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/S1743921307003390

Current NEO surveys

Stephen Larson

Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA
email: slarson@lpl.arizona.edu

Abstract. The state and discovery rate of current NEO surveys reflect incremental improvements in a number of areas, such as detector size and sensitivity, computing capacity, detection software efficiency and availability of larger telescope apertures. The result has been an increase in the NEO discovery rate. There are currently eight telescopes ranging in size from 0.5-1.5 meters carrying out full- or part-time systematic surveying in both hemispheres. The sky is covered 1-2 times per lunation to V$\tilde{1}$9, with a band near the ecliptic to V$\tilde{2}$0.5. We review the current survey programs and their contributions towards the Spaceguard goal of discovering at least 90% of the NEOs larger than 1 km.

Keywords. Surveys; telescopes; discoveries

1. Establishment and Evolution of NEO Surveys

The identification of the Chicxulub impact crater as the source of the iridium anomaly at the Cretaceous-Tertiary boundary (e.g., Hildebrand *et al.* 1991) provided strong evidence of the ongoing process of impacts as an important agent of evolution of life on Earth. This, coupled with the emergence of appropriate technology to detect moving asteroids, triggered a directive from NASA to quantify the impact threat of objects large enough to create global consequences. The result was a congressional mandate to discover and catalog to the 90% confidence level near-Earth objects one kilometer in diameter and larger by the end of 2008-the Spaceguard Survey.

The original Spaceguard Survey study recommended the construction of six 2.5-m telescopes in a coordinated international network in both northern and southern hemispheres (Morrison 1992) at an estimated cost of US $50M to build and US $10M per year to operate. A second NASA workshop report (Shoemaker 1995) studied in greater detail existing telescopes and more NASA/USAF cooperation, and effectively defined the budget level of the NASA Near Earth Objects Observation Program (US $4 Myr). The available funds dictated the use of existing, little-used telescopes outfitted with modern CCDs and modern computer control, which has resulted in various evolutionary paths and timescales among the surveys.

The characteristics of the current NASA-supported NEO surveys are a result of a range of entrepreneurial approaches and technology development to carry out the mandate. With attention turned towards the next phase of deep, extensive surveys for smaller NEOs that can cause regional damage, changes to the current surveys have slowed, and the characteristics of the current Spaceguard Survey capabilities may represent a stable end state for the existing surveys.

2. Current Survey Characteristics

We briefly summarize the current characteristics of the surveys in order in which they originally came on line with details listed in Table 1. They can be compared with

Tables 1 and 2 in the chapter in Asteroids III by Stokes *et al.* (2002). The URL for the various surveys are included for more information.

2.1. *Spacewatch*

The first CCD small-bodies survey was begun by the University of Arizona's Lunar and Planetary Laboratory Spacewatch group using the Steward Observatory 0.9-m reflector on Kitt Peak. It was originally used in 1984 in a drift-scan mode using a single CCD, but was upgraded in 2002 with a mosaic camera and new telescope optics to provide a larger field. A 1.8-m telescope was completed in 2001, which is used mostly for follow-up of fainter NEOs (Spacewatch.lpl.arizona.edu).

2.2. *NEAT*

The Near Earth Asteroid Tracking project of the Jet Propulsion Laboratory utilizes the Oschin 1.2-m Schmidt telescope with its wide-field Quest camera on Palomar Mountain for the first half of each lunation. The NEAT survey originally used 1.0-m GEODSS and 1.2-m MOTIF telescopes on the Air Force Maui Optical Station. It developed autonomous data acquisition, reduction, and detection software that allowed remote operation and vetting of NEO candidates from JPL. The survey also developed the SkyMorph online archive, which facilitates searches for pre-discovery images of new NEOs (neat.jpl.nasa.gov; skys.gsfc.nasa.gov/; skymorph/skymorph.html).

2.3. *LONEOS*

The Lowell Observatory Near Earth Object Survey uses a 0.6-m wide-field Schmidt telescope at the Anderson Mesa site for dedicated, full-time NEO searching. The mosaic camera gives a large 8.3 square degree field (asteroid.lowell.edu/asteroid/loneos/loneos1.html).

2.4. *LINEAR*

The Lincoln Lab's Near Earth Asteroid Research Program uses two identical 1.0-m GEODSS telescopes at the Experimental Test Site at the north end of the White Sands Missile Range near Socorro, New Mexico. It utilizes very fast, frame-transfer readout CCD arrays to cover large swaths of sky each night. LINEAR became the dominant NEO survey in 1998, and is responsible for the vast majority of NEO discoveries. It utilizes five visits per field, and is the only survey that regularly searches in the galactic plane and high north ecliptic latitudes (www.ll.mit.edu/LINEAR/).

2.5. *Catalina Sky survey*

The University of Arizona's Lunar and Planetary Laboratory Catalina Sky Survey (CSS) uses a wide-field 0.7-m Schmidt and 1.5-m reflector in the Santa Catalina Mountains north of Tucson, and the 0.5-m Uppsala Schmidt in Siding Spring Observatory in New South Wales, Australia. These three components provide complementary characteristics in terms of field, depth, and sky coverage, while sharing the same control and detection software. Since being upgraded with thinned, sensitive CCDs in late 2004, the CSS has led in the discovery of NEOs. The CSS relies heavily on the observer to make real-time decisions on where to survey, and to validate the reality of NEO candidates flagged by the software. Software tools help the observer make same-night follow-up of likely NEOs to check validity of the objects and extend the observed arc for subsequent follow-up (www.lpl.arizona.edu/css).

Program	Spacewatch	NEAT	LONEOS	LINEAR	Catalina	Siding Spr.	Mt.Lemmon
Observatory	Kitty Peak	Palomar	Lowell	Socorro	Catalina	Siding Spr.	Mt.Lemmon
Aperture	0.93 m	1.2 m	0.6 m	1.0 m	0.68 m	0.5 m	1.5 m
f ratio	3.0	2.5	1.9	2.2	1.8	3.4	2.0
FOV	2.9	7.0	8.3	2.0	8.2	4.2	1.2
No. CCD	4	112	2	1	1	1	1
CCD size K	2×4	2.4×0.6	2×4	2×2.6	4×4	4×4	4×4
V limit	21.7	22.0	18.9	19.0	19.5	19.0	21.5
No. visits	3	3	4	5	4	4	4
Exposure, s	120	60	45	8	30	30	20
Coverage rate	15	70	110	120×2	120	60	18
Recent results 1/2005–6/2006							
No. all NEOs	128	41	55	191	230	83	210
No. > 1 km	12	9	5	25	27	8	9
No. PHAs	16	9	10	29	35	25	13

Table 1. Characteristics and recent 18 month results of the current NEO search program telescopes.

3. Need for Follow-up

Because it typically requires 24-48 hours of observation to reasonably define an NEO orbit, rapid follow-up is an integral part of NEO discovery. The efforts of many amateur observers worldwide provide the bulk of follow-up positions, and are important in preventing NEOs from becoming lost. With sensitive, commercial-science-grade CCD cameras and sophisticated, computer-controlled, and sometimes robotic telescopes, amateur astronomers can do what professionals could not do 10 years ago. There are some amateurs who can regularly reach V=21 with modest apertures using stack-and-add techniques.

The MPC NEO Confirmation Page (cfa-www.harvard.edu/iau/NEO/ToConfirm.html) and the Minor Planet Mailing List are powerful communications tools for both amateur and professional observers. It is fair to say that without the drive and dedication of these many volunteer observers, the Spaceguard goal would be out of reach.

For the fainter objects, the JPL Table Mountain 0.6-m, Mt. John 0.64-m, Klet Observatory Klenot 1.1-m, Spacewatch 1.8-m, and Mt. Lemmon 1.5-m are used regularly for follow-up.

Extended follow-up on timescales of weeks and months is usually required for subsequent return recoveries, and may become critical in PHAs not becoming lost.

4. Results

4.1. *Discovery Rate*

As Figure 1 shows, the discovery rate varies with time with each survey according to its technical status. Taken as an ensemble, the plot of all NEOs shows an increasing trend in discovery rate throughout the Spaceguard period, while the $H < 18$ NEOs show the expected decrease as an increasing proportion of the population becomes known.

4.2. *Coverage*

The number and efficiency of the surveys means that the sky is being covered almost twice per clear lunation, with the ecliptic covered more often (Fig. 2). There is currently little coordination between the surveys with LINEAR systematically covering the observable sky in a pre-planned sequence (unless affected by weather), while Spacewatch

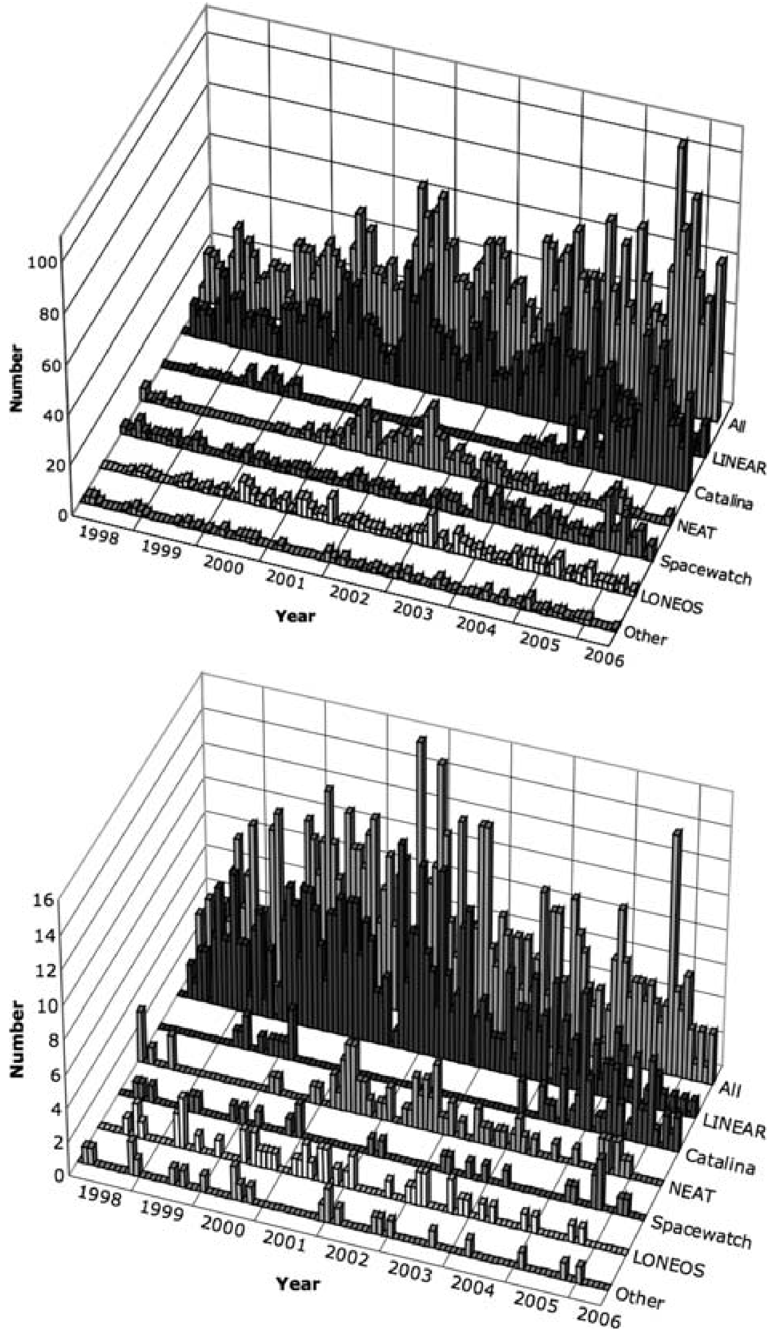

Figure 1. Monthly discoveries of all NEOs (upper) and $H < 18$ NEOs (lower) for the surveys.

concentrates in the opposition regions, and the Catalina Sky Survey make nightly decisions based on covering areas not recently observed. Movies of the nightly build-up of coverage for some example lunations can be found on the CSS web site.

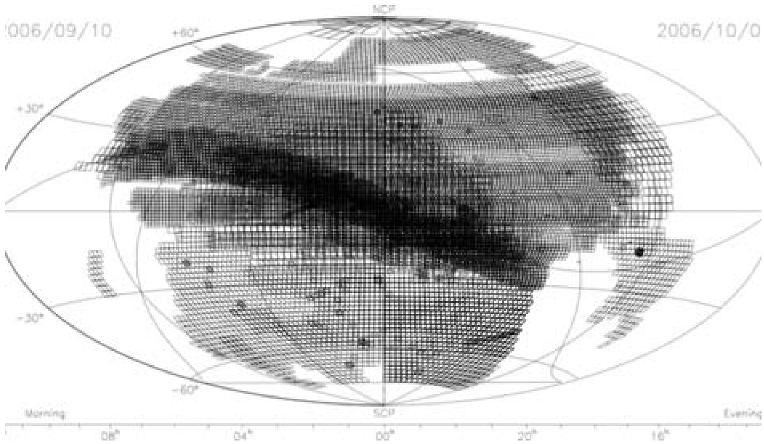

Figure 2. Sky coverage for all surveys during the 2006 September 10 to October 7 lunation.The ecliptic plane near opposition is covered multiple times, while the galactic plane is covered only by LINEAR. This plot is courtesy of the Minor Planet Center.

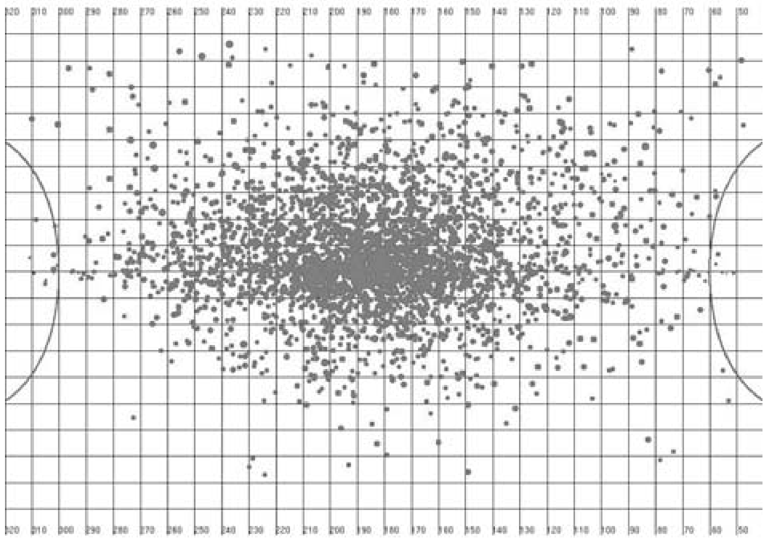

Figure 3. The discovery locations for all NEOs in ecliptic coordinates with respect to the Sun. Arcs at each edge are 60° from the Sun.

4.3. *Discovery Circumstances*

The discovery circumstances are dictated by a complicated convolution of coverage, limiting magnitude, and the intrinsic distribution of NEOs and their phase effects. Figure 3 shows the distribution of the discovery location of all NEOs in ecliptic longitude and latitude with respect to the Sun. The N-S asymmetry results from the greater coverage in the north, while the higher density near opposition is a combination of opposition effect and increased coverage. The expected increase near sun "sweet spots" is not apparent for the magnitude range or coverage represented here.

4.4. *Survey Efficiency*

Significant advances in computing power, detector sensitivity and effective array sizes have made the current survey telescopes as efficient as those recommended in the

Spaceguard Report. Although there may be incremental improvements in detection software in the remainder of the Spaceguard Survey, it is not likely that more aperture or larger detector arrays will come on line as most of the improvement in NEO surveying is being directed towards the next goal of finding and cataloging NEOs down to 140-m sizes.

Although it is generally accepted that the ideal survey telescope is fast (to minimize trailing losses during exposure), large field, and minimal cycle time, the current discovery results shown in Table 1 fail to show a clear correlation among the survey systems.

4.5. *Prospects for Attaining the Spaceguard Goal*

Studies are underway to estimate the population of $H < 18$ NEOs based upon current statistics and of the discovery/re-observation ratio. As of this writing, there are 845 such NEOs out of an estimated 1050+/−60 (Boattini *et al.* 2006). Given the relatively high efficiency the surveys have attained, it may still be possible to satisfy the Spaceguard goal in the two remaining years of the survey.

Acknowledgements

The author thanks the various surveys for their updates and input for this review. Alan Chamberlin (JPL) provided the monthly statistics in fig.1, and Gareth Williams (MPC) provided a new tool in the MPC NEO Coverage tool that allowed the generation of Fig. 2. Ed Beshore, Eric Christensen and Rik Hill provided help with the graphics. This work is carried out through the support of the NASA NEO Program.

References

Boattini, A, Abramo, G. D., Harris, A. W. & Valsecchi, G. B. 2006, *BAAS* 38, 581

Hildebrand, A. R., Penfield, G. T., Kring, D. A., Pilkington, M., Zanoguera, A. C., Jacobsen, S. B., & Boynton, W. V. 1991, *Geology* 19, 867–871

Morisson, D. 1992, *The Spaceguard Survey. Report of the International Near-Earth-Object Detection Workshop*, NASA Office of Space Science, Solar System Exploration Office.

Shoemaker, E. M. 2002, *Report of the Near-Earth Objects Survey Working Group. NASA Office of Space Science, Solar System Exploration Office.*

Stokes, G. H., Evans, J. B. & Larson, S. M. 2002, in: W. F. Bottke, A. Cellino, P. Paolicchi & R. P. Binzel (eds.), *Asteroids III* (University of Arizona Press, Tucson), p. 45