

Near-Earth Asteroid Search Programs

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The discovery of the potentially hazardous near-Earth asteroid (NEA) component of the minor-planet population has been enhanced by better detecting and computing technology. A government mandate to quantify the terrestrial impact hazard and to detect 90% of all NEAs larger than 1 km can be realistically addressed. The characteristics, capabilities, and strategies of the major search programs illustrate the challenges and solutions toward meeting the Spaceguard goal. This chapter reviews the historical context of early asteroid detection and of the current and anticipated search programs. It describes the search systems and discusses challenges in maximizing the NEA detection rate.

1. INTRODUCTION AND BACKGROUND

The past decade has witnessed an explosion in the number of cataloged asteroids. Of the more than 35,000 numbered asteroids discovered in the last 200 years, 62% of these were found in the past decade. Similarly, of the 1785 NEAs that are now known, 89% have been discovered in the past 10 years. During this time the total number of observations published by the Minor Planet Center (MPC) has grown from 792,439 in 1992 to 11,626,118 in 2002, and the total routinely grows by more than 300,000 per month. This dramatic increase in the observation and discovery rate has been enabled by the charge-coupled-device (CCD)-based search systems that have replaced their film-based predecessors. This chapter will give a brief historical perspective of asteroid searches and an overview of general search strategies and specific search systems in existence today. In addition, we will address the current status and issues facing the continuing search for asteroids.

2. HISTORICAL SEARCH METHODS

Ceres, the first asteroid discovered, was found in 1801 by Giuseppe Piazzi, who was in the process of using direct visual telescopic observations to construct a star catalog. Ceres was recorded as a star the first night it was noticed, but moved the next night it was observed. Thus, Ceres became the first of a new class of objects based on its motion relative to the fixed background stars. This original method of discovering asteroids by differentiating their motion from that of the stars has not changed since 1801; however, the technology available to apply that original method has evolved significantly. Search technology evolved from direct telescope observations, which led to the discovery of

the first few hundred asteroids, to film-based observations in the 1890s. The first asteroid discovered by photography, (323) Brucia, was discovered by Max Wolf in 1891. The most common photographic-based search methods were either (1) to take a single long exposure and visually inspect the plate or film for trails as the asteroid moved during the exposure, or (2) to take two successive exposures and visually compare them for moving objects. The latter was accomplished either with a blink comparator to show the asteroid moving between two positions, or by viewing the two images stereoscopically, rendering the moving object as suspended above the plane of the nonmoving background. Asteroid search systems based on photography dominated the field until the mid-1980s when modern CCD- and computer-based systems emerged.

Photographic search techniques employed during the 1900–1990 era had a number of advantages over direct visual observation techniques: Large areas could be photographed with much less observer fatigue and a permanent record of the observations was maintained. Photographic systems, however, have two limitations that are overcome by the new solid-state detector technology of the 1990s. First, the sensitivity of the film is poor, with a QE of ~1% for objects having the solar spectrum, and secondly, the moving object detection process relied on humans who are subject to fatigue and nonuniform performance.

The conversion to CCD-based detection systems and computer processing of the data was first demonstrated by the Spacewatch system in 1984 (Gehrels, 1986). At the time, the readout rate of astronomical-quality CCD detectors was very slow (~25 Kpx/s for optimal photometry), and the computation capability that could be applied to processing the data was quite limited by today's standards. T. Gehrels and R. McMillan developed a search system that accommodated

the available technology in a very clever way. They developed a drift-scan technique where the readout rate was clocked to the sidereal drift rate across the CCD. The long scans produced images with minimal pixel-to-pixel (flat-field) variation, and readout overhead was limited to ramp-up and ramp-down fields at either end. The data rate was well matched to the capabilities of the processing equipment available at the time. The use of CCDs enabled much more sensitive search systems due to their ability to achieve quantum efficiencies as high as 65% for objects having the solar spectrum, almost 2 orders of magnitude over that of film. Spacewatch achieved a faint limiting magnitude because of the long integration time achieved as a star drifts across the CCD. Thus, the Spacewatch system was very well tailored for the available telescope and technology.

Evolution to the more commonly used CCD-based “step-stare” asteroid search approach came in late 1995 with the development of the Near-Earth Asteroid Tracking (NEAT) search program (*Pravdo et al.*, 1999), a joint project between NASA’s Jet Propulsion Laboratory (JPL) and the U.S. Air Force. NASA/JPL developed a 4080 × 4080 CCD camera that was mounted in the space of the usual Ebsicon camera on a 1-m U.S. Air Force GEODSS (groundbased electro-optical space surveillance) telescope. A step-stare system works much like a film-based search, with multiple images taken over an hour or two. Each image is “exposed” while the telescope tracks at the sidereal rate and is then read out to a computer before the next exposure is taken. Faster, multichannel readout rates generate a much higher data rate requiring greater computing capacity and offer more flexibility in balancing coverage and depth. The NEAT system was able to search more sky than Spacewatch by using a CCD array with 4× as many pixels and a larger angular pixel scale and by using shorter integration times and not going as deep.

Step-stare search systems were also developed in the late 1980s for use by the U.S. Air Force to find and track Earth-orbiting satellites, a process that has many elements in common with searching for asteroids. Both targets traverse the same cluttered background and are differentiated from the background based on their particular motion. Earth orbiting satellites are generally brighter, but move at a larger angular rate. The stringent military requirements for satellite search led MIT’s Lincoln Laboratory to develop a specialized search system, consisting of a custom-manufactured, frame-transfer CCD and a high-capacity computer processing system on a 1-m GEODSS-type telescope (*Viggh et al.*, 1998). In March 1998, the search system started operating in an asteroid search role as the Lincoln Near-Earth Asteroid Research project (LINEAR) (*Stokes*, 2000) and has since provided 70% of the worldwide asteroid discovery rate.

3. SEARCH OBJECTIVES AND MOTIVATION

Efforts to find and catalog asteroids over the past 200 years were initially inspired by scientific curiosity and a desire to understand the structure of the solar system. More

recently these efforts have been spurred by the NASA search goal and as part of the International Spaceguard effort. The NASA goal, mandated by the US Congress, is to discover 90% of all potential impactors with diameters in excess of 1 km by the year 2008 (*NASA*, 1998). One-kilometer-diameter asteroids are thought to mark the threshold size for globally catastrophic consequences in a collision, and various models indicate there are between 500 and 2100 such objects (*Morrison et al.*, 1992; *Rabinowitz et al.*, 2000; *Bottker et al.*, 2000; *Stuart*, 2000). The ability to achieve the NASA goal with existing and proposed systems can be viewed as a function of the search volume for these systems with respect to the size of the target object. Search volume is defined as the maximum range at which a system can detect an object of a certain diameter multiplied by the area of sky covered. As the diameter of the limiting object decreases, so does the maximum range at which it can be detected, and the search volume therefore decreases. Longer integration times may increase the limiting range but will decrease the area of sky covered due to limited time available for searching, thereby not necessarily increasing the volume. Improved detector and computing technology has stretched the search volume for 1-km objects to make the NASA goal potentially achievable in the future with the current smaller aperture telescopes, and discussion is shifting toward extending the inventory to smaller objects that could cause significant regional damage. For example, a catalog 90% complete to the 300-m size is one of the proposed objectives of the Large-aperture Synoptic Survey Telescope (*NRC*, 2001) recommended by the recent astronomy decadal study. The Spaceguard report (*Morrison et al.*, 1992) estimates that there are between 12,500 and 50,000 NEAs larger than 300 m. Below a few hundred meters in size, the limited search volume of existing or proposed search systems precludes near-term cataloging. Such objects will require a continuous search effort that could also address detection of potentially dangerous long-period comets not amenable to cataloging. Below ~100 m, the mass that survives entry through the atmosphere is likely too small to create widespread destruction.

Despite 200 years of searching for asteroids and the dramatic increase in discoveries and observations in the past decade, we are just now approaching the point of having found approximately one-half of the large NEAs set as the goal by NASA. This state of affairs testifies to the inherent challenges associated with finding asteroids in general and NEAs in particular. Searching for asteroids has all the typical difficulties associated with finding faint objects in a cluttered and complex environment. Specifically, the faint observed magnitudes limit the search volume; search areas and times are denied by the Sun, Moon, and weather; and the cluttered stellar background makes detection difficult, especially in the galactic plane. In fact, the instantaneous image of an asteroid observed from Earth is essentially indistinguishable from a star. Given this state of affairs, asteroid searchers have labored to achieve sustained, high search-rate operations while maintaining good sensitivity. Searchers have attempted to access as much as possible of the total

volume where asteroids could reside. This leads to the obvious questions: Where do asteroids reside, where are they most easily detected, and how is the sensitivity and limited search volume best utilized?

To optimize survey efficiency, it is necessary to understand the time-dependent spatial distribution of asteroids, their rates of motion, and apparent brightnesses. This has been covered by *Bowell and Muinonen (1994)* using simulations and by *Harris (1998)*. The earlier results are supported by the large quantity of new data collected in recent years. A brief summary with new plots is presented for completeness.

The apparent ecliptic rate of motion with respect to ecliptic longitude of a typical main-belt asteroid is shown in Fig. 1 along with the rates of motion of similar asteroids with varied semimajor axes. NEAs have a wider distribution of orbital elements than main-belt asteroids and therefore display a wider distribution of apparent angular motions. As the search region moves away from opposition toward 60°, the angular rates decrease and the difference in apparent angular rates between NEAs and main-belt asteroids decrease, making them more difficult to distinguish. In addition, the favorable addition of the Earth’s motion to the asteroid’s motion is lost. As a result, searching at opposition has traditionally been considered the most productive method for detecting NEAs.

A second factor affecting searches is the apparent visual magnitude. The visual magnitude is a function of the solar phase angle, the distance between the asteroid and Earth, and the distance between the asteroid and the Sun. Consider the apparent magnitude of a 1-km asteroid ($H = 18.0$) on the ecliptic plane as its location is varied away from opposition. Figure 2 is a contour plot showing how the relative magnitude varies. The intrinsic phase function of the asteroid adds to the peak brightness at opposition, which is added to the increased brightness due to the decreased distance between the asteroid and the observer and between the as-

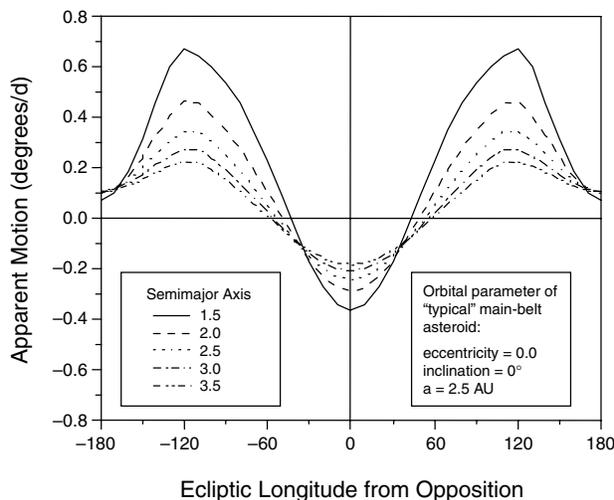


Fig. 1. Ecliptic rates of motion of asteroids.

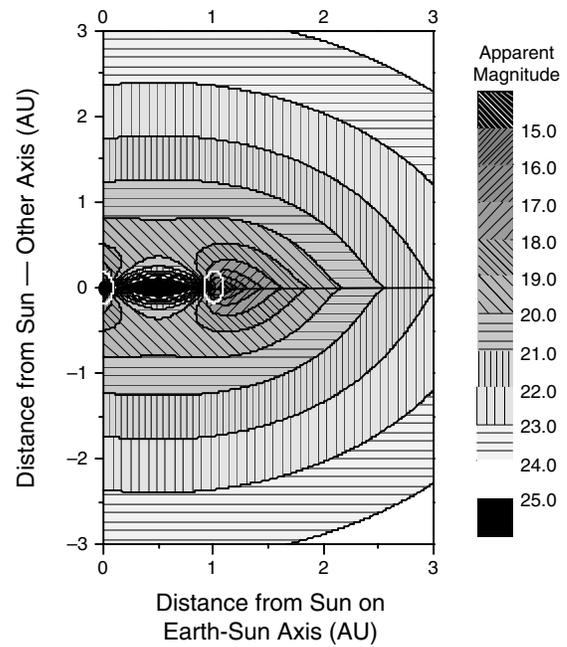


Fig. 2. Visual magnitude of an $H = 18.0$ asteroid as a function of its ecliptic position.

teroid and the Sun. The candle shape of Fig. 2 also describes how the relative magnitude varies as an asteroid located at opposition is varied along ecliptic latitude. The maximum brightness occurs at the ecliptic and decreases at higher declinations, much as the maximum occurs at opposition when the ecliptic latitude is held constant.

In summary, it would appear that an observer’s best chance of detecting an NEA is to search near the ecliptic at opposition for optimal rates of motion and apparent visual magnitude. Given that all asteroids, regardless of their inclination, will pass through the ecliptic twice at their nodes with each orbit, this is a reasonable approach. This is also the most common practice. A review by *Marsden (1994)* shows that 86% of all the numbered asteroids at that time were discovered within 30° opposition and 96% were discovered within 20° of the ecliptic. However, with the advent of the CCD, and the introduction of full-sky search capabilities by modern surveys, alternative search strategies need to be considered. What are the benefits of looking away from opposition and away from the ecliptic?

A contour plot showing the number of known NEAs per cubic AU as a function of ecliptic plane coordinates is shown in Fig. 3. The plot was generated by computing the percentage of time each known NEA spends in each heliocentric cylindrical bin, then summing over the bins. The current known NEA population, uncorrected for observational bias, was used for this model. The highest density of NEAs is located in the ring around the Sun that includes Earth, and the density of observable NEOs diminishes with geocentric distance. The contour plot also shows potential search directions at various solar elongations (labeled as angle from opposition). Of interest when considering vari-

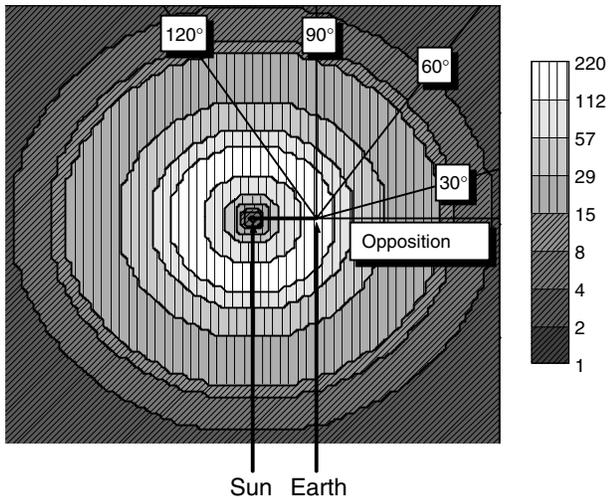


Fig. 3. Density of known NEAs in ecliptic coordinates, and potential search lines.

ous search strategies is the NEO sky density as a function of detection limit. This plot shows heuristically that at the simplest level the probability of detecting NEAs actually increases away from opposition due to the longer line of sight through higher-density regions of NEOs. The negative aspects of such a search include observing through greater air mass and less favorable solar phase angles. Each of these effects should be considered, and each varies system to system with the location and sensitivity of equipment. A rigorous discussion of probabilities of detection is covered by *Jedicke (1996)* and supports a similar conclusion regarding the potential benefits of searching away from opposition: The probability of detection increases away from opposition if you can search deep enough.

Searching away from the ecliptic generally does not provide for optimal detection efficiency. For any given asteroid, it is generally easier to detect it near the ecliptic. However, NEAs on an inclined orbit are less likely to be found at small ecliptic latitudes because they reside longer at high apparent latitudes. This may justify an all-sky search strategy. In 1998, three large search programs began operation: LINEAR, Catalina Sky Survey, and LONEOS. Due to the significantly increased search capability with the introduction of these surveys, full-sky searches have become more common, primarily through these three programs. The effect has been to refine our understanding of the statistical distribution of the known population. Figure 4a shows the distribution by inclination of all known NEAs with $H \leq 18.0$ discovered by LINEAR, LONEOS, and Catalina Sky Survey as compared to those discovered by other surveys more likely to be concentrating near ecliptic opposition. Note that the distribution is both flatter and has a longer tail towards higher inclinations for discoveries by these three. Figures 4b and 4c show similar plots for eccentricity and semimajor axis, with some differences amongst

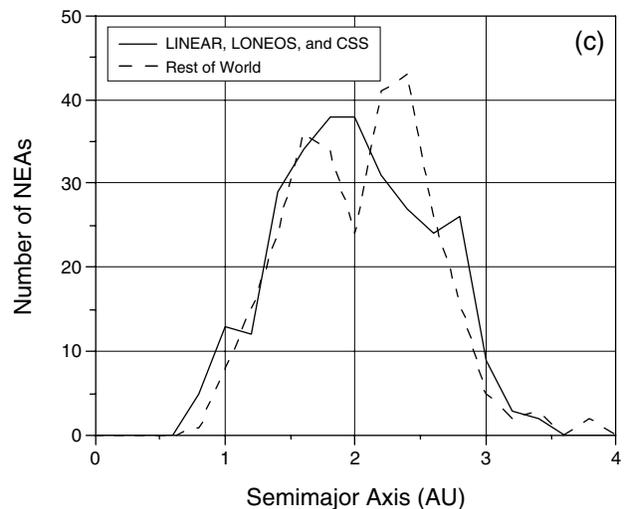
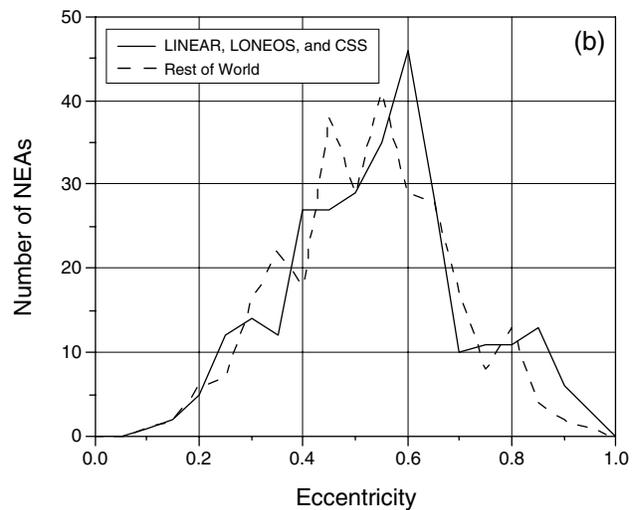
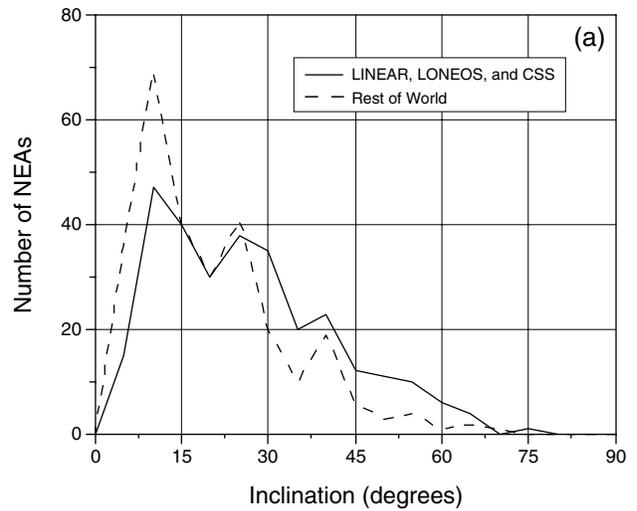


Fig. 4. (a) Inclination distribution for NEAs discovered by LINEAR, LONEOS, and CSS and NEAs discovered by others. (b) Eccentricity distribution for NEAs discovered by LINEAR, LONEOS, and CSS and NEAs discovered by others. (c) Semimajor axis distribution for NEAs discovered by LINEAR, LONEOS, and CSS and NEAs discovered by others.

these parameters. This variation may indicate the current distribution for all these parameters has been biased by past search methods.

Regarding the question at the beginning of this section on the best place to search, there is no single answer. If the goal is to detect an NEA, traditional opposition ecliptic searches are fine. If the goal is to find and catalog all NEAs, given the apparent sky distribution of NEAs, an all-sky search is appropriate if it is possible. However, the details of any search strategy are determined by the individual search system's capabilities. An overview of the current major search systems is given in the following section.

4. NEAR-EARTH-OBJECT SEARCH PROGRAMS

The characteristics of the major existing NEO search surveys and a few of the planned surveys are summarized in Table 1. Their individual approach and emphases are described below in the approximate order they became operational. Additionally, Table 2 lists the total discoveries, total NEA discoveries, length of time each survey has been operating, and discovery rates. The equipment used by each survey often dictates the basic way the survey operates, with the detection algorithms and search patterns also contributing to a survey's discovery rate.

4.1. Spacewatch

The Spacewatch program, started by T. Gehrels and R. McMillan of the University of Arizona's Lunar and Planetary Laboratory in 1980, was the first NEO search program to utilize CCD imagers to look for NEOs (*Carusi et al.*, 1994). Spacewatch has had exclusive access to the Steward Observatory 0.9-m telescope ($f/5.34$) on Kitt Peak outside of Tucson, Arizona, since 1982 and made the first test scans in 1983. As described previously in the historical section, the program uses a drift-scanning mode in which the telescope is kept stationary while the CCD is read out at the sidereal rate of the sky (*Gehrels*, 1991). Spacewatch first used an RCA 320×512 -pixel CCD, then upgraded to a Tektronics (now SITE) 2048×2048 -pixel CCD with 0.027-mm pixels in 1989, and finally switched to a 2048×2048 -pixel, thinned, backside-illuminated CCD with 0.028-mm pixels in 1992. With the current system, each pixel is 1.05 arcsec. In a drift-scan mode, a swath of sky about 0.5° in declination and 7° in right ascension is completed in about 30 min with an effective integration time (on the equator) of 143 s. This permits detection of objects as faint as $V = 21.7$ on good nights. Due to star trails at higher declinations moving in arcs that smear during readout, the useful declination range of the drift-scan system is limited to $\pm 30^\circ$. To access higher declinations, Spacewatch uses a stare mode.

TABLE 1. Comparison of current near-Earth object search programs.

Program	Spacewatch	Spacewatch	NEAT	NEAT	LONEOS	LINEAR*	CSS	Bisei
Aperture (m)	0.9	1.8	1.2	1.2	0.6	1	0.4	0.5
f Number	5.3	2.7	1.9	2.5	1.9	2.2	3.0	1.9
Telescope Type	Newt.	folded	prime	Schmidt	Schmidt	folded	Schmidt	Cass.
Array Dimensions	2048×2048	2048×2048	4080×4080	$4080 \times 4080 \times 3$	$2048 \times 4096 \times 2$	1960×2560	4080×4080	$2048 \times 4096 \times 2$
Pixel Size (mm)	0.024	0.024	0.015	0.015	0.0135	0.024	0.015	0.015
Pixel Size (arcsec)	1	1	1.4	1	2.5	2.25	2.5	3.2
FOV (deg ²)	0.3	0.3	2.5	3.8	8.3	2	8.1	3.1
Cooling (°C)	-90	-90	-20	-40	-130	-50	-30	-100
Readout Mode	drift scan	ds/stare	stare	stare	stare	stare	stare	stare
CCD Type	thin	thin	thick	thick	thin	thin	thick	thin
Exposure (sec)	150	150	20	60	45	5	60	23
Magnitude Limit	21.7V	22.6V	19.5V	21V	19.3V	19.2V	19.3R	19
Coverage (deg ² /h)	7.4	7.4	174	174	400	1050	194	—
Number of Visits	3	3	3	3	4	5	4	—
Effective Coverage	2.5	2.5	58	58	100	210	48	—

*Two identical telescopes.

TABLE 2. Discovery statistics for current search programs as of February 2002.

	Spacewatch	NEAT	LONEOS	LINEAR	CSS	Bisei
Total Discoveries	48,054	12,803	12,713	157,346	4309	141
NEA Discoveries	254	158	106	925	46	1
Months of Operation	135	70	45	75	15	—
Discovery Rate	356	183	282	2098	287	—
NEA Discovery Rate	1.88	2.26	2.36	12.33	3.07	—

The Spacewatch automated detection system utilizes three visits and a default S/N limit of 2.5σ . The observer is able to visually inspect the candidate objects near real time, and based on the rate of motion, can estimate if the object is an NEA.

Spacewatch's future plans include upgrading the 0.9-m telescope with a shorter focal length primary and a mosaic of four 2048×4608 -pixel Marconi CCDs with 0.0135-mm pixels. This will give 1-arcsec pixels, but will have $9\times$ the field coverage of the current system and will be used in stare mode. Additionally, a 1.8-m ($f/2.7$) telescope has very recently come online with a fainter detection limit of $V = 22.6$. It has a thinned 2048×2048 -pixel CCD with 0.024-mm, 1-arcsec pixels. The telescope altitude-azimuth mount drive system is designed to allow scanning in any direction over a wide range of rates, as well as in stare mode.

Spacewatch is the longest-running survey of the currently existing surveys, and has consistently contributed toward the cumulative knowledge of NEOs. This survey has discovered some of the smallest and nearest NEOs known (*Rabinowitz, 1992*).

4.2. Near-Earth Asteroid Tracking (NEAT)

The Near-Earth Asteroid Tracking (NEAT) program is run by JPL (E. Helin, S. Pravdo, K. Lawrence, and D. Rabinowitz) and is currently operating at two sites: one at the U.S. Air Force Maui Optical Station in Hawai'i (NEAT/MSSS), and the other at Palomar Observatory in California (NEAT/Palomar).

Beginning in 1995, this program utilized a GEODSS 1-m ($f/2.2$) telescope with a Loral large-format, 4080×4080 -pixel CCD with 0.015-mm, 1.4-arcsec pixels. The telescope was shared with the USAF at Haleakala, where NEAT was able to utilize 12 nights per month centered on the new moon from December 1995 to December 1996 and 6 nights from January 1997 to February 1999. To help ensure more telescope time per month, NEAT modified the 1.2-m telescope of the U.S. Air Force Maui Space Surveillance System (MSSS), managed by the Air Force Research Laboratory, with a similar camera at the prime focus. This telescope became their operational system in February 2000. It maintains the 1.4-arcsec pixel scale and field of the GEODSS configuration, but is optically faster at $f/1.9$. It is capable of detecting objects to $V \sim 19.5$ with unfiltered exposures of 20 s.

The NEAT detection software utilizes three visits and was written to work autonomously in real time and to present small subarrays for visual inspection by scientists at JPL. The JPL-located scientists generate the nightly pointing lists for a computer in Maui that controls the sequencing of the telescope automatically once onsite operators open the telescope.

To further extend the telescope time available to NEAT, the 1.2-m ($f/2.5$) Oschin Schmidt telescope at Palomar Observatory has been recently upgraded for autonomous pointing, and a camera with three thick 4080×4080 -pixel CCDs with 0.015-mm, 1.0-arcsec pixels that provide a total 3.8-

deg² field of view (FOV). It is capable of detecting objects to $V \sim 21$ with 60-s exposures. Looking toward the future, a camera of $112\,2400 \times 600$ -pixel thinned CCDs with 0.013-mm, 0.9-arcsec pixels covering 9.3 deg² is expected to reach $V \sim 21.5$ and is being constructed at Yale University. It is scheduled to replace the current NEAT camera in late 2002 and JPL/NEAT and YALE/QUEST will share the telescope time thereafter.

NEAT was one of the early CCD search surveys and many of their past images have been archived at the Skymorph online archive where compressed versions of the images can be accessed to search for and measure prediscovery images of interesting objects. Skymorph is linked to the JPL Horizons site to facilitate easy identification of potentially useful imagery.

4.3. Lowell Near-Earth Object Survey (LONEOS)

The Lowell Near-Earth Object Survey (LONEOS) is run by Lowell Observatory (E. Bowell, B. Koehn) and utilizes a 0.59-m ($f/1.0$) modified Schmidt telescope located at the Lowell Anderson Mesa site near Flagstaff, Arizona. Two cryocooled 2048×4096 Marconi CCDs with 0.0135-mm, 2.4-arcsec pixels provide a total FOV of 8 deg². Using an unfiltered stare mode with 45-s integration, the system is capable of reaching $V \sim 19.3$ and can be run automatically.

The system utilizes four visits, and moving-object detection is automatic, although the observer can visually inspect candidate objects in near real time and compute short-arc Vaisala orbits to identify possible NEAs.

The LONEOS approach of using a large-format CCD with large pixels and large FOV has been successful.

Future plans include a collaboration with scientists at the U.S. Naval Observatory Flagstaff Station using a new mosaic camera on their 1.3-m telescope, which should double the current LONEOS discovery rate. Even further in the future is the potential 4-m Next Generation Lowell Telescope with a 3.2-deg² FOV and $V \sim 22.3$.

4.4. Lincoln Laboratory's Near-Earth Asteroid Research (LINEAR)

Lincoln Laboratory's Near-Earth Asteroid Research (LINEAR) program is run by the MIT Lincoln Laboratory using two experimental 1-m ($f/2.2$) GEODSS telescopes at the Lincoln Laboratory Experimental Test Site (ETS) near Socorro, New Mexico (*Stokes et al., 2000*). Each telescope has a specialized low-noise, frame-transfer, eight-channel, 1960×2560 -pixel, thinned CCD designed and fabricated by Lincoln Laboratory (*Viggh et al., 1998*). The 0.024-mm, 2.25-arcsec pixels provide a 2-deg² FOV. While the system is capable of shutterless exposures of 0.1–100 s, the nominal operation mode is exposures from 5 to 30 s depending on the phase of the Moon and the time of the year. At 10-s integration, the system is capable of $V \sim 19.2$.

The LINEAR detection software utilizes five visits ~30 min apart and requires only three hits for a detection. This approach is effective even in dense star fields near the

galactic plane. Rates of moving objects are used as a means of identifying potential NEAs, which are then verified visually. All interesting objects are automatically followed up on the subsequent observing night.

This survey approach is to cover large areas of sky by maximizing efficiency and minimizing cycle time between frames. Additionally, using two nearly identical telescopes, it is possible to cover the entire available sky each lunation and to cover some areas of the sky more often than once per lunation. These characteristics have enabled LINEAR to be the most productive of the surveys thus far.

4.5. Catalina Sky Survey (CSS)

The Catalina Sky Survey (CSS), a project of the University of Arizona's Lunar and Planetary Laboratory, utilizes the 0.42-m ($f/3$) Schmidt at the Catalina Observatory station north of Tucson (Larson et al., 1999). The 4080×4080 thick, single-channel, Loral CCD has 0.015-mm, 2.5-arcsec pixels and a FOV of 8.1 deg^2 . It is capable of detecting objects to $R = 19.5$ with 60-s integrations. Upgrades underway include a full-aperture, 0.7-m corrector and a cryogenically cooled, four-channel, thinned CCD.

The CSS detection software utilizes four visits to reduce false positives with the default S/N limit setting of 1.5σ . Sequencing is automated, freeing the observer to visually validate the candidate objects.

Future plans include developing a southern hemisphere component by modifying the 0.6-m Uppsala Schmidt at Siding Spring, Australia. The system is being modified for surveying and will utilize the same CSS detector and software. The project will have exclusive use of the telescope for surveying and will concentrate on the southern sky not reachable by the other surveys.

4.6. Bisei Spaceguard, Japan

The Bisei facility is a new facility devoted to NEO and space debris studies (Isobe et al., 2000). The facility consists of a 0.5-m ($f/2$) Cassegrain telescope with two 2048×4096 -pixel thinned SITe CCDs and a 1.0-m ($f/3$) Cassegrain telescope with 10 CCDs of the same size. These provide 9.6- and 6.8- deg^2 FOVs with 3.2- and 1-arcsec pixels respectively. At the time of this writing, the facility is preparing to come online.

Being outside of the southwestern U.S. weather pattern where most of the other surveys are located will allow for continued surveying during traditional seasonal lows.

4.7. Detection Algorithms

Automated moving-object detection is a key element of any search program. It is a nontrivial task to develop and write code to efficiently identify moving objects in a star field and generate astrometric positions to report to the Minor Planet Center. Search programs spend a significant fraction of their resources in producing and refining code to maximize detection efficiency.

Each project has independently developed its own code according to the type of data obtained and other numerous constraints such as available computer speed. It is beyond the scope of this review to describe the details of detection algorithms used by the various surveys, but we describe some basic elements that are commonly used.

In all cases, three, four, or five images of the same field are taken at appropriate intervals to allow the moving objects with the targeted range of apparent rates to move more than a few pixels. The larger the number of visits to a field, the easier it is to compensate for the effects of spurious "cosmic-ray" events and the merging with field stars. This has to be balanced against being able to cover more sky with fewer visits.

The most common detection method involves generating a list of the centroid positions of objects in the image, performing an astrometric solution using a reference catalog such as the USNO-A2 or UCAC-1 catalogs, and eliminating objects whose positions do not differ between visits by some predefined amount. The remaining objects are tested for consistent motion and are grouped as potential moving-object candidates.

Another method is to work in image space by registering images and taking differences between individual visits and a median of all the visits to eliminate the stationary field stars. This method is computationally intensive, but may be better able to differentiate moving objects from field stars. On the other hand, the added noise of the median image degrades the signal-to-noise ratio of an object.

In most cases, the candidate objects are validated visually by blinking or similar means. The ratio of false to real objects and available personnel may dictate how close to the noise floor objects are extracted from the images. It may also restrict visual validation to only the obvious NEO candidates.

4.8. Followup Observations

Maximizing survey coverage precludes making followup observations of potential NEOs that are more efficiently made with smaller field telescopes. Confirming observations on subsequent nights provide the extended arc needed to determine their orbits with sufficient precision to identify NEOs. Fortunately, there is a sizable network of amateur and professional observers who consult the Minor Planet Center's NEO Confirmation Web page each night and provide the bulk of additional astrometry needed to identify NEOs. In the past few years, the development of affordable CCD cameras, fast computers, sophisticated software, better reference star catalogs, larger telescopes, and the ability to communicate effectively over the Internet has enabled amateurs and professionals at small observatories to out-produce the professionals at major observatories of 10–15 years ago. Amateur followups have become a vital component in the NEO inventory effort down to $V \sim 20$. In addition to providing the necessary astrometry, this followup contribution is expanding toward obtaining better time-resolved photometry from which sizes and shapes of NEOs can be estimated.

While followup of objects to $V \sim 20$ are well supported by the various amateurs and professionals, followup observations of the fainter objects, such as those found by Spacewatch, have proven to be more difficult. Followup of these objects are being made more routinely with the Spacewatch 1.8-m telescope, Catalina and Mt. Lemmon 1.5-m telescopes, and the 1-m Siding Spring telescope. As the existing and proposed search systems continue to improve their sensitivity and search to fainter magnitudes, these followup limitations will need to be addressed.

5. COORDINATION OF SEARCH PROGRAMS

Asteroid searches over the past 20 years have been carried out by a number of independent groups using a variety of telescopes and detectors. Prior to the U.S. Congressional mandate, there were only three groups consistently observing. There was relatively little competition for funding and regions of the sky to search. As support to achieve the congressional mandate became available through NASA, development of detectors and efficient detection algorithms became the natural outcome of a more competitive environment. Today, with the growing number of mature survey systems, it is possible to cover the entire observable sky on a monthly basis. To optimize efficiency and minimize needless duplication, it is appropriate to consider coordination among the major search programs

An active series of discussions started in 1999 between the major U.S. survey teams to address the issue of coordination. The premise of the discussions has been that the resources available for asteroid search should be applied in such a way as to maximize the total joint productivity of the search systems. One notable result has been the e-mail distribution to all the surveys of coverage lists of fields successfully observed with estimates of typical limiting magnitudes. This is represented graphically by the Minor Planet Center (MPC) Web site and the Lowell Observatory site. An example is shown in Plate 1. This method of coordination allows each search program to plan the night's observations with an understanding of what other area programs have covered recently, and how deep the coverage was. As an added benefit, the site is available to amateur observers and other small-scale programs that want to work around the major systems.

The next phase of the coordination effort centers on finding some *a priori* method of coordinating the various cooperating search systems in a way that achieves a larger joint productivity. This objective is quite complex due to the considerable differences between the operation's concepts and tempos, capabilities and maturities. The current consensus of the discussions is that most of the survey systems are evolving quickly and have not yet demonstrated their ultimate capability. In addition, we believe that in order to achieve a level of coordination beyond that currently operating, the capabilities of each of the systems must be evaluated in a common framework and against a common stan-

dard. Considerable discussion on the subject has led to an agreement to pursue this goal on several fronts as follows:

Task 1. Maintain comparable search experience information for all searches. This will allow a better understanding of how the search programs compare with one another and will allow extraction of experience information on a common basis. This will be accomplished by defining common elements for each search program's database, which will contain look-by-look standard measures of the seeing and magnitude limit based upon star measurements.

Task 2. Develop a common understanding of the most effective search strategies to effect a search for 1-km and larger asteroids. For example, decide how to distribute observation effort across the sky for best productivity. This task was initially approached by plotting the LINEAR detections of all NEAs and all large NEAs ($H > 18$) relative to the opposition in ecliptic coordinates. Only the first detection during a lunation was included and detections resulting from directed followup activities were excluded. The results of these plots are shown in Figs. 5a and 5b. The plots indicate that LINEAR detects asteroids at all declinations and an all-sky search is an appropriate strategy for systems with similar capability. If search systems can achieve a limiting magnitude performance substantially better than LINEAR, the strategy question will need to be revisited.

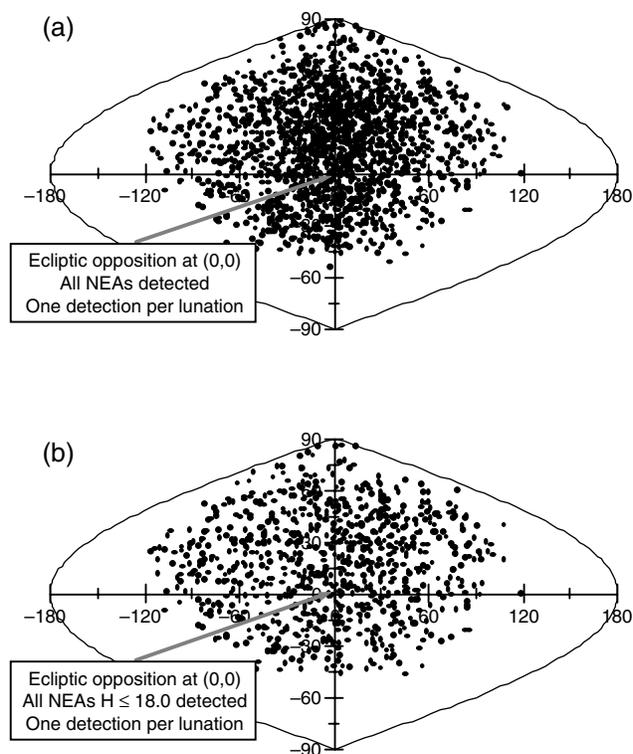


Fig. 5. (a) Distribution of all NEAs detected by LINEAR and plotted with respect to ecliptic opposition. (b) Distribution of all large NEAs ($H \leq 18$) detected by LINEAR and plotted with respect to ecliptic opposition.

Task 3. Develop a common measure of capability/capacity for each search system to enable a systematic approach to coordinating the search programs. One of the most important metrics for a search effort is the volume of space that the survey can search for asteroids larger than $H = 18$. This volume may be calculated by calibrating, on a field-by-field basis, the depth of the search for the detection of an $H = 18$ object. Once a reliable calibration method is found, the volume of each field can simply be accumulated over a period of time to generate an effective search volume.

Achieving a reliable field-by-field calibration is complex due to the variable conditions under which the observing is accomplished, and the fact that considerable data-dependent processing occurs to detect moving asteroids. The calibration method chosen by the LINEAR program is discussed here as an example of such a process. The most obvious method to calibrate the magnitude performance of a system is to pick stars of known magnitude from the fields and determine how bright a star must be to achieve some standard signal-to-noise ratio in the detection system. Given that the CCD pixels are large and the integration times are short, asteroids do not streak and are indistinguishable from stars in any given frame. This process of computing signal-to-noise to determine a system's sensitivity takes into account many of the factors effecting the performance of the search, such as weather and seeing, but fails to consider the aspects of the detection algorithm that look for moving objects. In order to validate the star S/N ratio as a valid general indicator of search depth, a large set of data taken near the ecliptic was identified and the detections extracted. Objects in the MPC catalog expected to be in the LINEAR search area and with known absolute magnitudes were identified and their magnitudes corrected for distance and illumination geometry. With these inputs, a field-by-field calibration of the search's ability to detect asteroids could be accomplished by plotting the known asteroids detected and those not detected as a function of magnitude. An example of such a plot is shown in Fig. 6. Such a calibration process is possible near the ecliptic, where there are abundant known asteroids, but breaks down off the plane where there may only be a few to zero detections per field.

The moving-object calibration process described above validated the process of using the star signal-to-noise ratio as a measure of the search depth on a frame-by-frame basis. Thus, the accumulated search volume of the search may be calculated and is shown in Fig. 7 in cubic AU.

Another relevant piece of information yielded by the volume calculation is the ability to measure the evolution of a search system. Current asteroid search systems are all in various stages of an evolution toward increased maturity and capability. As search systems add capability, the rate of volume searched should grow. The second curve in Fig. 7 shows a running computation of the volume searched by LINEAR in the preceding year. Note that the system search capability evolved rapidly over 1999/2000 and appears to have leveled off in 2001. After achieving the funda-

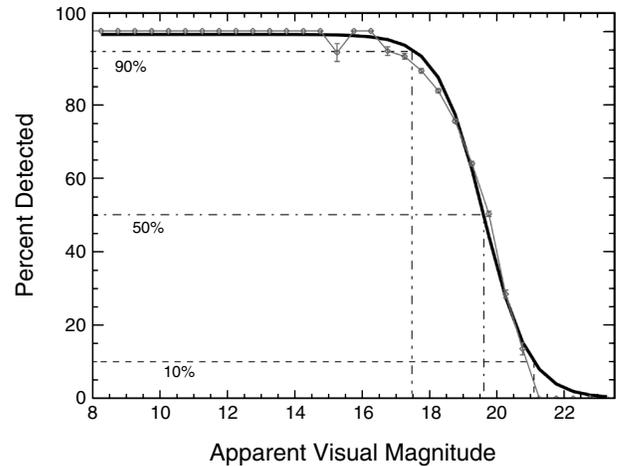


Fig. 6. A single night's detection efficiency plot from LINEAR.

mental capability of the existing telescope/detector/processing system, the variations in the plot should reflect observing experience (i.e., lunations, weather, equipment failure, staff availability, etc.). Once the fundamental capabilities of the various systems have been reached and characterized, the coordination process between the search systems in pursuit of the common goal of maximizing joint detection rate will be much easier to arrange.

6. THE FUTURE OF SEARCH TECHNOLOGY

This chapter has given an overview of the current search systems, how they came about, and how the steps taken by them, both alone and together, have furthered our general knowledge of NEAs. What does the future hold for these and yet-to-be-developed systems?

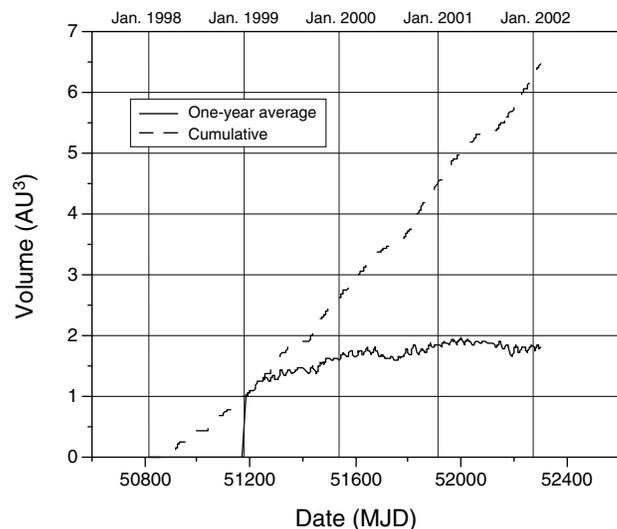


Fig. 7. Actual volume searched by the LINEAR program.

The march of Moore's Law has allowed the development of CCD detectors and the processing capacity to match to the point that there are probably no more factors of 2 in increased search performance for search systems using 1-m telescopes such as LINEAR. In designing the LINEAR system, considerable effort went into minimizing bottlenecks by matching the capabilities of each of the subsystems to work well with the rest of the system and to maximize the total system capability. It would appear that given unlimited detector mosaic sizes, the limitation of asteroid search systems is aperture size. Historically, the astronomical community has built telescopes with ever-increasing aperture, but with small FOVs compared to that needed to search a reasonable fraction of the sky; sensitivity to bore down on interesting objects has been the mainline interest rather than search. In addition, wide-FOV telescopes become progressively harder and more expensive to build as the aperture size increases. Therefore, there are very few existing wide-FOV telescopes with apertures exceeding 1 m. The very thick corrector plate on the venerable 1.2-m Palomar Schmidt is testament to the difficulties of building large-aperture, wide-FOV telescopes.

As the existing systems evolve toward maximum capacity, and when new larger aperture systems join the search in the future, the interest in coordination will grow. The first steps toward coordination have been defined and a few steps taken. The future holds more thorough system analysis and characterization for the sake of optimizing search strategies for objects of ever decreasing size. When the goal of cataloging 90% of all NEAs greater than 1 km in diameter has been reached, the bar will most likely be lowered to NEAs >300 m in diameter. If that goal is met, NEAs of 100 m still pose a serious regional threat.

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