Detection and Discovery of Near-Earth Asteroids by the LINEAR Program

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■ **The Lincoln Near-Earth Asteroid Research (LINEAR) program, which applies space surveillance technology developed for the U.S. Air Force to discovering asteroids, has been operating for five years. During that time LINEAR has provided almost 65% of the worldwide discovery stream and has now discovered 50% of all known asteroids, including near-earth asteroids whose orbital parameters could allow them to pass close to the earth. In addition, LINEAR has become the leading ground-based discoverer of comets, with more than one hundred comets now named "LINEAR." Generally, LINEAR discovers comets when they are far away from the sun on their inbound trajectory, thus allowing observation of the heating process commonly missed previously when comets were discovered closer to the sun. This article provides an update to recent enhancements of the LINEAR system, details the productivity of the program, and highlights some of the more interesting objects discovered.**

Astronomers have been engaged in efforts to find and catalog asteroids for the past two hundred years. Initially the searches were inspired by scientific curiosity and a desire to understand our solar system. More recently, however, these searches have also been motivated by the desire to understand—and possibly react to—the threat of a potential collision between the earth and certain asteroids near the earth's orbit.

The search for a missing planet believed to be located between the orbits of Mars and Jupiter led to the discovery of the first asteroid, Ceres, by Giuseppe Piazzi in 1801. Ceres, like the vast majority of asteroids, populates the main asteroid belt between Mars and Jupiter. The material spread across the main belt is really a planet that never coalesced properly because of the disruptive effect of Jupiter's gravity. Asteroids in the main belt represent no direct collision threat to the earth. Over millions of years, however, asteroids in the main belt can be perturbed into orbits that can come close to that of the earth [1, 2]. These asteroids are called near-earth asteroids (NEA). The first known NEA, designated (433) Eros, was discovered in 1898, nearly a century after the discovery of Ceres.

Ceres was discovered through the laborious process of making direct visual observations with a telescope in order to create a hand-drawn star chart. After observations were made over a period of days, Ceres was found to move in the sky, leading to the conclusion that it was a planet-like object in orbit around the sun. The visual observation process employed to discover Ceres ultimately led to the discovery of the first few hundred asteroids in the nineteenth century. This original method of discovering asteroids by differentiating their motion from that of stars has not changed significantly since 1801, but the technology used for these observations has progressed, especially in the last decade. The visual observation process was used until the late 1800s, when more precise and capable photographic methods were introduced, which led to the discovery of the asteroid known as (323) Brucia by Max Wolf in 1891. Film was used to record a pair of images of the same area of the sky separated by a couple of hours. The images were typically blinked back and forth later to allow an analyst to see the motion that distinguished the asteroid from the background stars. The advent of photographic technology led to an explosion of discoveries of both main-belt asteroids and NEAs.

Photographic search techniques employed during the era from 1890 to 1990 obviously had important advantages over direct visual observation techniques. Large areas of the sky were photographed with much less observer fatigue, and a permanent record of the observations was maintained. Photographic search systems, however, had two limitations that were not overcome until the introduction of solid state detector technology of the 1990s. First, the sensitivity of photographic film was poor, with a solar-weighted quantum efficiency of approximately 1%. Second, the process of detecting moving objects relied on the close and careful attention of scientists and technicians who were subject to fatigue and nonuniform performance.

The conversion to solid state charge-coupled-device (CCD)–based detection systems and computer processing of the data was first demonstrated by the Spacewatch search system in 1984 [3]. At the time, the readout rate of astronomical-quality CCD detectors was very slow (about twenty-five kilopixels per second for optimal sensitivity), and the computation capability that could be applied to process 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 clever way. They developed a drift-scan technique in which the readout rate was clocked to the sidereal drift rate across the CCD. As a result, 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 at the time. The use of CCDs resulted in significantly more sensitive search systems because of their ability to achieve a solar-weighted quantum efficiencies as high as 65%, a result which is almost two orders of magnitude greater than that of film. The Spacewatch system achieved a faint limiting magnitude because of the long integration time as a star drifts across the CCD. Spacewatch tailored the system to the existing telescopes and available technology, and became the most productive asteroid search system for over a decade.

Current state-of-the-art CCD-based detection systems, with faster readout rates and greater computing capacity, now use the step-stare approach, which was first implemented in 1995 with the Near-Earth Asteroid Tracking (NEAT) program [4], a joint project between NASA's Jet Propulsion Laboratory and the U.S. Air Force. A step-stare system works much like a traditional film-based search, with multiple images taken over an hour or two. The NEAT system was able to search more sky than Spacewatch by using a CCD array with four times as many pixels and with a larger angular pixel scale, but also by using shorter integration times, which allows for greater sky coverage albeit at decreased sensitivity and depth of search.

Asteroid Collision Effect

As indicated earlier, the primary motivation for searching for asteroids has moved from scientific curiosity to a desire to understand and possibly react to the threat of a collision with an asteroid. As our knowledge of the population of known asteroids continues to increase, we gain a better understanding of the effect of collisions. A collision between the earth and an asteroid is essentially a problem in dissipating kinetic energy. Asteroids with diameters smaller than approximately fifty meters typically dissipate their energy in the atmosphere, although they can cause severe local damage from air blast effects (e.g., the Tunguska collision in 1908, which flattened over eight hundred square miles of forest in Siberia, is believed to have been caused by an asteroid that was fifty to seventy-five meters in size [5, 6]).

Asteroids exceeding a hundred meters in diameter can reach the surface of the earth and cause considerable regional damage in a collision; large asteroids—typically defined as those with diameters exceeding one kilometer—may cause devastating global effects

FIGURE 1. Examples of impact craters caused by asteroid collisions with the earth. The upper image shows the Wolf Creek crater in western Australia, a well-preserved crater partly buried under windblown sand. This crater is 0.85 kilometers wide, and is estimated to be 300,000 years old. (Aerial photo courtesy of V.L. Sharpton.) The lower image shows the larger New Quebec crater in Quebec, Canada. This crater is 3.4 kilometers wide, with a 250-meter-deep circular lake, and is estimated to be 1.4 million years old. (Image courtesy of George Burnside, Manotik, Ontario, Canada.)

[7, 8]. Figure 1 shows images of impact craters in western Australia and in Quebec, Canada, made by two relatively small asteroid collisions. The global reach of the devastation from large asteroids is thought to be caused by the large mass of material splashed from the impact site, which then spreads through the atmosphere and falls around the globe. Damage from ocean impacts may be enhanced in coastal areas by the creation of tsunamis [9].

Inspired by the growing understanding of the asteroid threat and the recent collision of comet Shoemaker-Levy 9 with Jupiter, the U.S. Congress began seriously considering the threat of an earth impact by comets and NEAs. A report, called the Spaceguard Survey, was generated by a group of well-known astronomers who assessed the risk to earth and made recommendations as to how to best address the threat [10]. In 1998, Congress issued a mandate to NASA requiring that 90% of the NEAs with diameters greater than one kilometer be discovered and cataloged by 2008.

At the time the Spaceguard report was written, the number of known NEAs was 450, of which 223 were large. The total number of large NEAs was estimated to be near 2200. Because of the significant increase in asteroid discovery rates in the last five years, the asteroid community is currently better able to assess the risk presented by NEAs. Today there are 2606 known NEAs, of which 691 are large; the population of NEAs with diameters exceeding one kilometer is currently estimated to be 1090 ± 180 [11, 12]. The population of such objects with diameters between a hundred meters and one kilometer is estimated to be around 56,000 [13]. Note that the more accurate population estimates are derived primarily from the Lincoln Laboratory search data described below.

Lincoln Near-Earth Asteroid Research Program

The Lincoln Near-Earth Asteroid Research program (LINEAR) began regular operations in March 1998, just as NASA formally embraced the task of cataloging 90% of the largest NEAs, and quickly became the most productive asteroid survey program in history. LINEAR is an outgrowth of space surveillance technology developed by Lincoln Laboratory for the U.S. Air Force; searching large areas of the sky for faint moving objects is common to developing a catalogue of earth's orbiting satellites and a catalogue of asteroids. Applying the highly refined Air Force space surveillance technology to the asteroid search task has provided an order-of-magnitude increase in capability to the worldwide asteroid search effort.

The LINEAR program and technology have been reported previously, both in the *Lincoln Laboratory Journal* [14] and in the open literature [15]. This article updates these reports, with a focus on recent system developments and enhanced productivity.

The LINEAR System

Since the start of routine operations in March 1998, LINEAR has provided 65% of the worldwide discovery stream for NEAs, and has now discovered more than 50% of the known population of these objects. LINEAR has accomplished this productivity by using

FIGURE 2. One of two one-meter Ground-Based Electro-Optical Deep-Space Surveillance (GEODSS) search telescopes at the Lincoln Laboratory Experimental Test System (ETS) at White Sands Missile Range, New Mexico. This telescope, which previously was used for space surveillance, is now a component of the Lincoln Near-Earth Asteroid Research (LINEAR) asteroid search program.

two one-meter Ground-Based Electro-Optical Deep Space Surveillance (GEODSS) telescopes, located at the Lincoln Laboratory Experimental Test System (ETS) on the White Sands Missile Range near Socorro, New Mexico. Figure 2 shows one of these GEODSS telescopes, and Figure 3 shows ETS, which is adjacent to the U.S. Air Force GEODSS site. The telescopes are equipped with Lincoln Laboratory–developed CCD focal planes, and utilize a step-stare process rather than a drift scan [16, 17].

The CCD focal plane, shown in Figure 4, contains an array of 2560 × 1960 pixels and has an intrinsic readout noise of only a few electrons per pixel. The CCDs are constructed with a back-illumination process, which provides peak quantum efficiency exceeding 95% and solar-weighted quantum efficiency of 65%. A frame-transfer feature produces a quick image transfer time from imaging area into frame buffer of only several milliseconds, which allows fields to be acquired as fast as the telescope can step and settle. This advanced CCD, in combination with agile wide-field-of-view GEODSS-type telescopes, rapid processing capability, and sophisticated moving-object detection algorithms, forms a unique and powerful asteroid search system that can survey essentially the entire available sky each month.

Figure 5 shows a diagram of the LINEAR system as it exists at the ETS today. The core of the LINEAR detection system has not changed significantly in recent years, and thus is quickly summarized here. Five frames of data corresponding to the same part of the sky are collected by a LINEAR telescope at approximately thirty-minute intervals (to give the asteroid motion enough time to become apparent between successive frames). The frames are aligned and registered, and then background noise is suppressed via a fixed threshold. The resulting binary quantized data are further processed for candidate streaks, and the velocities and astrometric positions of these streaks are determined. Objects moving faster than 0.5° per day and objects with an unusual motion, as determined by their rate and direction of motion as a func-

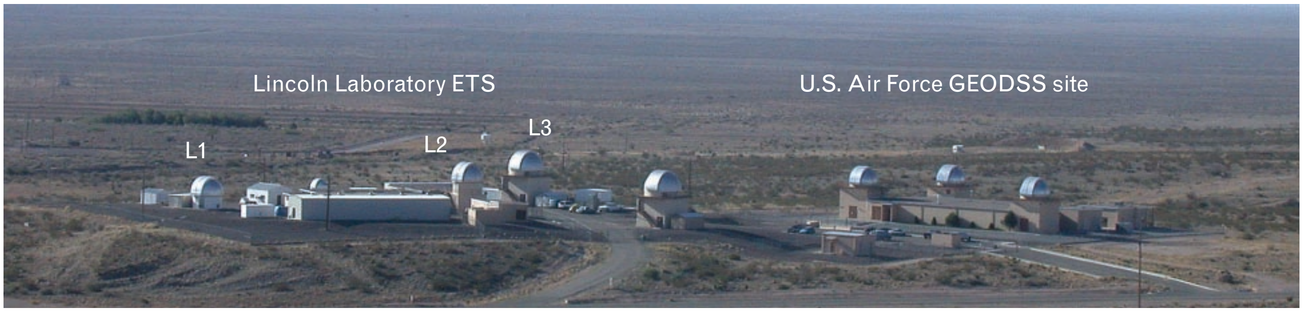


FIGURE 3. The ETS at White Sands Missile Range, near Socorro, New Mexico, adjacent to the U.S. Air Force GEODSS site. The LINEAR program operates two search telescopes, called L1 and L2, and one follow-up telescope, called L3.

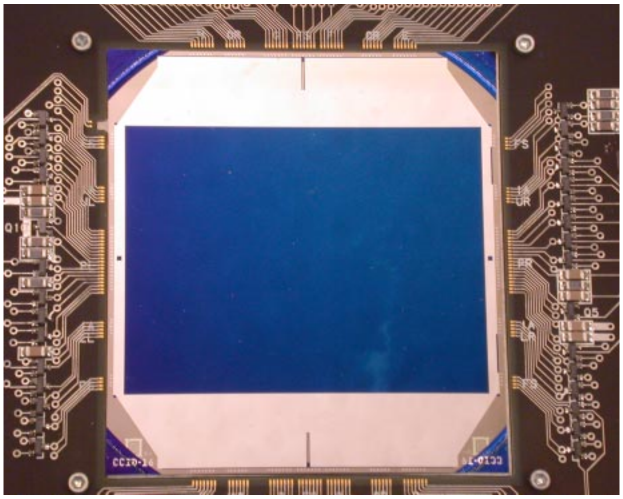


FIGURE 4. The charge-coupled device (CCD) developed by Lincoln Laboratory is a large-format, back-illuminated, low-noise, high-quantum-efficiency, fast frame-transfer device.

tion of their location in the sky, are flagged as potential NEAs [18]; these are visually confirmed by observers and are deemed *interesting*. All remaining objects are more likely to be main-belt asteroids; these are too numerous to be confirmed visually and are deemed *uninteresting*.

After comparison to a star catalog for position and magnitude information, all observations for both interesting and uninteresting moving objects are sent to the Minor Planet Center (MPC) at the Harvard-Smithsonian Center for Astrophysics, in Cambridge, Massachusetts, where both sets of data are used for locating potential NEAs or for updating known asteroid positions. The MPC acts as the central repository charted by the International Astronomical Union to collect and publish all observations of asteroids [19]. In addition, the MPC maintains the catalogue of known minor planets (the formal name for asteroids), and issues formal notification of new discoveries. The two object categories—interesting and uninteresting—allow the MPC to prioritize their data processing so that potential NEAs receive appropriate attention in a timely manner. On a long dark winter night, LINEAR typically detects 10,000 to 12,000 moving objects (mostly main-belt objects) and sends the resulting 50,000 to 60,000 observations (one for each frame) to the MPC. Perhaps half of these objects represent previously uncataloged bodies.

Recent Improvements

The performance of LINEAR has been considerably improved since 1998, when a previous article on

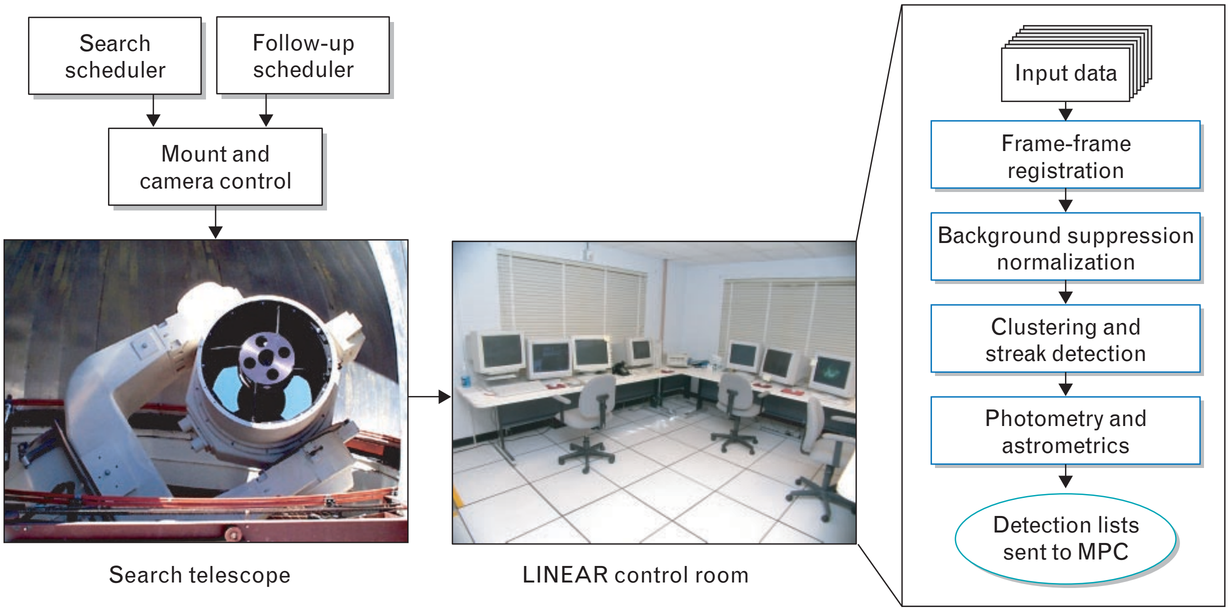


FIGURE 5. The LINEAR detection and processing system at the ETS. Each lunation LINEAR searches the entire 15,000 to 18,000 square degrees of unique sky available to it. The automated telescope and data acquisition system receives input from schedulers, collects five frames of data, processes the data, and sends output detection lists to the Minor Planet Center (MPC) at the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts, where the data are collected and cataloged.

LINEAR appeared in the *Lincoln Laboratory Journal* [14]. Five system improvements are responsible for most of the enhancements in the number of detections. These improvements, in chronological order, are (1) the unbinning of pixels read from the CCD, (2) the addition and continued improvement of a search scheduling system, (3) the advent of a follow-up scheduler, (4) the addition of a second search telescope to the system, and (5) the development of more finely tuned detection algorithms.

The first of these system changes occurred in June 1999. Prior to that date, all data were collected in a 2 × 2 binned mode in order to save a factor of four in data processing, even though this mode incurs a detection loss by mixing background noise from a larger area of the sky with the signal. After a data-processing hardware upgrade, it became feasible to use an unbinned mode for data collection. The result of this change is an improvement in sensitivity of almost one visual magnitude.

The search scheduler and follow-up scheduler, indicated in Figure 5, were the second and third notable improvements to LINEAR. The search scheduler algorithm translates a description of the area of sky to be searched into a sequence of right-ascension and declination field center positions that can then be acquired in an automated manner by the telescope and data-acquisition systems. The search area is described in terms of degrees from opposition (i.e., the point opposite from the sun), and northern and southern limits. The pattern then automatically minimizes telescope step and settle times, and also efficiently orders the fields to account for the rotation of the earth throughout the course of a night.

The follow-up scheduler performs a similar task by using the predicted right-ascension and declination positions of previously detected, unidentified, interesting moving objects and MPC-determined NEA candidates as the input. Since LINEAR on a good observing night finds many more NEA candidates than can be posted by the MPC on the web (via the NEA confirmation page) for follow-up by others in the astronomical community, LINEAR itself must take some responsibility for following up the potential NEA objects it discovers. An orbit predictor estimates the right-ascension and declination positions of each follow-up object for the approximate time when the follow-up observing will be done. Next, the predicted positions of the NEA candidates on the MPC confirmation page are automatically downloaded. The interesting objects and NEA candidates are combined and follow-up observations of these positions are scheduled, on the basis of their locations in the sky, to minimize telescope motion. An output file is created and fed directly into the telescope control software.

Objects from the follow-up scheduler take precedence over the search scheduler when search telescopes are employed for follow-up operations. Historically, follow-up has been done by the LINEAR search telescopes, which takes time away from search operations. Recently, a third telescope dedicated to follow-up efforts has started operations for LINEAR, as discussed in the sidebar entitled “Search versus Follow-Up: The LINEAR 3 Story.”

Figure 6 shows a histogram of the amount of data collected and the amount of sky searched from March 1998 through September 2003. In May and October 1999, the large relative increase in square degrees of data collected was due to tests of the second LINEAR telescope, called L2, which entered routine operations in February 2000. This second LINEAR search telescope represents the fourth major system improvement in the search capability of LINEAR. Approximately 600 to 700 fields of data are collected per night (1200 to 1400 square degrees) with each telescope, with up to 45,000 square degrees of data per lunation. Since some portions of the sky near opposition are covered more than once during a single month, this search strategy yields about 15,000 to 18,000 square degrees of unique sky visited during each month.

The fifth significant system enhancement is in the image processing algorithms, which have improved incrementally over the years. Some of the improvements are due to increased computing power, and others are due to improved understanding of the system characteristics and noises. An example of a processor-driven modification is that the processor-intensive plate modeling is now performed on all five input data frames, and not on just the first frame in a five-frame set. This processing upgrade allows for de-

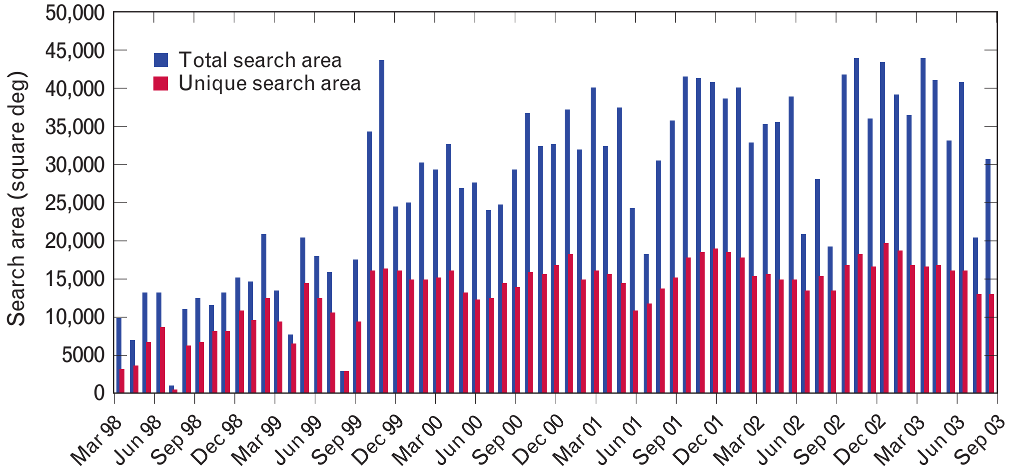


FIGURE 6. The amount of data collected and the amount of sky searched from March 1998 through September 2003. Seasonal variations in the data are clearly apparent. The large relative increase in data collected in May and October 1999 was due to testing of the second LINEAR telescope, which entered routine operations in February 2000.

tections in frame sets in which the first one or two frames of the night may be unusable because of clouds or arcs of light from the moon.

Improvements in sensitivity resulting from learned system characteristics include establishing eight constant false-alarm-rate thresholds, corresponding to the eight channels of the imager, and setting these thresholds as a function of object velocity. The resulting lower false-alarm rate allows the detection threshold to be lowered, thereby increasing overall system sensitivity while maintaining the same probability of false alarm.

LINEAR Observing Strategy

Much of the initial development effort dedicated to LINEAR was focused on constructing an automated detection system that could cover a large amount of sky with good sensitivity for detecting asteroids. Once that goal was largely accomplished, the focus shifted to developing a search pattern that resulted in the best productivity over the period of a lunation (i.e., one cycle of the moon's phase). When full, or nearly so, the moon is a large contributor to the sky background noise during observations. During the bright phase of the moon, high-sensitivity observations are not possible, and the best results are obtained far from the sky position of the moon.

Early in the monthly observing cycle, the moon is still bright during much of the night; images are thus collected well away from the ecliptic to avoid the moon. As the month progresses toward new moon, the search shifts closer to the ecliptic, the part of the sky where the solar phase angle is optimal and asteroids appear at their brightest.

Figure 7 illustrates the sky coverage typically achieved by LINEAR. Normally the best search experience is during the fall and winter months, when the nights are long and the sky is clear. Figure 7(a) shows typical coverage during a fall or winter month. The oval graph represents the entire sky as seen from the earth. Only about half of the sky is available for search in a given month; the rest is above the horizon only when the sun is up. During the spring and summer time, shown in Figure 7(b), the nights are not as long, the weather is less conducive to clear skies, and the galactic plane (the Milky Way) is above the horizon. The Milky Way contains a much larger background of stars, which increases the sky brightness, thus making it harder to detect asteroids. The areas containing the Milky Way are shown by the darker colors in Figure 7(b).

Figure 7(c) displays the composite coverage of the LINEAR system during the year 2002. These plots have been scaled to show a good-weather, background-corrected, single-frame-equivalent integration time, with the lighter colors displaying increased

SEARCH VERSUS FOLLOW-UP: THE LINEAR 3 STORY

EACH NIGHT, LINEAR observations are sent to the Minor Planet Center (MPC) in Cambridge for processing, and a small fraction of the objects are identified for posting on the MPC confirmation page accessible via the web. The posted objects are thought to be likely candidates for near-earth asteroids (NEA), and a worldwide network of amateur and professional astronomers collect observations to improve these objects' orbits. Because of a limited follow-up capacity, only a few dozen of the tens of thousands of objects detected by LINEAR each month are posted on the confirmation page.

Therefore, as many as a hundred interesting objects, and perhaps thousands of main-belt objects discovered by LINEAR in a good observing night, are left to chance follow-up. In addition, objects not posted to the confirmation page require a second night's observations linked to the first night's to obtain discovery credit in the form of provisional designation. Thus LINEAR is left with a quandary as to how to handle the potentially interesting objects it discovers. Some of these objects are unrecognized NEAs, but without a second night's data they are not credited to LINEAR. On the other hand, using the unique LINEAR search telescope to conduct directed follow-up is a poor use of these resources, since follow-up operations reduce the time available for searching new sky.

In the past, a compromise was reached whereby between 10% to 20% of LINEAR telescope time was devoted to directed follow-up of potentially interesting objects not initially posted to the confirmation page. These operations have been responsible for a number of credited discoveries, and over time we have gotten better at choosing the objects for follow-up, based on their motion relative to main-belt objects. Figure A shows an example of a scatter plot that is used to identify potentially interesting objects from thousands of main-belt detections. However, many potentially interesting objects are left to serendipitous follow-up during standard search operations.

Over the past year, LINEAR has begun operations of a new telescope system dedicated to automated follow-up of objects discovered by the LINEAR search telescope, thus allowing a greater percentage of the potentially interesting objects to be addressed.

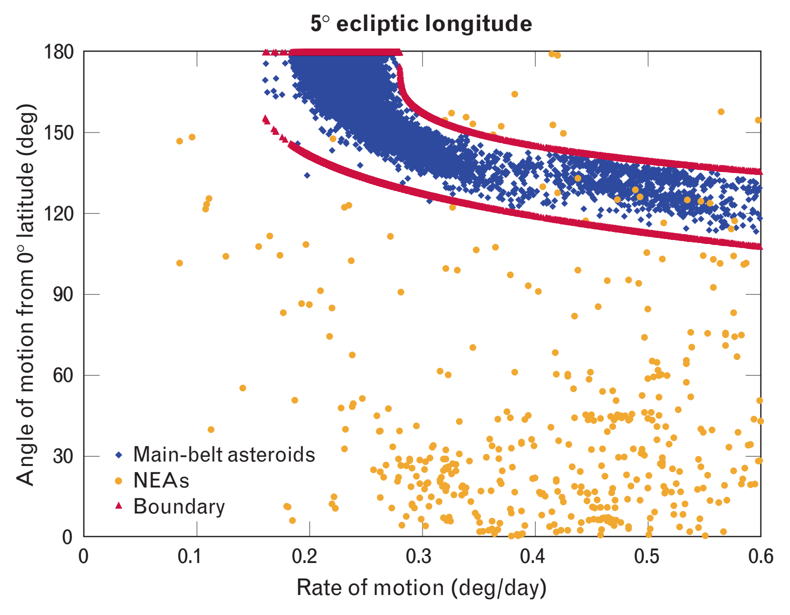


FIGURE A. A sample scatter plot showing the rate of motion versus angle of motion expected of various main-belt asteroid families as well as interesting out-of-boundary objects such as potential near-earth asteroids (NEA) that deserve a second look. More than a dozen similar plots are used by LINEAR, with each plot pertaining to a specific part of the sky (e.g., 5° ecliptic longitude).

Figure B shows this telescope system, called LINEAR 3, or L3 for short. It enhances the amount of sky that LINEAR can search by 10% to 20%, and captures second-night data on 100 to 200 objects each night.

The L3 system consists of a 30-inch telescope with a 1024 × 1024 Lincoln Laboratory CCD sensor in a camera system similar to the one in the Moron Optical Space Surveillance satellite tracking system. This camera was used in the LINEAR pre-prototype in 1996 and 1997. The L3 system searches the sky at one-fifth the rate of the other LINEAR systems, but it has a field of view large enough to find multiple follow-up objects in a single field.

A month after L3's inaugural operations, the system proved its worth by gathering second-night data on two asteroids, both of which were determined to be NEAs but were not initially posted to the confirmation page. In fact, both objects turned out to be potentially hazardous asteroids, and one, 2001 NT7, precipitated considerable press interest when an announcement was made (since retracted) of a potential collision with the earth, predicted for 1 February 2019.

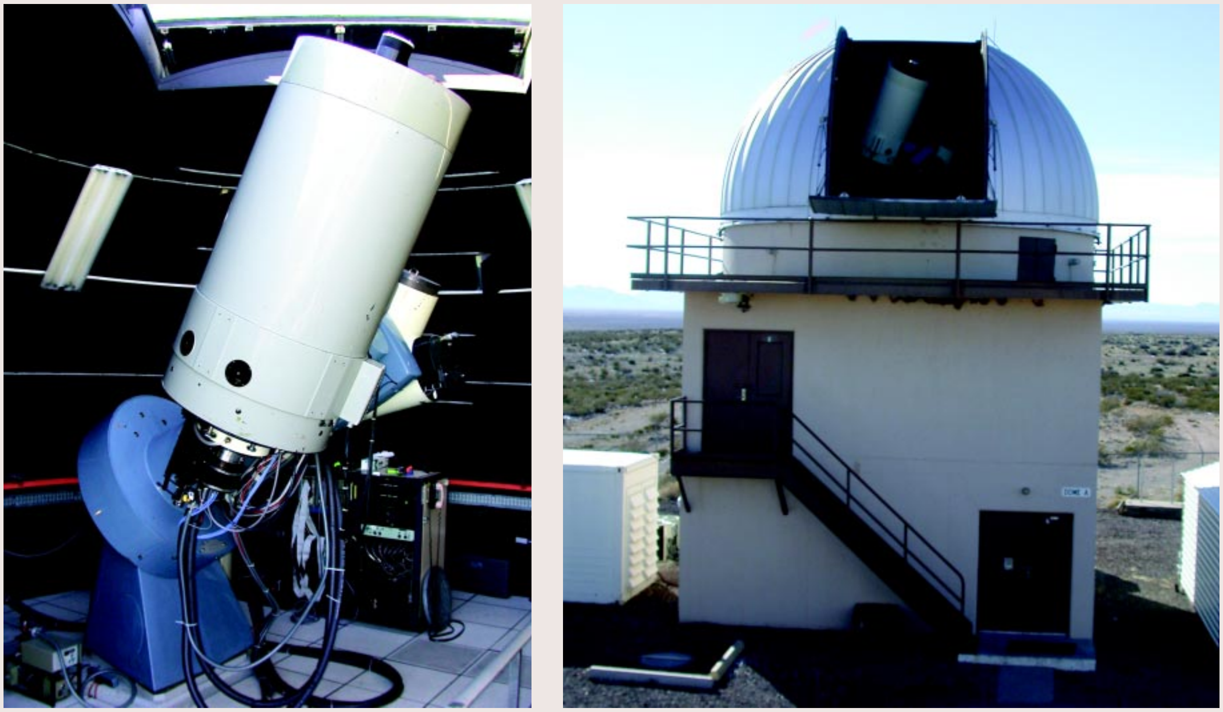


FIGURE B. The LINEAR 3 telescope and its dome at the Lincoln Laboratory–operated Experimental Test System in New Mexico. It is a Cassegrain telescope with a thirty-inch aperture and a 0.5 square-degree field of view. It can routinely detect objects with a visual magnitude of 19.0 with forty seconds of integration. (Photographs courtesy of Peter Trujillo.)

performance. Note that the LINEAR system is covering nearly the entire sky visible above our site's effective southern declination limit of –35°, although some of those areas are being covered at shorter integration times and to shallower depths than others. The longest and deepest searches are concentrated along the ecliptic.

LINEAR Search Results

Table 1 summarizes the productivity results of the LINEAR search system, showing the number of LINEAR observations from 1997 through 2003. The data reported include the number of observations accepted for publication by the MPC, the number of

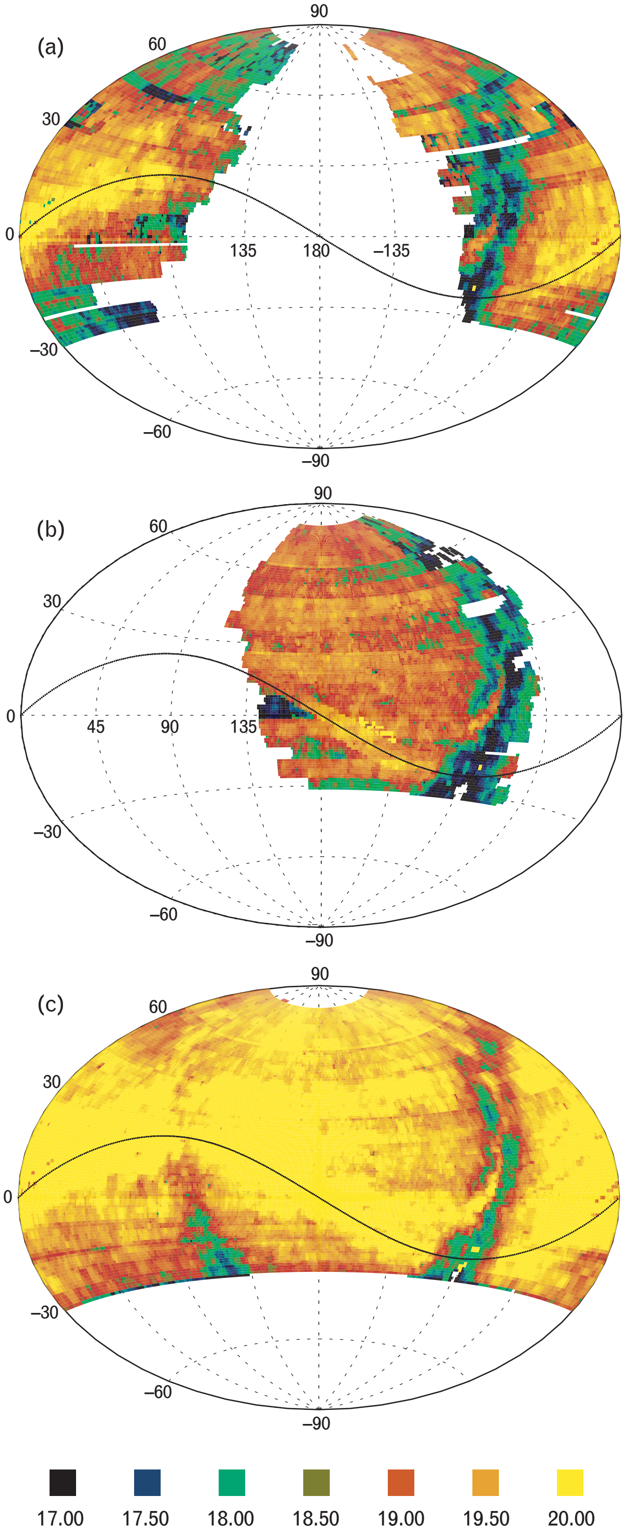


FIGURE 7. The area of sky searched by LINEAR is shown for (a) October 2002, (b) May 2002, and (c) composite coverage from January to December 2002. The depth of search shown is the good-weather, background-corrected, single-frame-equivalent limiting magnitude.

NEAs and comets discovered, and the total number of discoveries credited to LINEAR, including main-belt asteroids and other miscellaneous asteroid classes. The total database of observations published by the MPC was 21,002,723 observations at the end of 2003. Thus LINEAR in five years of operations has contributed over half of the total number of asteroid observations worldwide.

Figure 8 puts these numbers in perspective by illustrating the population of asteroids in the solar system interior to Jupiter. Main-belt asteroids are shown in yellow, NEAs are in red, comets are blue squares, and Jupiter trojans are blue dots (trojans are resonant asteroids approximately ±60° from the major planet). In addition to its discovery of nearly 200,000 asteroids, LINEAR has also discovered more than a hundred comets, which makes it the most prolific ground-based discoverer of comets as well. The appendix, entitled "Contribution of LINEAR to Comet Science," discusses some of the ways LINEAR has fundamentally advanced the study of comets.

Table 2 summarizes the percentage of worldwide asteroid discoveries made by LINEAR. Potentially hazardous asteroids (PHA) are NEAs whose size and potentially close approach to the earth make them the most threatening objects in the NEA population (the list of PHAs is maintained by the MPC). As previously noted, LINEAR currently accounts for nearly 65% of all NEA and PHA discoveries made during the five years of operation from March 1998 through 2003. Overall, LINEAR accounts for 53% of all NEA and PHA discoveries ever made, dating back to the first discovery over a hundred years ago.

Responding to a Congressional mandate in 1998, NASA set a goal of discovering, by 2008, 90% of all NEAs larger than one kilometer. At the time the goal was set, there were 223 known large NEAs, and the estimated number of large NEAs ranged from 500 to 2200 [10, 20]. Since that time another 468 large NEAs have been discovered—323 of them by LINEAR—bringing the total to 691. In addition to increasing the discovery rate of NEAs, LINEAR has provided significant quantities of search statistics and sky coverage information. This information has been used to improve the population estimate of large asteroids [11, 12]. Figure 9 illustrates the discovery rate

Table 1. LINEAR Observations and Discoveries

	Observations	*NEAs*	*Comets*	*Discoveries*
Pre-1998	69,092	18	0	2135
1998	553,518	135	16	18,268
1999	1,056,684	161	22	29,207
2000	2,016,162	258	17	52,642
2001	2,992,192	277	19	48,226
2002	2,914,715	286	26	31,636
2003	2,431,489	235	25	15,048*
Total	12,033,852	1370	125	197,107

* statistics not yet available

of large NEAs during the last thirty years for both LINEAR and the rest of the world. The figure also shows the current estimate of the number of large NEAs—about 1090 ± 180, which indicates the relatively small range of uncertainty in characterizing the population of large asteroids.

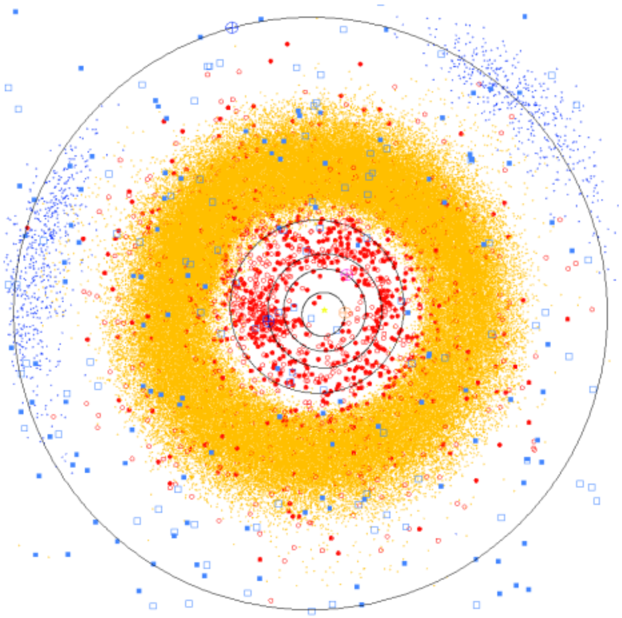


FIGURE 8. The asteroid population of the solar system interior to the orbit of Jupiter. Main-belt asteroids between Mars and Jupiter are shown in yellow, near-earth asteroids (NEA) are shown in red, comets are shown as blue squares, and Jupiter trojans are shown as clusters of blue dots. (Image courtesy of the Minor Planet Center.)

Interesting Discoveries

Not surprisingly, LINEAR's discoveries of nearly 200,000 asteroids and comets include some interesting and unique objects. The most notable discovery is a new class of inner-earth-orbit asteroids in February 2003; that is, an asteroid—2003 CP20—whose orbit is entirely interior to the earth's orbit. The existence of such objects had been theorized for years, but not proven until the discovery of 2003 CP20. LINEAR has also discovered two objects in resonance with the earth, both with unique horseshoe-type orbits, designated 2000 PH5 and 2002 AA29. While 2000 PH5 will maintain its horseshoe-type appearance only through the year 2006, 2002 AA29 will likely be the earth's companion for at least another hundred years.

In January 2000, LINEAR discovered a sun-grazing asteroid—2000 BD19—with the closest known approach to the sun. Even though no cometary activity has been spotted, some astronomers suggest that 2000 BD19 is an extinct comet. In November 2003 LINEAR discovered an object—2003 WT42—with the largest known aphelion (distance away from the sun). LINEAR also discovered the first-known retrograde asteroid in June 1999, which is now numbered and named (20461) Dioretsa. A week later a second retrograde asteroid was found, and a year later a third was found. LINEAR is credited with discovering four of the six known retrograde objects.

THE CERES CONNECTION: NAMING ASTEROIDS IN HONOR OF EXCELLENCE IN SCIENCE

UNDER THE RULES of the International Astronomical Union, the discoverer of an asteroid eventually obtains the right to suggest a name for it. In order for an asteroid to be formally numbered, and thus eligible for naming, its orbit must be well determined so that the asteroid will not be lost in the future. Developing a good orbit normally takes a few apparitions, or perhaps five years for a main-belt object. LINEAR has been observing continually since March 1998 and has accrued discovery credit for nearly 200,000 objects, of which more than 30,000 of them have been numbered and are available to be named. Each month several hundred more LINEAR discoveries are numbered, thus continuously adding to the total.

By 2001, LINEAR had accrued enough naming rights to precipitate serious thought on how to employ these rights to greatest benefit. Because the International Astronomical Union forbids the use of naming rights for financial gain, operating the search by selling names is not an option. LINEAR is discovering so many asteroids that the team felt an obligation to avoid devaluing the honor of an asteroid name.

After careful consideration, it was decided that the highest and best use of the honor of naming an asteroid was to invest it in promoting science education in the international community. We decided to name LINEAR-discovered asteroids in honor of junior high school and high school students who have demonstrated excellence in select science competitions. The name chosen for the asteroid-naming program is the Ceres Connection, since Ceres was the first minor planet, discovered by Italian astronomer Giuseppe Piazzi in 1801. The Ceres Connection program fits in well with the objectives of Lincoln Laboratory and MIT, and with the educational outreach objectives of NASA.

The Ceres connection was developed in cooperation with Science Service, Inc., an organizer and administrator of several national and international competitions. It was inaugurated on 23 October 2001, with an awards presentation in Washington, D.C., to the forty finalists and their teachers in the Discovery Science Challenge Competition. Each student and each teacher received a certificate denoting an officially numbered minor planet

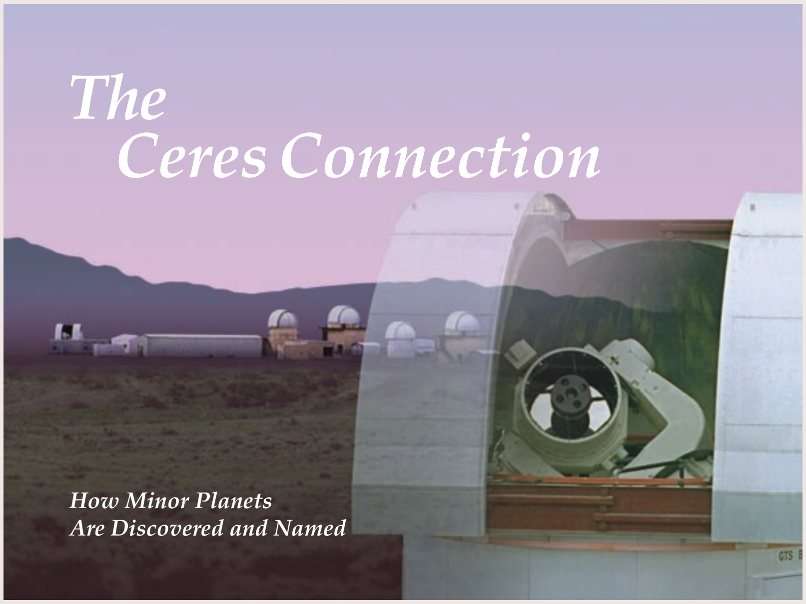


FIGURE A. An educational brochure is given to each honoree to describe the honor and explain the art and history of discovering asteroids.

named in their honor, along with explanatory material, as shown in Figure A. The minor planet name is either their last name or, if an asteroid was already named using their name or a similar sounding name, a name is derived from a combination of their first and last names.

During the 2001/2002 academic year, the Ceres Connection awarded additional naming honors to the forty finalists and their teachers in the Intel Science Talent Search, and to 105 student winners at the International Sciences Fair held in Louisville, Kentucky.

In addition to rewarding the specific achievements of these students, the Ceres Connection is intended to promote interest in science education in the broader community by popularizing science. Since the inauguration of the Ceres Connection in October 2001, a total of 828 top-ranking science students and teachers have returned to the classroom with the message that excellence in science can result in a part of the solar system being officially named in their honor.

Besides discovering asteroids with unique orbits, LINEAR has also found a number of asteroids with unique light curves. Radar observations have shown 1999 KW4 and 2000 DP107 to be binary objects, i.e., a pair of asteroids orbiting each other while orbiting the sun. The first binary asteroid pair was found in 1993 by the Galileo spacecraft, and these two binary objects account for the second and third known pair. Finally, an early LINEAR discovery—(25143) Itokawa—was chosen by the Japanese as the target destination for the Hayabusa mission to an asteroid. A rendezvous is expected in September 2005, with a return of a collected sample expected in late 2007.

The prolific discovery rate of the LINEAR program has enabled another project, entitled the Ceres Connection, whereby Lincoln Laboratory promotes science education worldwide by naming minor planets in honor of successful science students and their teachers and mentors. This award program, which was awarded the 2002 MIT Excellence Award for bettering our community, is described in the sidebar entitled "The Ceres Connection: Naming Asteroids in Honor of Excellence in Science."

LINEAR Search Calibration and Future Evolution

The productivity of LINEAR has been impressive over the past half decade, but further evolution of LINEAR and other asteroid search systems depends on having a better understanding of the most efficient methods of search, and a good quantitative calibration of the capability of the search. To that end, considerable effort is being applied to the following three analysis tasks.

Table 2. Worldwide Discoveries of Asteroids

	March 1998 to December 2003		*Total Known*	
	LINEAR/Total	*Percentage*	*LINEAR/Total*	*Percentage*
NEAs	1352/2146	63%	1370/2606	53%
Large NEAs	320/468	69%	323/691	47%
PHAs	271/418	65%	274/529	52%
Atens	126/175	72%	126/203	62%
Apollos	648/974	67%	659/1230	54%
Amors	581/996	59%	588/1173	50%

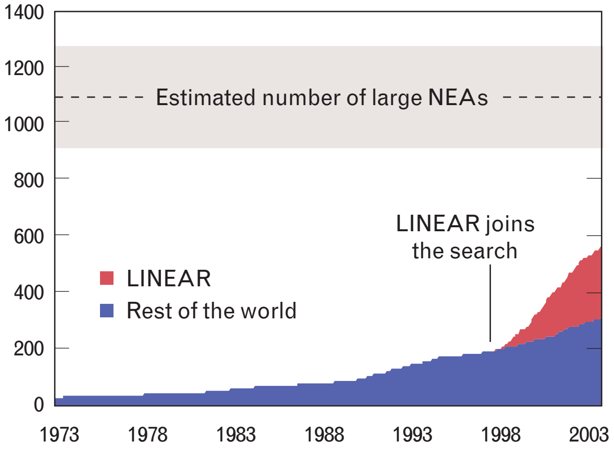


FIGURE 9. The cumulative number of large NEAs is estimated to be 1090 ± 180. The NASA goal of discovering 90% of the large objects by 2008 received a significant boost when LINEAR joined the worldwide asteroid search in 1998. The discoveries of asteroids in the past three decades by other institutions around the world are shown in blue; the recent discoveries by LINEAR are shown in red.

Search Experience Database. The first task is to maintain detailed search experience information for LINEAR. This information will give a better understanding of how LINEAR functions, and it will allow comparison of LINEAR with other asteroid searches. This task has been accomplished by defining a database containing look-by-look standard measures of the seeing and sensitivity achieved by each telescope as determined from star measurements.

Search Strategy Analysis. The second task is to develop a detailed understanding of the most effective strategies to search for asteroids one kilometer in diameter and larger. It is necessary to decide how to distribute observation efforts across the sky for optimal productivity. This task was initially approached by plotting the LINEAR detections of all NEAs and all large NEAs (absolute magnitude less than 18.0), relative to the opposition in ecliptic coordinates. Only the first detection during a lunation was included; detections resulting from directed follow-up activities were excluded. Figure 10 shows the results of these plots, which indicate that LINEAR detects asteroids at all declinations, and that for large objects such as those shown in Figure 10(a) the distribution is somewhat uniform. This suggests an all-sky survey is an appropriate strategy. Figure 10(b) shows all NEAs, displaying a detection bias toward ecliptic opposition due to smaller objects that are more likely to require optimal phase angles to be detectable. If future search systems can achieve a limiting magnitude performance substantially better than LINEAR, or if the primary goal of the survey changes, then the question of observation strategy should be revisited.

Search Capability Quantification. The third task is to develop a measure of search capacity that enables a systematic approach to evaluating the capability of the search. The driving metric for a search effort is the volume of space searched. This volume may be calculated by calibrating, on a field-by-field basis, the depth of the search for the detection of an 18th absolute magnitude 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.

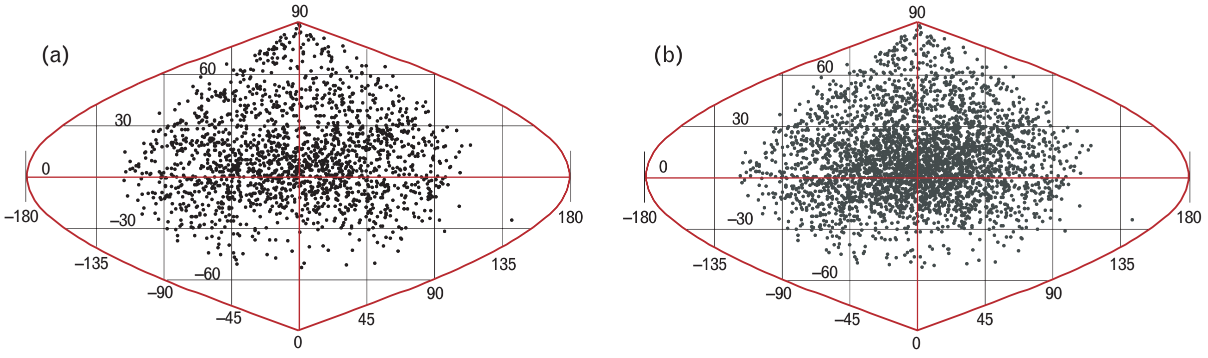
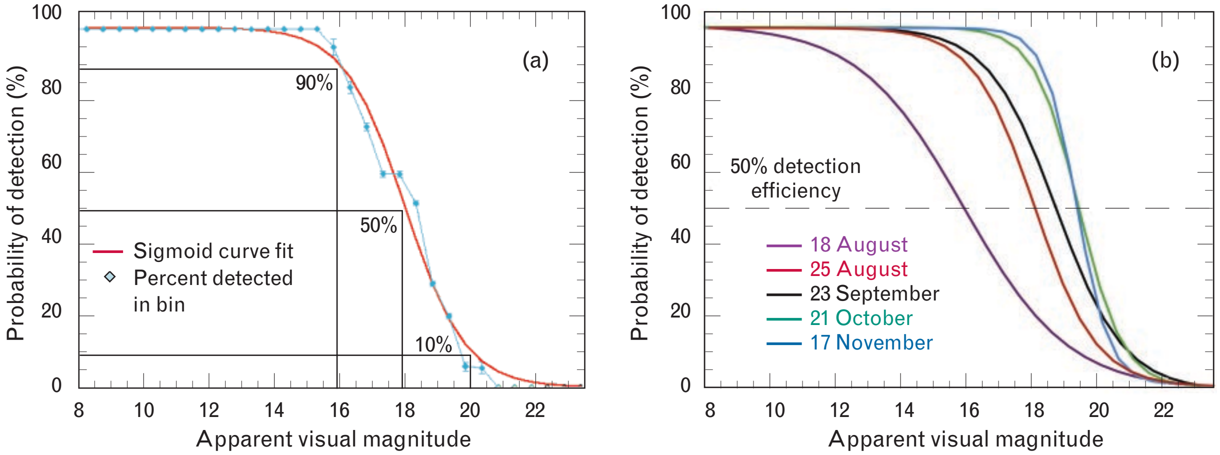


FIGURE 10. The location of NEA detections with respect to ecliptic opposition; (a) NEAs with absolute magnitude less than 18, (b) all NEAs. The plots show only the first detection per lunation for a single NEA, and detections made only during search mode. These data show that LINEAR detects large asteroids at all declinations, which suggests an all-sky search strategy is appropriate.



Date	*Objects detected*	*Declination searched*	*Weather comments*
18 August	2634	–4° to +4°	Haze early, developing into full clouds
25 August	4302	+7° to +14°	Occasional scattered clouds all night, haze by morning
23 September	5449	+0° to +6°	Scattered clouds with occasional haze
21 October	9634	+0° to +6°	Mostly clear with some high clouds
17 November	7771	+11° to +18°	Scattered clouds

FIGURE 11. The probability of detection for an asteroid search system decreases as the apparent magnitude of the objects becomes fainter. The limiting magnitude of the system can be estimated from the curve describing this relationship. (a) Detection efficiency curve for a single night of observing in 2001, including the bin-by-bin measured detection rates and the sigmoidal curve fit that models the detection efficiency. (b) Detection efficiency curves for multiple nights observing, showing the variation in limiting magnitude due to varying environmental factors.

Achieving reliable field-by-field calibration is complex because of the variable conditions under which the observing is accomplished and the fact that considerable data-dependent processing occurs to detect moving asteroids. 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 thus indistinguishable from stars in any given frame. This process of computing a signal-to-noise ratio to determine a system's sensitivity takes into account many of the factors affecting 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 signal-to-noise ratio as a general indicator of search depth, a large set of data taken near the ecliptic was identified and the detections extracted. Separately, objects in the MPC catalogue that were expected to be in the LINEAR search area with known absolute magnitudes were identified and their magnitudes corrected for distance and illumination geometry to generate apparent visual magnitudes. With these two inputs—the list of detections and the list of known objects—a field-by-field calibration of the search system's ability to detect asteroids could be determined by plotting the percentage of known objects detected as a function of apparent visual magnitude.

Figure 11 shows examples of such plots. Figure 11(a) shows the measured data and a sigmoidal fit for a single night in 2001, resulting in a single detection efficiency curve. Figure 11(b) shows the variation of the detection efficiency for five different nights in 2001, with significant differences between clear fall nights and hazy, cloudy summer nights. Unfortunately, this curve-fitting process for determining the detection efficiency breaks down away from the ecliptic plane where there are few to zero detections per

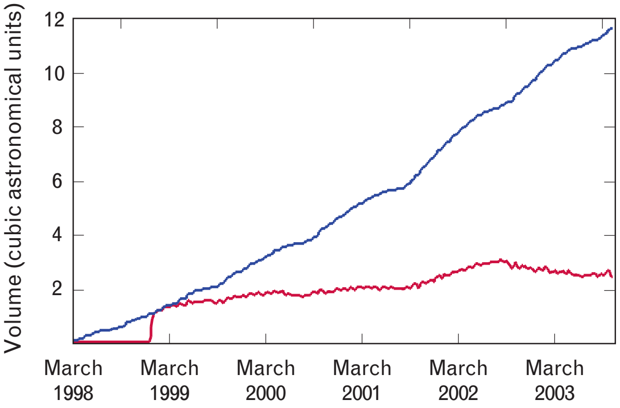


FIGURE 12. The volume searched by LINEAR is determined by multiplying the area of sky searched for each field of view by the depth of the search for that field, where the depth is determined from the limiting magnitude for an object of absolute magnitude 18. The upper line shows the cumulative sky searched; the lower line shows the annual volume searched.

field. However, there are more than sufficient data collected near the ecliptic to use this moving-object calibration process to validate the star signal-to-noise ratio as a measure of the search depth on a frame-by-frame basis. Thus the accumulated search volume can be calculated by using the star signal-to-noise ratio. Figure 12 shows this volume in cubic astronomical units. Changes in slope in the data identify intervals of particularly good or bad weather and the multiple system enhancements.

As the capabilities of a search system evolve, the rate of volume searched should grow. The lower curve in Figure 12 shows a running computation of the volume searched by LINEAR in the preceding year. The search capability of the system evolved rapidly between 1999 and early 2000, leveled off in 2000, and grew dramatically in 2001 and 2002 because of an algorithm enhancement and a hardware fix. In late 2002 and early 2003 the system was adversely affected by mount instabilities that have recently been addressed. As LINEAR evolves and achieves the fundamental inherent capability of the existing telescope/detector/processing system, the variations in the plot in Figure 12 should reflect observing experience (i.e., lunations, weather, equipment failure, and staff availability) rather than system limitations. Thus these variations represent a powerful tool to monitor the operation of the search and to identify problems that may arise.

The Future of Asteroid Search Technology

This article provides an overview of the current LINEAR search system and its recent evolution. What does the future hold for the next generation of asteroid search systems? Because of the exponential march of Moore's law, which has given us highly accurate CCD detectors and a phenomenal increase in processing capacity, there are probably no more factors of two in increased search performance for search systems using existing one-meter telescopes.

In designing the LINEAR system, the Lincoln Laboratory team put considerable effort 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. Given soon-to-be-available detector mosaic sizes, the limitation of asteroid search systems will be aperture size. Historically, the astronomy community built telescopes with increasing aperture but with small fields of view, compared to that needed to search a reasonable fraction of the sky. Sensitivity to characterize extremely faint objects has been the main interest driving the designs of these telescope systems, rather than wide-area search capability. In addition, telescopes with a wide field of view become progressively more difficult and more expensive to build as the aperture size increases. Therefore, few wide-field-of-view telescopes with apertures exceeding one meter currently exist.

The astronomical community, however, is now embracing synoptic astronomy, i.e., viewing large areas of the sky for time-variable phenomena. This interest will most likely drive the next generation of astronomical telescopes to a wider field of view, as evidenced by the proposed Large Synoptic Survey Telescope (LSST) and the Panoramic Survey Telescope and Rapid Response System (PanSTARRS).

In 2003 members of the LINEAR team participated in a special NASA study to address the feasibility of searching for smaller near-earth asteroids upon the completion of the current NASA goal. The NASA Science Definition Team was composed of a dozen top scientists from around the nation representing the various asteroid search and impact hazard specialties. The nine-month study resulted in a report that recommends the next NASA goal should be to eliminate 90% of the impact hazard risk by detecting 90% of all objects larger than 140 meters in diameter [21]. The report also offered a list of technologically feasible asteroid search systems that could accomplish such a goal in a given time period. While the recommended goal is beyond the capability of LINEAR and other current asteroid search systems, it is certainly attainable from space, or from the ground with multiple wide-field-of-view, large-aperture systems. If a new NASA goal is actually stated and later achieved, it is certain that yet another goal will follow—perhaps addressing comets.

Acknowledgments

Many talented people have worked over the years to make LINEAR a world-class NEA detection system. The authors would like to thank the many people at Lincoln Laboratory who contributed to the software, algorithms, and analysis that have helped the system to continue to evolve. In particular we thank Ron Sayer, Scott Stuart, Jeff Kommers, Caroline Klose, Herb Viggh, and Eric Pearce. The authors also thank the people at the Experimental Test System in New Mexico who develop the software, operate and maintain the system, and process the data, including Matt Blythe, Mike Bezpalko, Jeff English, Bob Huber, Julie Johnson, Ray Kracke, Heidi Love, Lisa Manguso, Matt McCleary, Doug Torres, Peter Trujillo, and Tom Ruekgauer. This work was sponsored by the Department of the Air Force and by NASA.

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APPENDIX: CONTRIBUTION OF LINEAR TO COMET SCIENCE

In addition to being the world's most productive asteroid search program, LINEAR has profoundly altered the field of comet science. LINEAR's detection algorithm, based on algorithms used to detect earth-orbiting satellites, is fundamentally a moving-object detector. Any object in motion across the fixed star pattern, within the dynamic range of the algorithm (about 0.1 to 10+ deg/day), is duly recorded. Since these rates of motion are characteristic of comets as they enter the inner solar system, LINEAR has discovered more than a hundred comets, making it the most prolific ground-based discoverer of comets in history. (The space-based Solar and Heliospheric Observatory [SOHO], the most prolific system, has discovered more than five hundred comets, typically shortly before they impact the sun.)

FIGURE 1. The cover of the 18 May 2001 issue of *Science*. The entire issue of this magazine was dedicated to comets, with a special focus on C/1994 S4 LINEAR. (Cover image reprinted with permission of *Science* magazine, copyright 2001, American Association for the Advancement of Science.)

Most of the comets discovered by LINEAR are found on their inbound trajectory, as they pass the orbits of Saturn or Jupiter. At this point, the comet starts to brighten as volatile materials are evolved by solar heating, and the comet becomes detectable by LINEAR. Typically, the LINEAR system at this time does not notice any comet-like trailing feature that would clearly identify the object as cometary. Thus the comet detection observations are routinely passed to the Minor Planet Center (MPC) along with hundreds of thousands of asteroid observations generated each month. At this point, one of two possible actions results in the object being identified as a comet: (1) the orbit of the object is calculated and determined to be comet-like, as opposed to asteroid-like, and the

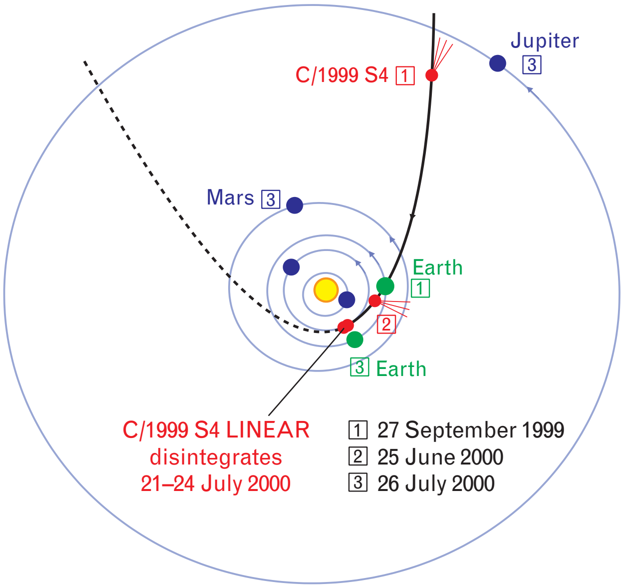

FIGURE 2. The path of comet C/1999 S4 LINEAR through the solar system. It was discovered at point 1 on 27 September 1999, and LINEAR S4 disintegrated from 21 to 24 July 2000 near its closest approach to the earth. The position of the earth is shown as a green circle for the discovery epoch (1) and for the disintegration epoch (3).

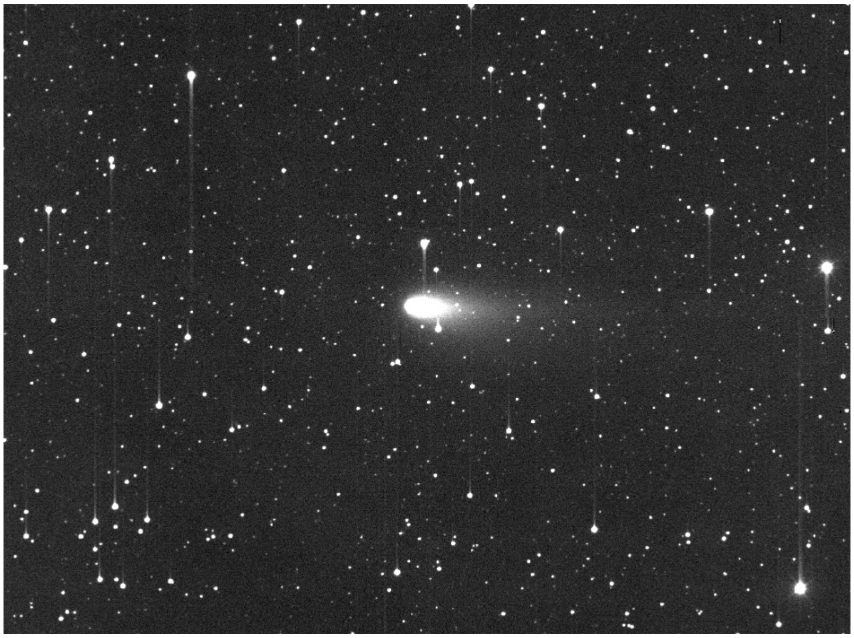

FIGURE 3. An image of comet C/1999 S4 LINEAR taken by one of the LINEAR telescopes on 25 June 2000, showing a characteristic well-developed tail.

MPC requests an observer with a large telescope to check the object for a tail; (2) if the object is posted on the MPC confirmation page because of its interesting rate of motion, a follow-up observer may detect a tail.

This process of comet discovery is fundamentally different from the process prior to LINEAR operations. In the pre-LINEAR era, amateur observers usually discovered comets by scanning regions close to the sun. By the time a comet is near the sun, it has heated up and formed a characteristic tail, which makes it detectable. The amateur method has two deficiencies: (1) only comets that travel close enough to the sun and are active enough to develop a large tail are discovered; (2) the comet is discovered only after it has substantially completed its inbound trajectory. Thus the heating and tail formation process are not observed or recorded.

By finding comets far from the sun, LINEAR helps to solve both these issues. Many comets that never form tails large enough to be visible are discovered, and—more importantly—comets are discovered early in their trajectory. This early detection enables comet scientists to gather observations covering the interval in their orbit where they become active, evolve a tail, and break into pieces. In addition, enough warning is provided to allow time to schedule additional observations by other assets such as the Hubble space telescope and the Keck Observatory.

These observation opportunities have led to some striking discoveries, and have resulted in the dedication of an entire 2001 issue of *Science* magazine to comets, with a special focus on comet C/1999 S4 LINEAR. Figure 1 shows the cover of that issue. The following sections describe a few of the fascinating comets discovered by LINEAR.

Comet C/1999 S4 LINEAR

Figure 2 illustrates the orbit of comet C/1999 S4 LINEAR, which was discovered on 27 September 1999 just inside the orbit of Jupiter. By June 2000, LINEAR S4 had a well-developed tail, as shown in the CCD image in Figure 3, and was expected to be visible to the naked eye at a closer approach to the earth (the dark adapted eye at a dark site is sensitive to objects of 5th to 6th magnitude). In reality, LINEAR S4 peaked with an intensity of about 6.5 in late July (visible through binoculars) and then disintegrated from 21 to 24 July 2000. Due to the long time between discovery of LINEAR S4 and its closest ap-

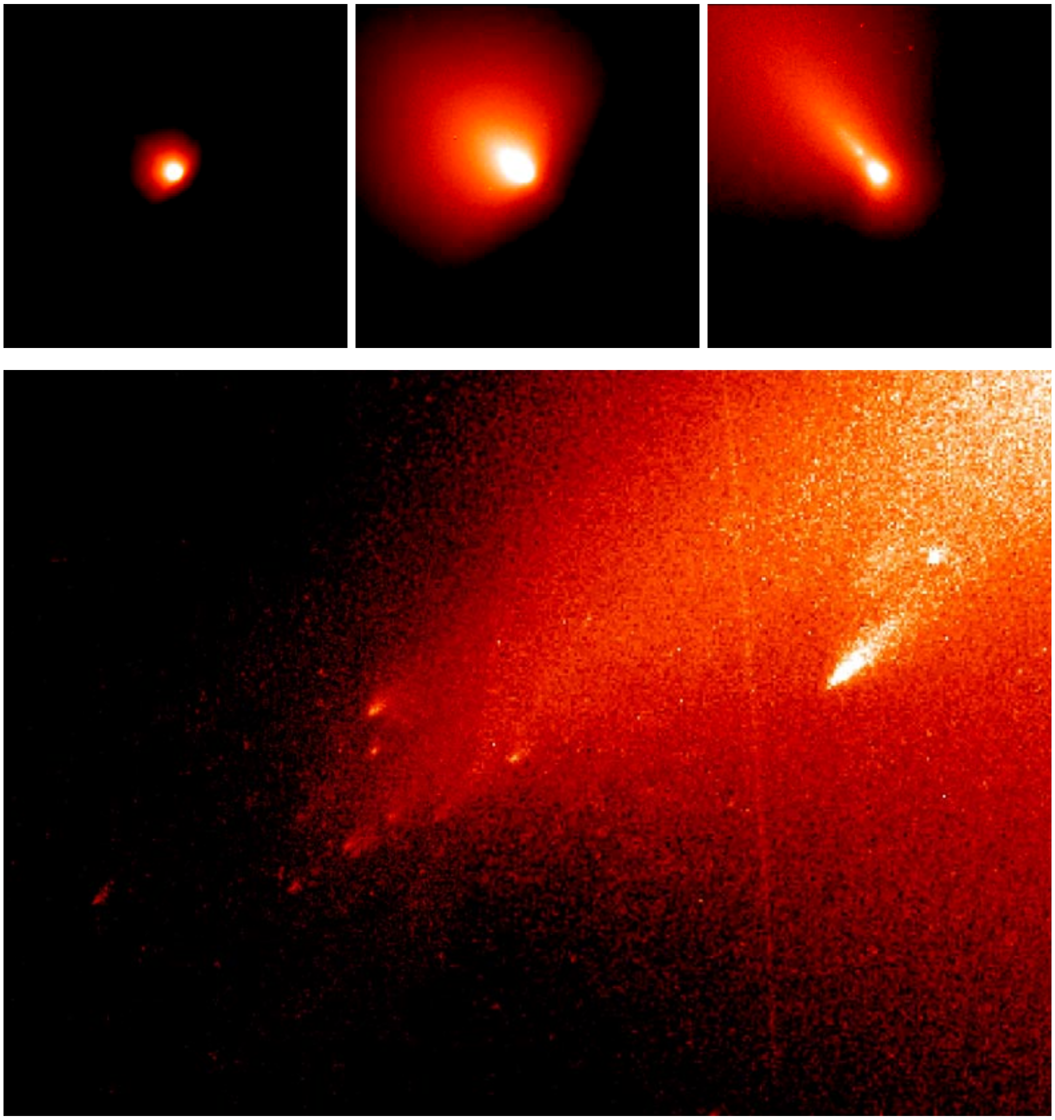

FIGURE 4. (top) Hubble space telescope observations showing C/1999 S4 LINEAR flaring up and beginning to disintegrate in early July 2000. (bottom) Later observations show the cometesimals remaining a couple of days after the breakup of LINEAR S4 on 24 July 2000. (Hubble images courtesy of H.A. Weaver [Johns Hopkins University], NASA, and the Space Telescope Science Institute.)

proach to earth, the Hubble space telescope was scheduled for observations of LINEAR S4 in July 2000 and recorded the comet's activity and residual cometesimals. These images of comet LINEAR S4 provided a wealth of insight into comet evolution and function. Figure 4 displays a sample of Hubble space telescope image data before and after disintegration of the comet.

Comet C/2000 WM1 LINEAR: The Christmas Comet

C/2000 WM1 LINEAR was discovered by LINEAR

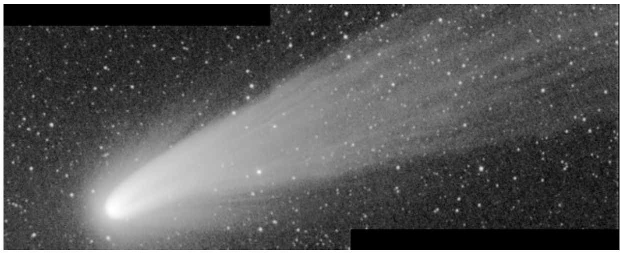

FIGURE 5. Image of the Christmas Comet as it appeared in the southern hemisphere on 30 January 2001. (Image courtesy Terry Lovejoy, Australia.)

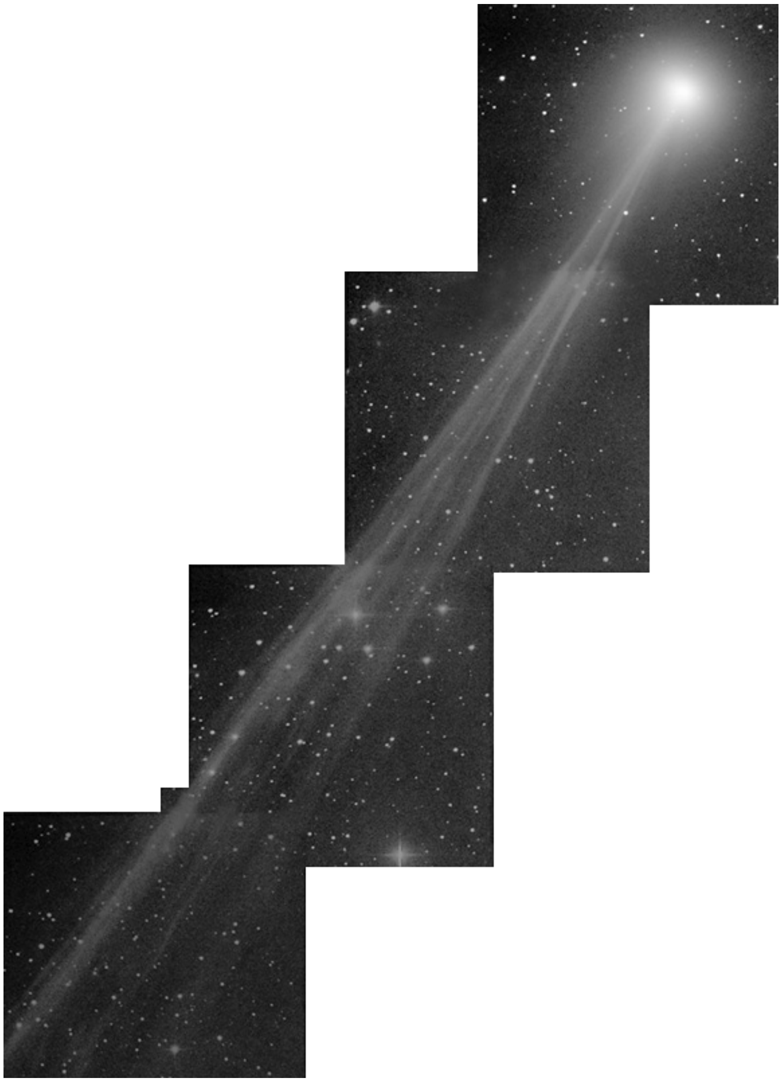

FIGURE 6. Composite picture of comet C/2001 A2 LINEAR, showing a sharp nucleus and a tail containing several streamers. (Copyright images courtesy Gordon Garradd.)

on 16 November 2000 between the orbits of Saturn and Jupiter. This comet is the first truly naked-eye comet discovered by LINEAR. Because it appeared at the end of 2000 it was dubbed the Christmas Comet by the media. It was as bright as 5th magnitude in the northern hemisphere and then dropped below the southern horizon, where it was as bright as 3rd magnitude as seen from Australia. Figure 5 shows an image of the Christmas comet.

Comet C/2001 A2 LINEAR

As mentioned earlier, one of the important contributions of the LINEAR program has been the discovery of comets before they have evolved tails. This early detection allows astronomers to observe the heating phase of the inbound trajectory, which results in data and insight on the behavior of these unique objects. Comet C/2001 A2 LINEAR shown in Figure 6 typifies the erratic behavior of comets. It had many outbursts in brightness—probably associated with a structure change that increased the outgassing of material—and the nucleus has split into several pieces. As characterized by one astronomer, “This comet became the kind of comet astronomers love—truly unpredictable in its behavior.”

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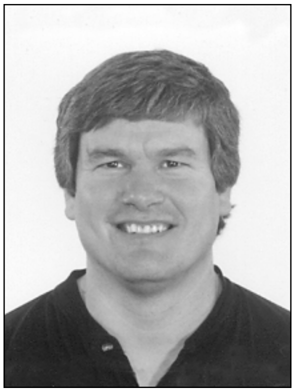
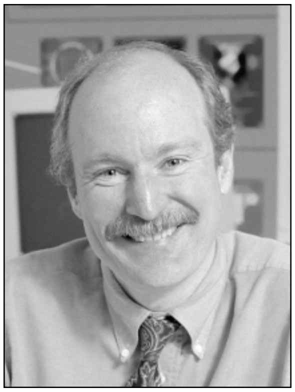


FRANK C. SHELLY
is an associate staff member of the Space Control Systems group, based at the Lincoln Laboratory Experimental Test System near Socorro, New Mexico. He develops image processing software that is used to automatically detect asteroids, comets, and satellites, as well as real-time control software for positioning telescope mounts. He also generates system software for interfaces to custom devices such as weather systems, mount encoders, digital-to-analog converters, CCD cameras, and filter wheels. He helped develop the Transportable Optical System (TOS), which the U.S. Air Force operates in Spain. He wrote most of the LINEAR asteroid detection software, and he continues to be heavily involved in the operations and improvement of the system. He joined Lincoln Laboratory in 1986 after studying computer science at the New Mexico Institute of Mining and Technology in Socorro.



GRANT H. STOKES
is the associate head of the Aerospace division, where he is responsible for the space control mission area at the Laboratory. He specializes in analysis, design, and operations of space surveillance systems, including the Space-Based Visible (SBV) and LINEAR programs. The SBV system provides the first space-based space surveillance capability to Air Force Space Command in Colorado Springs, Colorado. The LINEAR program utilizes space surveillance technology developed for the U.S. Air Force to search for near-earth asteroids. Before coming to Lincoln Laboratory in 1989, he worked as a senior scientist and operations manager at Geo-Centers Inc., a contracting company specializing in fiber-optic sensors. Previously, he performed nondestructive testing of laser fusion targets at Los Alamos National Laboratory in New Mexico, and developed fiber-optic data-acquisition systems and provided field support for underground nuclear tests in Nevada. He has a B.A. degree in physics from Colorado College, and M.A. and Ph.D. degrees in physics from Princeton University.