visits.

Larsen refined this code over the past year and in May 2005 deployed it on a brand new 64 node Scyld Beowulf cluster at the US Naval Academy where it is now available to run in real time on incoming data. The code was also retroactively applied to the 2004 September - 2005 May observing season in which we tried to revisit the same "cohorts" of distant asteroids three times per lunation by walking the observed centers along at the average rate of main belt asteroids between visits. Initial results are promising, with 8500 linkages of main belt objects plus numerous candidates for EAs. We estimate we will have three times the opportunities to recognize EAs than we had prior to linking. The opportunity may be higher than this because the distant EAs are closer to the ecliptic plane, requiring less sky coverage to observe per EA.

Assuming our current survey method, a pessimistic limiting magnitude, no improvement in survey speed, typical weather, and a synthetic population of plausibly undiscovered EAs, we predict that linking could yield an additional 7∀2 EAs with H < 20 and 3∀2 EAs with H#18 per year. These
discoveries would be in addition to our current rate of detections and discoveries of EAs.

Data Archiving and Reprocessing:

With support from a grant from NASA/AISRP to Larsen, all 1.5 terabytes of data previously stored on magnetic tape between 1990 and 1999 were copied to DVD-RAM media. This stabilized the data and simplified reprocessing. The data covered 75,000 square degrees to a limiting V magnitude of ~21.5. All of those data were reprocessed with Larsen=s newest generation of asteroid detection software to yield 190,830 detections of moving objects that were undetected by the pre-Larsen software, making a total of 423,220 detections of asteroids by Spacewatch from 1990 to 1999 inclusive. (One Adetection@ usually equals three positions.) Thus the reprocessing yielded a 82% percent improvement on Spacewatch=s effort over almost 9 years, equivalent to 7 additional years of Spacewatch operations at the level of performance at that time.

The newly derived positions were submitted to the MPC. One immediate result was that the virtual impactor 1994 UG was retired from the JPL impact risk page. The MPC has linked 55,852 of our new archival detections with known asteroids and will continue to try to identify our detections and use them to extend the arcs of asteroids. Among the positions derived from the reprocessing, we reported 597 previously undetected asteroids with high probabilities of being EAs. The MPC has so far linked 237 of those objects with known asteroids and 66 of them have been identified with known EAs. Out of those 66 EAs, 21 are PHAs. The remaining 360 EA candidates in our reprocessing output that are as yet unlinked with known objects cannot be recovered at the telescope solely on the basis of such old data. However, our data will provide immediate information (precoveries) to the arcs of new discoveries that are identified with our earlier observations.

Statistics of Earth Approachers:

We promised that Athe statistical properties of [EA detections] will be presented as constraints on the numbers of EAs with H#22, their distribution with absolute magnitude, the number of PHAs, and on the evolution of EA orbits@. A study has been made by our collaborator and former Spacewatch staff member Jeffrey A. Larsen, now an Assistant Professor in the Department of Physics of the U. S. Naval Academy in Annapolis, MD. Larsen has used knowledge of Spacewatch sky area coverage and EA detections to extrapolate to the total number of EAs with H#22 detectable by Spacewatch all over the sky. At any instant of time, there should be approximately 360∀40 EAs with H#22 within reach of Spacewatch. This corresponds to about 1 object per 115 square degrees, or an average angular separation of 11 degrees between objects. To detect the thousands of such objects, observations would have to be continued for decades because only a small fraction of the NEOs are within reach at any given time. However, it is possible to estimate the size of the population by using knowledge of their orbital distribution. Figure 5, following a similar plot by Harris and Bowell (2005), compares the distribution of EAs versus absolute magnitude determined by Larsen from Spacewatch data with previous studies. The agreement with all but one study is good. Larsen also found that the work by Rabinowitz (1993) contained a conceptual error that explains its departure from the other studies.

Other Research:

Asteroid Detection: Gural, Larsen and Gleason (2005) developed a matched filter processing algorithm that shifts and stacks images at the rate of motion of an asteroid being sought. While execution time and false candidates make the software impractical to use in survey mode, the algorithm works better than our survey software when presented with only a small number of hypothesized motions, as for a recovery. In that case, the observer is presented with review candidates which match only the specified target motion.

NEO Families: Scotti collaborated with Fu, Jedicke, Durda and Fevig on a study of the identification of Near Earth object families using the D-criterion (Fu et al., 2005). Drummond (1991, 2000) concluded that at least one Near-Earth Object (NEO) family existed using the D-criterion to analyze the similarity of asteroid orbits. Fu et al. found that the Drummond families were unlikely to be anything more than random fluctuations in the distribution of NEO osculating orbital elements. This conclusion was a result of simulations of randomly generated synthetic populations that contained no genetically related NEOs as well as dynamical studies of the decoherence timescales of synthetic NEO families resulting from collisions between an NEO and a main belt asteroid. A new criterion was found that can be used to select real NEO families in future analyses of the NEO population as the number of discovered NEOs continues to rise.

Automation of a Spacewatch Telescope:

In 2002, NASA provided funds to automate one of the two Spacewatch telescopes. In April and May 2005 the 0.9-meter telescope was operated for the first time with computer control of dome rotation. This large, old electromechanical system was the final and most difficult component to be put under automatic control. It is now possible to let the automatic scheduler run the telescope, CCD, and dome in survey mode all night after initial setup by the observer. However, the observer at that telescope still has to review all the images of candidates for asteroids, designate and mail interesting objects to the MPC, organize followup observations by the 1.8-meter telescope, and deal with weather and contingencies with the equipment. In November 2005 we installed an electromechanical hardware unit independent of the computer to prevent any software bugs or servo malfunctions from driving the dome superstructure into the telescope. With that safety system, it became possible for the 0.9-meter telescope to run unattended while the remaining duties of the observer at the 0.9-meter telescope are taken by the observer at the 1.8-meter. This mode of operation was first used in December 2005. As obseervers become trained in this new mode, observer duty will reduce to one person at a time. However, managing the data from two telescopes may require assistance from a second person reviewing images in Tucson in the daytime after each night of observing.

COLLABORATIONS

Asteroid Astrometry in Mongolia: Mongolian observers (q.v. our earlier reports) are doing astrometry of asteroids with equipment purchased with funds from AFOSR. Their limiting V magnitude is about 18, typical for that detector and aperture of telescope. Their photometric accuracy is also reasonable for that equipment. The effect of low ambient temperatures in the winter on the declination bearings of the telescope was still a problem during the winter of 2003-4. They visited Tucson in January 2004 with funds from a grant from AOARD/Tokyo, during which time we provided additional training and advice for them. We also provided them with a new larger CCD imaging detector, a new computer, and other needed accessories. Later they suffered the loss of their electronics that controls the declination drive of their telescope during an electrical storm. They mailed the affected circuit board to us for repair and/or replacement. We will not charge them for that.

Asteroid Astrometry in Northwest Australia:

We collaborated with astronomer John A. Kennewell at the Learmonth Solar Observatory near Exmouth in Northwestern Australia, who plans to do followup astrometry of bright EAs and measure lightcurves of selected asteroids. The addition of this new astrometric station in the southern hemisphere will help refine the orbital parameters of asteroids that move south after discovery. This telescope will also survey the southern hemisphere sky for EAs and other asteroids. The site has a dry climate and clear skies for 80% of the year. The telescope will provide a monitor of EAs in the southern sky to better than magnitude 18. Rotational photometry at the Learmonth site will investigate spin rates and principal axes of EAs. These are physical characteristics that are vital for the applied mitigation phase of planetary defense.

A complete 14-inch (0.36-meter) telescope system, CCD imaging detector, and software, purchased with funds from a previous year of AFOSR funding, are in Dr. Kennewell=s observatory dome. Kennewell expects to operate at least five nights per lunation. Initially at least, 70% of the observations will be devoted to follow-up positional determination, 30% to searching regions of the sky not readily accessible to northern telescopes, with the possibility of a small amount of time devoted to light curve determinations (asteroid rotation analysis). Kennewell came to Tucson in January 2004 to help train the Mongolian astronomers with the new equipment we provided them.

Recently Dr. Kennewell responded favorably to my suggestion to observe the lightcurve of the bright EA 1992 UY4 that is currently well-placed for observing in the southern hemisphere. This object is of high priority because the Goldstone and Aricebo radar stations plan to observe it August 1-10. A lightcurve determined by ground-based telescopes can provide knowledge of the object=s rotation rate, which is important in both planning and interpreting the returning radar signals. In particular, the ground-based data help to estimate the three dimensional shape from delay-Doppler radar images.

Relationship of Spacewatch to the WISE spacecraft mission:

E. L. Wright of the UCLA Astronomy Dept. is the PI of the Wide-field Infrared Survey Explorer (WISE) MIDEX spacecraft mission. WISE will map the whole sky at thermal infrared wavelengths with 500 times more sensitivity than the IRAS mission 20 years ago and will detect a few hundred EAs with diameters > 600 m, as well as tens of thousands of asteroids in the main belt. The WISE team selected Spacewatch in 2001 as their ground-based collaborator because the EAs that WISE expects to discover will run as faint as V~21. Because WISE will observe along a great circle 90E from the Sun, some of the EAs it detects may be ones that would have eluded ground-based surveys. This elongation also happens to be where Earth impactors tend to dwell the longest (Chesley and Spahr 2004). Spacewatch would do ground-based astrometric and photometric recovery and followup of EAs detected by WISE. Spacewatch has demonstrated the capabilities to both survey as well as followup at small elongations.

WISE=s detections in the thermal infrared will also provide a size-limited sample of asteroids instead of the brightness-limited surveys being done at visible wavelengths. This advantage results from the dependence of infrared flux on (1- albedo) instead of the visual magnitude=s dependence on albedo. The range of albedo values for EAs is 0.05 - 0.5 (Morbidelli et al. 2002), a factor of 10, while the corresponding range for (1-albedo) is Aonly@ a factor of 2. Therefore diameters derived from IR flux are more certain than those estimated from visual absolute magnitude in the absence of albedo information. WISE will provide the first qualitatively new determination of the size distribution since the analyses of detections by ground-based surveys were published some years ago. Knowing the size distribution of EAs is essential to establish when the Spaceguard goal of finding 90% of all EAs larger than 1 km has been achieved. Specifically, it will reveal how much the optically-determined size distribution we've been using for asteroids has been biased against low albedo objects. This is relevant to the conversion between absolute mag H and diameter D and thus the corresponding estimate of the number of

EAs with H#18 vs. the number of EAs with D∃1 km. Spacewatch has extensive experience with the analysis and publication of such studies.

In August 2004, WISE was authorized to proceed into Phase B, with a Preliminary Design Review (PDR) in June 2005. Launch is currently scheduled for June 2009. In a possible Phase F of an enhanced and extended WISE mission, data from WISE would be processed more rapidly to allow detection of moving objects in time for followup. McMillan continues to advise the WISE team on asteroid detection, especially to propose Phase F to NASA.
A possible Education/Public Outreach (E/PO) activity related to the WISE mission would be for students to do visual reviews of images of candidates for moving objects detected by WISE, using the methods & experience of the Spacewatch FMO Project that is staffed by on-line volunteers (McMillan, Block, & Descour 2005).

Assistance to Pan-STARRS: The next few years will see the beginning of the operation of the Air-Force-funded Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) of the University of Hawaii's Institute for Astronomy. The PI of Pan-STARRS is Nick Kaiser, and former Spacewatch team member Robert Jedicke is now the Manager of the moving object processing system of Pan-STARRS. The Pan-STARRS group will begin discovering asteroids in 2006 with their first prototype telescope, PS1. PS1 will detect asteroids down to about R~23, and should find an order of magnitude more PHAs per lunation than all other current surveys combined (Jedicke 2005, personal communication). (The final Pan-STARRS configuration is expected to find asteroids yet another order of magnitude faster than the prototype.)
Pan-STARRS' revisits of areas surveyed during a lunation will allow the Pan-STARRS group to determine preliminary orbits of asteroids spanning 4-8 days. However, additional followup observations with other telescopes would help Pan-STARRS make linkages in their archives. The Spacewatch 1.8-meter telescope can reach V=23.3, the faintest limit available from a dedicated asteroid followup telescope. Spacewatch personnel are also eligible to apply for time on larger telescopes of the University of Arizona. Spacewatch has also agreed to collaborate with Pan-STARRS by providing Pan-STARRS with samples of Incidental Astrometry (IA) and the corresponding pointing history on which they could test their new software. The samples would have to be from several lunations and include revisits of regions, as Spacewatch has been doing since 2004 September. A copy of the agreement between Pan-STARRS and Spacewatch is provided here:

>From kaiser@ifa.hawaii.edu Mon May 30 13:07:24 2005
To: bob@lpl.arizona.edu
Cc: Nick Kaiser <kaiser@ifa.hawaii.edu>, jedicke@ifa.hawaii.edu
Subject: Pan-STARRS/Spacewatch cooperation?

Dear Bob,

This is a follow-up to discussions I understand you have had with our moving objects specialist Rob Jedicke. As you know, the Pan-STARRS Moving Object Processing

System (MOPS) is being designed and tested to operate at asteroid detection rates almost 100X higher than existing surveys. First light on the prototype system, PS-1, on Haleakala is expected to be early in 2006 with actual asteroid observations available late in that year. We believe that Spacewatch and Pan-STARRS can operate synergistically in the next few years in two ways.

First, the MOPS team is working diligently on testing their pipeline using synthetically generated data, but want to ensure that the system is capable of handling data from other surveys and operating on realistic data with all their idiosyncracies. The wide-area and depth of Spacewatch coverage with your mosaic camera makes it the best system in the world for testing the MOPS. We would like to arrange access to your astrometry for that purpose. If possible, we would like access to all the astrometry for any possible detections identified by your system rather than only the incidental astrometry reported to the MPC. The MOPS must operate under the presence of false detections.

Secondly, your 1.8m system is the only dedicated asteroid surveying system that can consistently and regularly reach the R=23 limit expected for PS-1. While PS-1 should obtain three nights of observation for many asteroids in any lunation, there will be many more occasions when only two nights of observations are available, or when a PHO of considerable interest requires follow-up observations that are difficult to obtain with PS-1. PS-1 is designed as a survey system, not for follow-up. Thus, we see that cooperation between Pan-STARRS and Spacewatch could provide your team multiple targets each month for follow-up that will extend the observational arc of Pan-STARRS detections and allow more precise orbit determination and impact calculations.

Please let me know whether Spacewatch is interested in either of these forms of collaboration with Pan-STARRS.

Sincerely,

Dr. Nick Kaiser, PI
cell: 808-520-3680
Pan-STARRS
Institute for Astronomy
2680 Woodlawn Dr.
Honolulu, HI, 96822

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FIGURE CAPTIONS

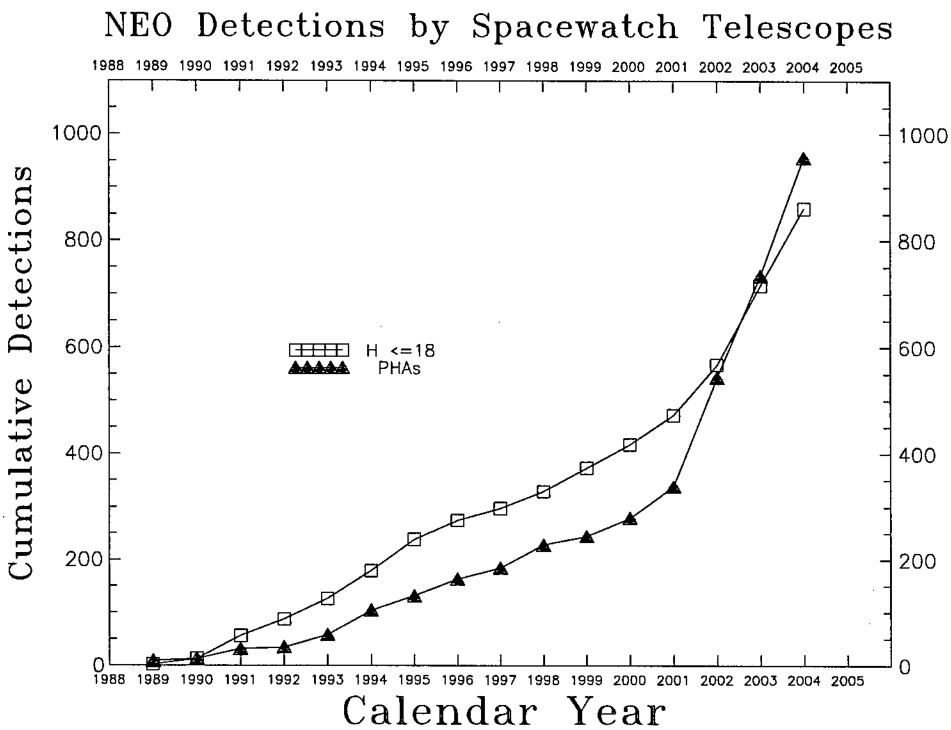
Figure 1. Cumulative count of Spacewatch detections of H#22 PHAs (triangles) and H#18 EAs (squares) vs. time. A Spacewatch Adetection@ consists of three positions, and only one detection per object per night is counted on this plot.

Figure 2. Numbers of distinct PHAs with H#18 observed while faint in the last 3 years, by station.

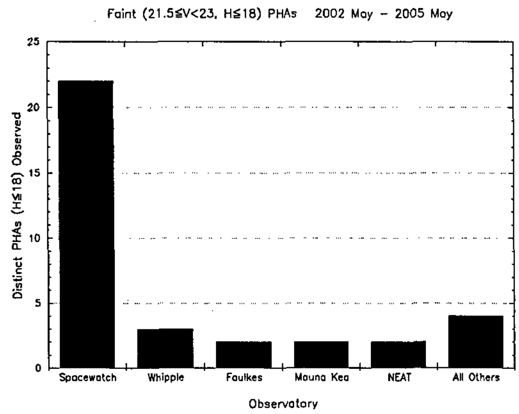
Figure 3. Numbers of distinct PHAs with H#22 observed while faint in the last 3 years, by station.

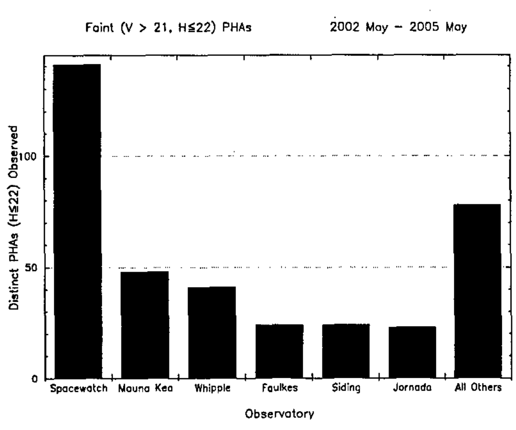
Figure 4(a), (b), (c). Regions observed with the Spacewatch mosaic of CCDs, 2003 Mar. - 2005 May. The ecliptic and Milky Way are also shown.

Figure 5. Cumulative distribution of NEOs vs. absolute magnitude corrected for observational bias and selection effects. The results of the survey with the Spacewatch mosaic are compared with previous work, according to the symbols. The approximate impact intervals and diameters are shown on the right hand and top scales, respectively.

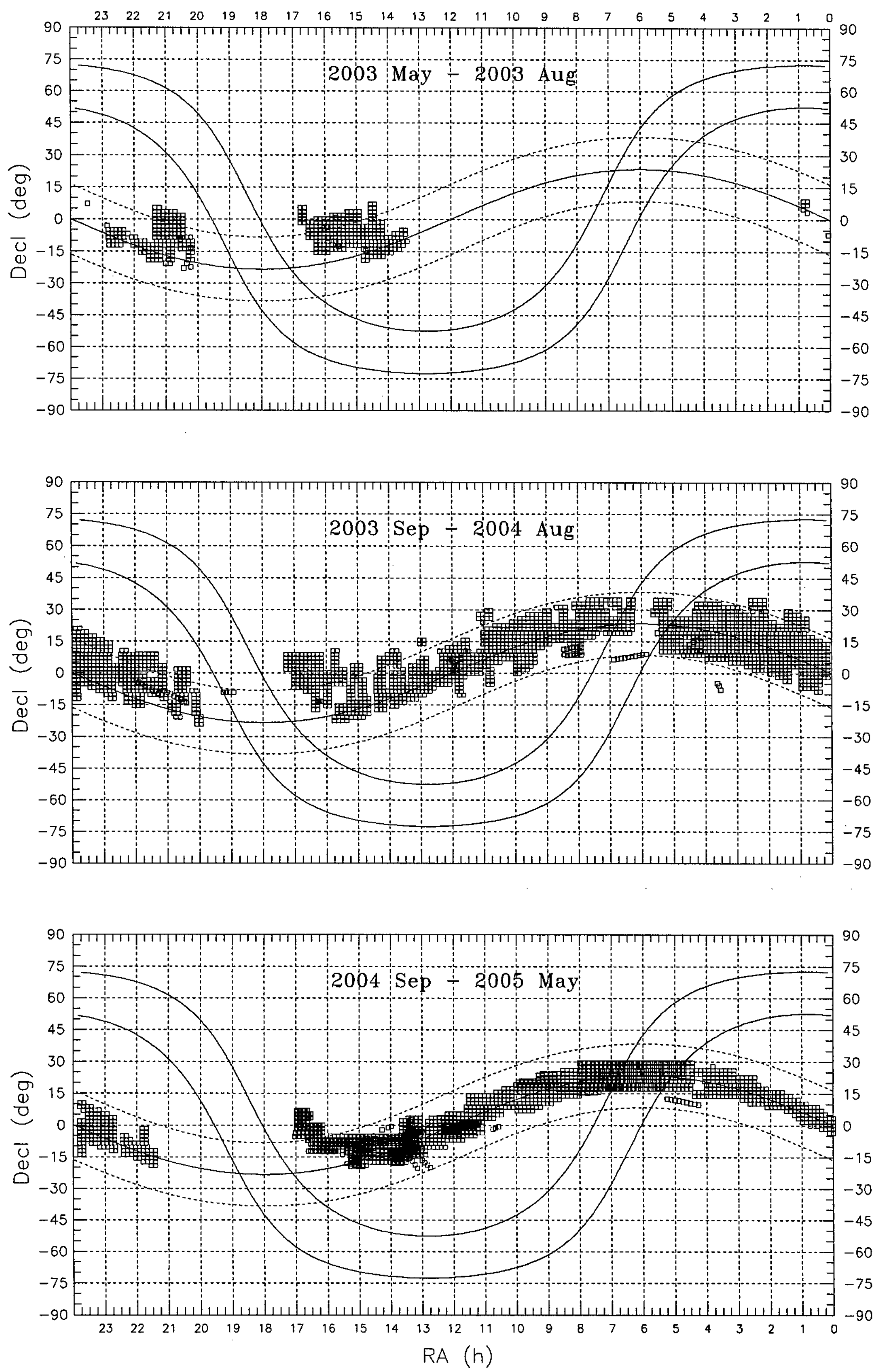


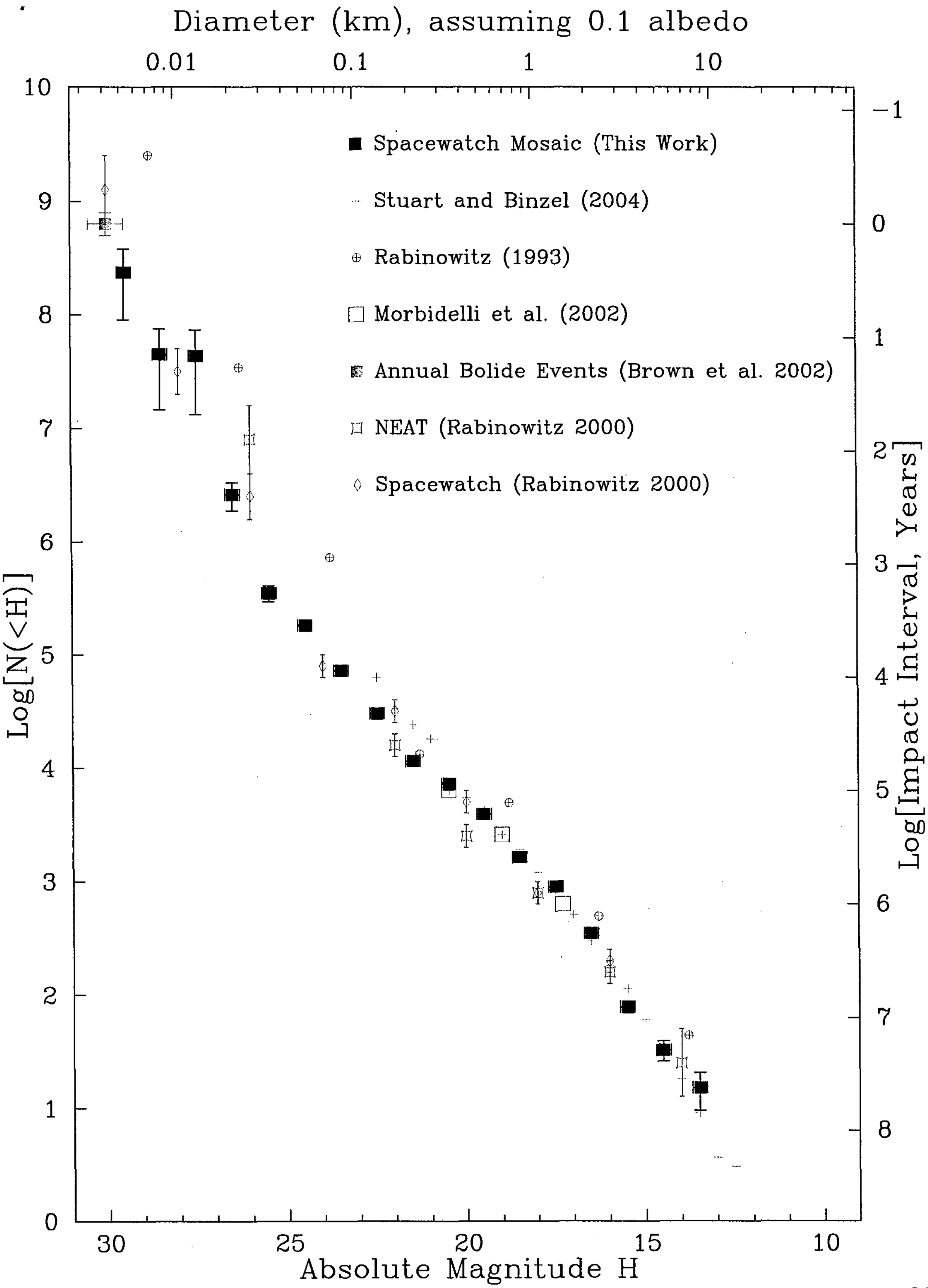
NEO Detections by Spacewatch Telescopes
Cumulative Detections
Calendar Year
H <=18
PHAs
0
200
400
600
800
1000
1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005


Faint (21.5≤V<23, H≤18) PHAs 2002 May – 2005 May
Distinct PHAs (H≤18) Observed
25
20
15
10
5
0
Spacewatch
Whipple
Faulkes
Mauna Kea
NEAT
All Others
Observatory



Faint (V > 21, H≤22) PHAs
2002 May – 2005 May
Distinct PHAs (H≤22) Observed
0
50
100
Spacewatch
Mauna Kea
Whipple
Faulkes
Siding
Jornada
All Others
Observatory


2003 May – 2003 Aug
2003 Sep – 2004 Aug
2004 Sep – 2005 May
Decl (deg)
RA (h)



Diameter (km), assuming 0.1 albedo
0.01
0.1
1
10
Spacewatch Mosaic (This Work)
Stuart and Binzel (2004)
Rabinowitz (1993)
Morbidelli et al. (2002)
Annual Bolide Events (Brown et al. 2002)
NEAT (Rabinowitz 2000)
Spacewatch (Rabinowitz 2000)
Log[N(<H)]
Log[Impact Interval, Years]
Absolute Magnitude H
30
25
20
15
10

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