The Lincoln Near-Earth Asteroid Research (LINEAR) Program

Grant H. Stokes, Frank Shelly, Herbert E.M. Viggh, Matthew S. Blythe, and Joseph S. Stuart

Lincoln Laboratory has been developing electro-optical space-surveillance technology to detect, characterize, and catalog satellites for more than forty years. Recent advances in highly sensitive, large-format charge-coupled devices (CCDs) allow this technology to be applied to detecting and cataloging asteroids, including near-Earth objects (NEOs). When equipped with a new Lincoln Laboratory focal-plane camera and signal processing technology, the 1-m U.S. Air Force ground-based electro-optical deep-space surveillance (GEODSS) telescopes can conduct sensitive large-coverage searches for Earth-crossing and main-belt asteroids. Field measurements indicate that these enhanced telescopes can achieve a limiting magnitude of 22 over a 2-deg^2 field of view with less than 100 sec of integration. This sensitivity rivals that of much larger telescopes equipped with commercial cameras.

Working two years under U.S. Air Force sponsorship, we have developed technology for asteroid search operations at the Lincoln Laboratory Experimental Test Site near Socorro, New Mexico. By using a new large-format 2560 × 1960-pixel frame-transfer CCD camera, we have discovered over 10,000 asteroids, including 53 NEOs and 4 comets as designated by the Minor Planet Center (MPC). In March 1998, the Lincoln Near-Earth Asteroid Research (LINEAR) program provided over 150,000 observations of asteroids—nearly 90% of the world's asteroid observations that month—to the MPC, which resulted in the discovery of 13 NEOs and 1 comet. The MPC indicates that the LINEAR program outperforms all asteroid search programs operated to date.

Asteroids and comets have crashed into Earth since the formation of the solar system. In the late 1980s, scientists established that the impact of a large asteroid or comet on the edge of the Yucatan Peninsula caused the extinction of the dinosaurs [1]. The recent collision of the comet Shoemaker-Levy 9 with Jupiter shows that such massive collisions still occur in our solar system. While such large-scale collisions occur only once in a million years, smaller impacts that cause severe regional destruction happen about once in a hundred years [2]. The presence of many asteroids in orbits that may eventually collide with Earth has generated considerable discussion among the press, scientists, and government agencies about how to estimate the likelihood of such a collision and prevent it from happening. To date, no consensus on the most effective methods for intercepting or otherwise diverting such a collision has emerged; however, there is agreement that the first step toward protecting Earth is to find and catalog all potentially threatening asteroids, and track new comets entering the solar system.

Figure 1 depicts the inner solar system, showing the main asteroid belt between the orbits of Mars and Jupiter. Most asteroids in the main belt have low-eccentricity orbits that will not encounter Earth. Aster-

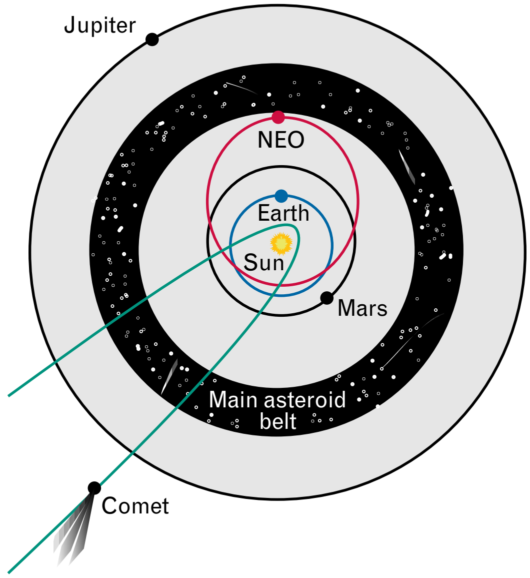


FIGURE 1. Inner solar system showing the orbits of asteroids and comets in the main asteroid belt between Mars and Jupiter (relative orbits drawn to scale). Most asteroids in the main belt have nearly circular orbits and so do not pose a threat to Earth. Asteroids with highly elliptical orbits that cross or approach Earth's orbit are called near-Earth objects (NEOs).

oids with orbits that cross or approach Earth's orbit are one of three types of near-Earth objects (NEOs): Aten, Apollo, and Amor. Aten asteroids typically spend most of their time closer to the Sun than to Earth, crossing Earth's orbit at aphelion, when they are farthest from the Sun. The semimajor axis of an Aten's orbit is less than that of Earth's orbit, which is one astronomical unit (150 million km). Apollo asteroids spend most of their time farther away from the Sun than from Earth, crossing Earth's orbit near perihelion, when they are closest to the Sun. This perihelion distance averages less than the semimajor axis of Earth's orbit. The NEO in Figure 1, therefore, is an Apollo asteroid. Amor asteroids approach Earth's orbit, but their orbits pass inside the semimajor axis of Mars' orbit and do not cross Earth's orbit. Amor asteroids must be closely monitored because they come quite close to Earth's orbit. Comets from the outer solar system can also cross Earth's orbit, often with little warning and at high velocities.

The Spaceguard Survey, a NASA study on NEOs, estimates that 320,000 asteroids exist with diameters greater than 100 m, and of these, 2100 asteroids have diameters greater than 1 km, as shown in Figure 2 [2]. Researchers have cataloged about 10% of asteroids with diameters larger than 1 km, and they know of an even smaller percentage of asteroids with diameters below 1 km. Larger asteroids could cause global damage in an Earth collision. Smaller-diameter asteroids colliding with Earth could cause considerable regional damage, especially in coastal areas because of impact-generated tsunamis. The remaining asteroid population must be detected and cataloged to assess the near-term threat of such objects. As each asteroid is discovered, researchers can calculate its orbit to determine if the asteroid will pass close to Earth.

Historically, the task of discovering asteroids has been expensive and time consuming. The traditional search technique relied on photographic plates and labor-intensive manual detection and measurement of objects. Newer electronic imaging techniques that use charge-coupled devices (CCDs) are faster than photographic surveys because the CCD images are processed with computers and the detection and measurement of objects is automated.

In the early 1980s, Tom Gehrels of the University of Arizona began the Spacewatch survey with a 0.9-m telescope at Kitt Peak Observatory [3]. The survey uses commercial CCDs operated to minimize the data readout and processing load. During a search, the telescope is stationary and the sky drifts past the focal plane of the telescope. The CCD output is read electronically at a rate that matches the star

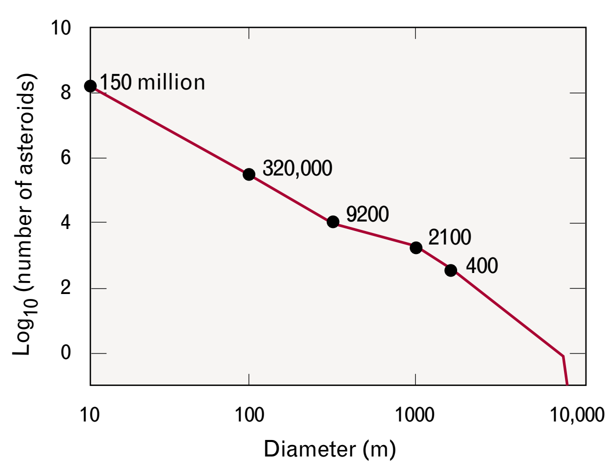


FIGURE 2. Estimated population of Earth-crossing asteroids with diameters above a given size. About 10% of asteroids with diameters larger than 1 km are known.

motion. Multiple passes of the data are then processed on a workstation to find moving objects. This approach was chosen to accommodate the slow data readout rate of the CCD and the computer processing capabilities available at the time. The Spacewatch program has discovered more asteroids than any other search program, finding 164 NEOs, of which 37 are 1 km or larger in size.

Since November 1995, the National Aeronautics and Space Administration (NASA) and the Jet Propulsion Laboratory (JPL) have operated a survey with a telescope from the ground-based electro-optical deep-space surveillance (GEODSS) site on the island of Maui in Hawaii [4]. This survey, called Near-Earth Asteroid Tracking (NEAT), uses a front-illuminated commercial 4096 × 4096-pixel CCD manufactured by Lockheed-Martin-Fairchild. NEAT operates in a step-stare mode that images a portion of the sky while moving the telescope to track the stars. Three images of the same portion of sky are collected over several hours and processed by a workstation to identify moving objects. The NEAT program has discovered 29 NEOs, of which 12 are 1 km or larger in size.

The commercial CCDs and computers typically used by astronomers have limitations that compromise the productivity of an NEO search. First, many of the commercial CCDs are front illuminated, meaning that the incoming photons must penetrate the wiring of the CCD device before being detected. The fraction of incident photons detected, known as the solar-spectrum-weighted quantum efficiency, is limited to about 30% or less. Second, large-format commercial CCDs must be read out slowly to maintain low-noise performance, which reduces search efficiency. Because a single image can take tens of seconds to read out, the CCD integrates photons during only a fraction of its operation time.

The solution to these problems can be found in the CCDs that Lincoln Laboratory designed to track Earth-orbiting satellites. These CCDs are back illuminated for higher quantum efficiencies and have a frame-transfer design that eliminates slow readout. For asteroid search and detection, we estimate that a network of two or three 1-m telescopes equipped with such CCDs could complete a twenty-five-year Spaceguard-type survey in a decade.

Space-Surveillance Technology

Space surveillance involves detecting and tracking Earth-orbiting satellites and space debris, as well as maintaining a catalog of such objects. Lincoln Laboratory has been developing technology for the U.S. Air Force Space-Surveillance Network (SSN) for over forty years. In 1957, for example, the Laboratory tracked Sputnik, the first artificial satellite, by using the Millstone Hill Radar in Westford, Massachusetts. The Laboratory continues to use the Millstone Hill facility to develop and transfer radar and software technology for the SSN.

At the Experimental Test Site (ETS) at White Sands Missile Range near Socorro, New Mexico, Lincoln Laboratory is testing its new generation of sensitive large-format frame-transfer CCD focal planes to upgrade GEODSS. Figure 3 shows the space-surveillance facilities at White Sands Missile Range.

A number of GEODSS sites are deployed worldwide, each currently equipped with 1-m-class telescopes and ebsicon (electron-bombarded silicon) detector systems based on 1970s television technology. The new Lincoln Laboratory focal-plane CCD and camera system provides three benefits: significantly improved sensitivity, which reduces integration times and allows tracking of fainter objects; fast frame-transfer readout, which allows the integration of the next image to be started while the previous image is read out; and stringent blemish specifications, which minimize the loss of detections attributed to focal-plane defects. The improved focal-plane CCDs have been installed in a new generation of camera systems and are currently undergoing testing at the ETS. Figure 4 shows the telescope used for the CCD camera tests and asteroid searches.

The new focal-plane and camera technology gives the 1-m GEODSS telescopes considerable capability to conduct sensitive, large-coverage searches for space-surveillance applications. With some modifications, these capabilities can be extended to searches for Earth-crossing asteroids. Field measurements at ETS with a GEODSS telescope equipped with Lincoln Laboratory's new-generation CCD and camera indicate that the CCD-equipped GEODSS telescope can achieve a limiting magnitude of 22 at a signal-to-

FIGURE 3. Space-surveillance facilities at the White Sands Missile Range near Socorro, New Mexico. The four telescopes near the middle and the far-left telescope with open dome represent Lincoln Laboratory's Experimental Test Site (ETS). The three telescopes on the right represent an operational ground-based electro-optical deep-space surveillance (GEODSS) site.

noise ratio of 4 over a 2-deg^2 field of view in less than a 100-sec integration. This sensitivity compares to that of much larger telescopes equipped with existing cameras. In addition to the high sensitivity, the frame-transfer capability enables the high coverage rates of the sky needed for asteroid search operations.

Detector Technology

The latest-generation Lincoln Laboratory CCD chip features a focal-plane array of 2560 × 1960 pixels and an intrinsic readout noise of only a few electrons per pixel (Figure 5). The CCD chips are constructed by using a back-illumination process, which provides peak quantum efficiency exceeding 90% and solar-spectrum-weighted quantum efficiency of 65%. After an integration is finished, the resulting image is quickly transferred to the frame-store buffers, allowing the active imaging area to conduct the next integration while the image is read from the frame-store buffers. This feature eliminates the need for a mechanical shutter to define the exposure, since the image transfer time from the imaging area into the frame buffer is only several milliseconds. The focal plane is equipped with eight parallel readout ports to allow the five million pixel values to be read out of the frame-store buffers in about 0.2 sec. The Lincoln Laboratory CCDs described above have been constructed specifically to allow large portions of the sky to be searched for faint moving targets. Consequently, they have the best combination of large format and detection performance among current CCDs.

Initial Field Tests

We conducted initial field tests of the new CCD and camera system at ETS in August 1995 and July 1996. We wanted to determine the system's ability to detect asteroids and to meet design specifications for satellite surveillance. The Lincoln Laboratory CCD allows a 1-m GEODSS telescope to achieve impressive limiting-magnitude performance in short integration times. Figure 6 indicates the limiting magnitude achieved as a function of integration time for the Lin-

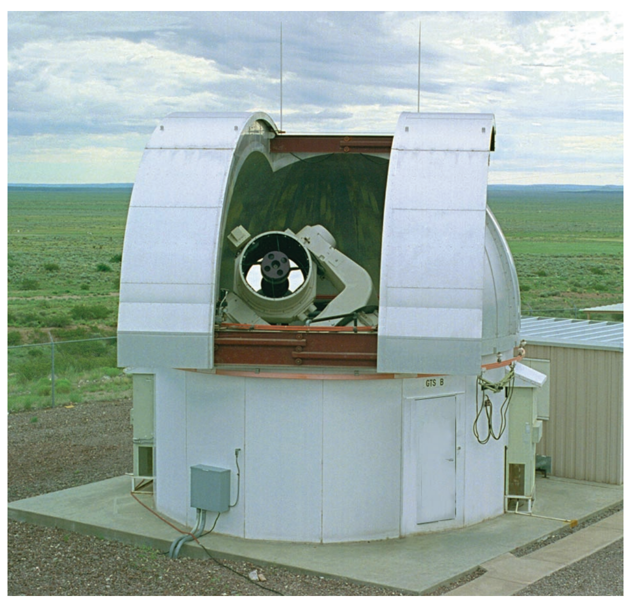


FIGURE 4. ETS telescope used to test the Lincoln Laboratory large-format CCD camera and search for asteroids. The telescope is identical to an operational GEODSS telescope.

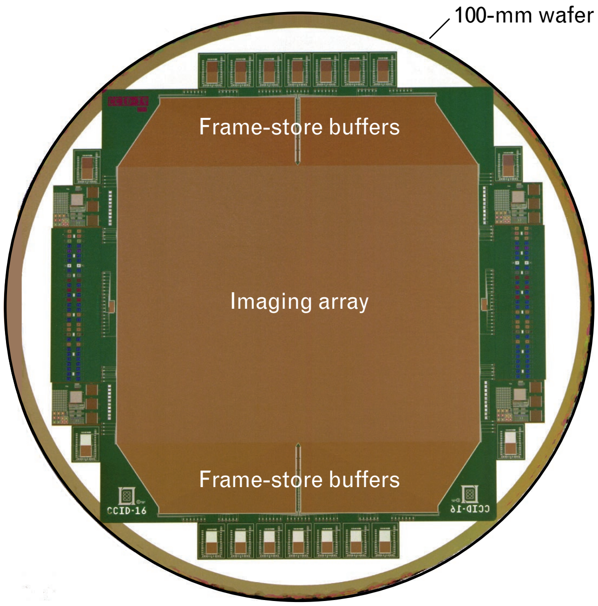


FIGURE 5. Five-million-pixel Lincoln Laboratory CCD chip. This chip is constructed by using a back-illumination process and features a 2560 × 1960-pixel focal-plane array. Four frame-store buffers hold an image after integration, allowing the active imaging array to conduct the next integration while the current image is read from the frame-store buffers.

coln Laboratory CCD compared with the same information estimated for the JPL NEAT system, which employs a commercial CCD [5]. The difference in performance is significant because the observing site for NEAT on Maui generally has better seeing than the ETS site near Socorro.

During the initial tests, a small amount of observing time was dedicated to searching for asteroids. That effort yielded a total of 177 asteroid observations, which were sent to the Minor Planet Center (MPC) in Cambridge, Massachusetts. From these observations, 49 new objects received designations from the MPC, including a confirmed NEO, designated 1996 MQ.

The LINEAR Program

Our initial results were modest in terms of the portion of sky covered and the numbers of asteroids discovered because they were made with a preliminary camera and data system that provided a fraction of the possible discovery rate of a complete operational system with the same CCD technology. Even so, the results convinced the U.S. Air Force that this approach had considerable merit and potential. Consequently, the Lincoln Near-Earth Asteroid Research (LINEAR) program began with funding in early 1997. We designed a new system to boost the search, processing, and discovery capabilities by integrating real-time hard-disk storage, improved signal processing, and automation of data management tasks.

Figure 7 displays the process flow of the LINEAR system at ETS. The input data consist of three to five CCD image frames of the same location of the sky collected at intervals of about thirty minutes. The detection algorithm includes four major steps: image registration, background suppression and normalization, binary quantization, and clustering and velocity-matched filtering. First, image registration corrects any pointing errors between the images by shifting the second through last frames to line up their stellar backgrounds with that of the first image. Next, the LINEAR system normalizes the registered images to remove background noise in the background suppression and normalization block. Estimates of background mean and standard deviation are computed at each pixel, averaging over all the frames. Data are normalized pixel by pixel by using the local background mean and standard deviation. The normalized data are then binary quantized with a simple threshold (currently 99.9%).

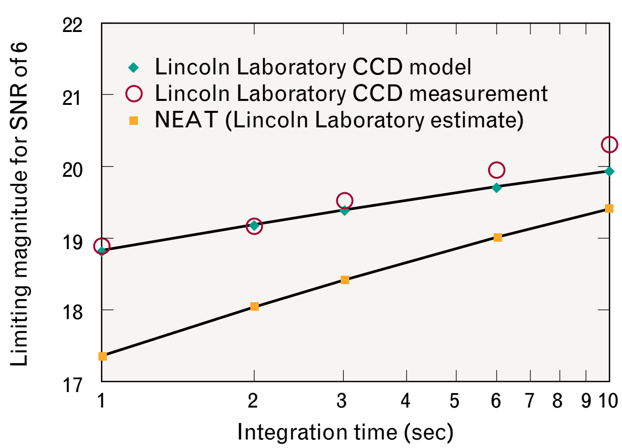


FIGURE 6. Limiting magnitude for a signal-to-noise (SNR) ratio of 6 as a function of integration time for the Lincoln Laboratory CCD and the Near-Earth Asteroid Tracking (NEAT) system. For a specified integration time, the Lincoln Laboratory CCD system detects fainter asteroids having higher magnitudes.

The binary-quantized data are clustered on a frame-by-frame basis to group adjacent pixels. The centroids and extents of these pixel groups, or clusters, are computed. Each cluster in the first image frame is paired with each cluster in the last image frame that falls within a specified radius, selected as an upper limit on asteroid rates of motion. These pairs form the list of candidate detections, or streaks. Each candidate streak is assigned a velocity by dividing the displacement from the beginning to the end of the streak by the time interval that it spans. For each candidate streak, the LINEAR detection algorithm searches intermediate frames for clusters with the appropriate displacement to match the streak's velocity. These matching clusters are added to the candidate streak. Once all of the candidate streaks have been filled out, the LINEAR algorithm rejects those streaks which have too few clusters. The streaks remaining are considered detections. Plate solutions are generated by using a star-matching algorithm and a star catalog, and then the precise locations of the detections in each frame are calculated. Detection locations are converted to final observations formatted in right ascension and declination sky coordinates. Detections of fast-moving objects, which are potential NEOs, are manually reviewed to identify and eliminate any false positives that have leaked through the system.

Figure 8 shows an example of the detection of an NEO asteroid. Figure 8(a) is a composite of five image frames, each separated by twenty-eight minutes. Figure 8(b) shows output of the LINEAR detection system in which asteroid 1998 KD3 is highlighted with a sequence of four red circles and an arrow that indicates the direction of motion. Detections of slower-moving main-belt asteroids are in green. The images in Figure 8 were cropped from a much larger CCD image.

LINEAR searches are typically repeated to search a given area of the sky twice within a seven-day period. Occasionally, an area of the sky is searched three times if one of the previous two nights of searching had marginal observing conditions. In addition, the output of the detection system depicted in Figure 7 for

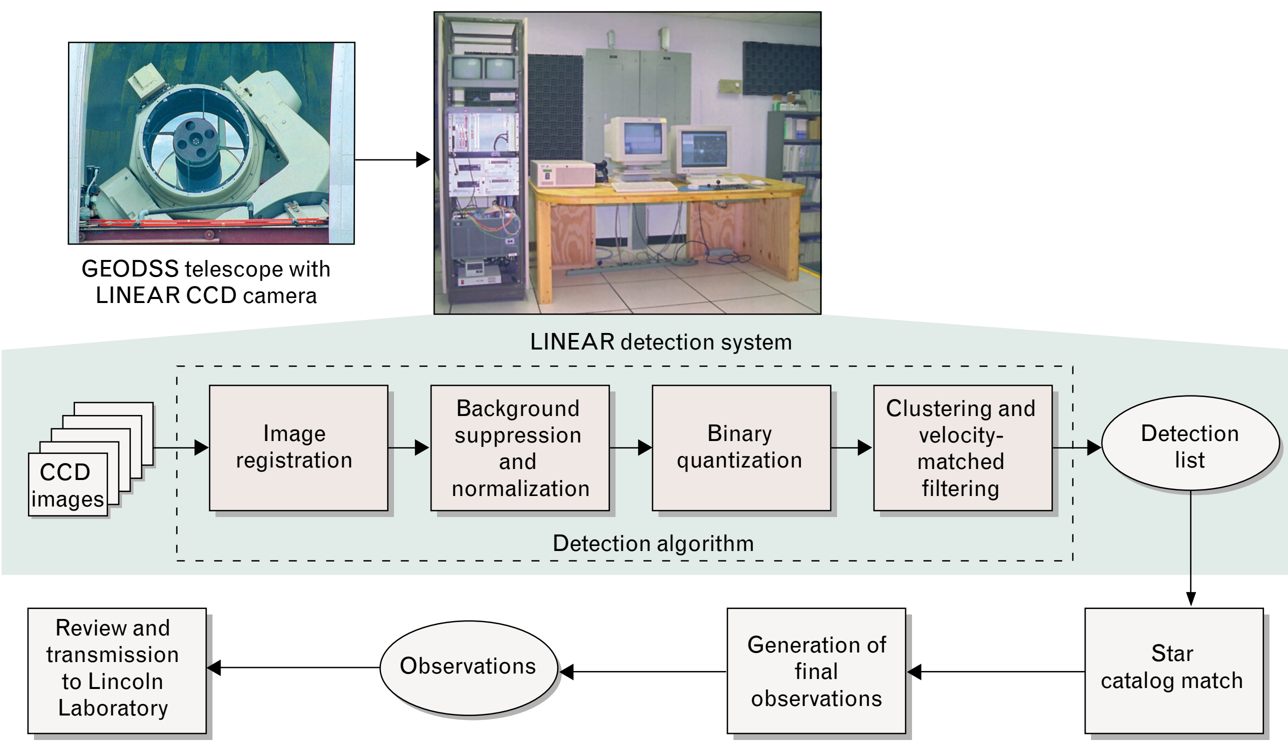
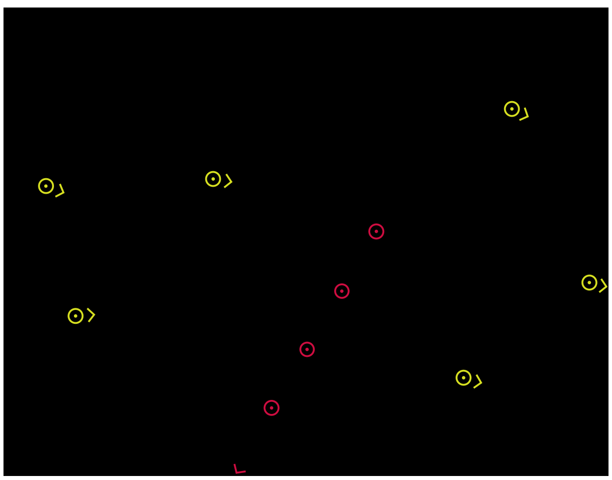


FIGURE 7. Process flow at the Experimental Test Site (ETS) for the LINEAR detection system, which acquires and processes a series of CCD images of the sky to detect moving objects. The detection list is matched against a star catalog to produce a set of final NEO observations, which are then sent to Lincoln Laboratory.

(a)



(b)

FIGURE 8. Processing a series of image frames to detect moving objects. (a) This composite of five image frames, each separated by twenty-eight minutes, shows the clutter from which faint yet moving asteroids must be extracted. The vertical streaks, associated with brighter stars, are a saturation effect in the CCD readout. (b) The bottom image shows the output of the LINEAR detection system, with the newly discovered NEO—asteroid 1998 KD3—highlighted in red. Detections of slow apparent-motion main-belt asteroids are colored green.

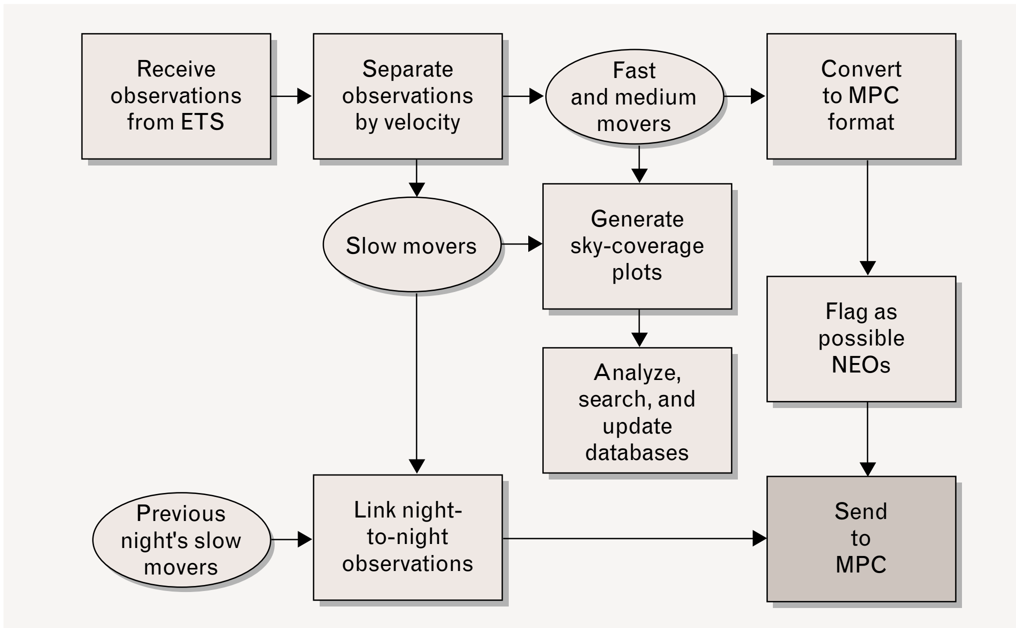
transmission to Lincoln Laboratory in Lexington, Massachusetts, requires additional processing before submittal to the MPC.

Interactions with Minor Planet Center

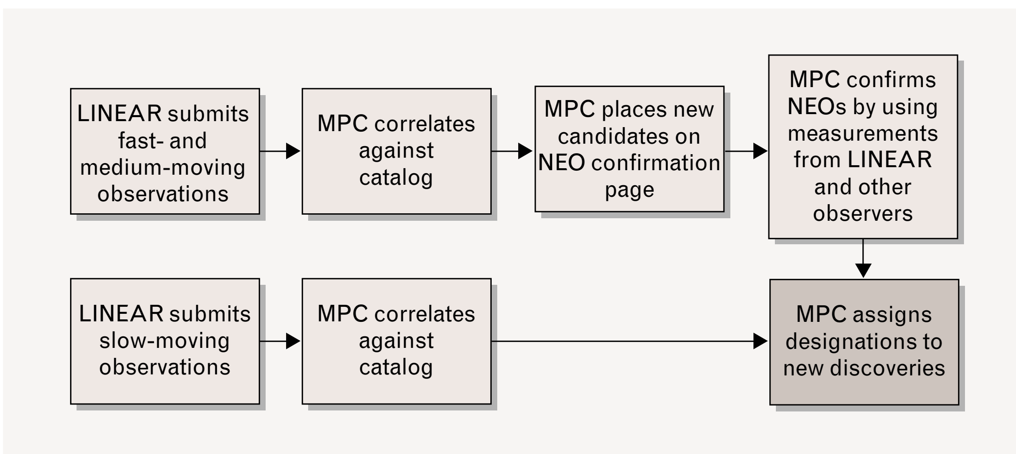
The MPC, which is part of the Harvard Smithsonian Astrophysical Observatory, maintains a catalog of all known asteroids, comets, and other minor planets. The role of the MPC for asteroids is analogous to the role of Cheyenne Mountain in Colorado Springs, Colorado, for satellite tracking and cataloging. To support their cataloging efforts, the MPC receives asteroid and comet observations from professional and amateur observers around the world. These observations are checked against the catalog to identify those observations which are of known objects, whose orbits are updated by using the new data.

The MPC assigns designations to new objects with sufficient observations and credits discoveries. Generally, a main-belt asteroid discovery is credited to the first observers who submitted their observations to the MPC for processing and were able to observe the object on two nights within a ten-day period. Fast-moving new objects that are possible NEOs are immediately reported and placed on the MPC's NEO Confirmation Page on the World Wide Web. Professional and amateur astronomers who specialize in follow-up observation can download the predicted position of NEO candidates, observe them, and send the resulting observations to the MPC. Once confirmed, a new NEO receives a designation and a *Minor Planet Electronic Circular* announcing its discovery. Discovery of the NEO is credited to the first observer supplying the data leading to placement of the object on the confirmation page.

At Lincoln Laboratory, we process LINEAR observations received from ETS to extract fast-moving objects with apparent motion greater than or equal to 0.4 deg/day, medium-speed objects with motions between 0.4 and 0.3 deg/day, and slow-moving objects with speeds less than 0.3 deg/day. Because NEOs tend to have faster apparent motion than main-belt asteroids and move faster as they leave the main belt and approach the sun, the fast movers are definite NEO candidates. Figure 9 illustrates the process for cataloging observations. The fast movers are converted to MPC observation format, assigned temporary LINEAR designations, and electronically mailed to the MPC for priority processing. Medium movers are possible NEO candidates, but typically turn out to be unusual, though not threatening, asteroids. These are processed and sent to the MPC in the same manner as the fast movers, but are processed at a lower priority.



(a)



(b)

FIGURE 9. (a) Processing flow of Lincoln Laboratory ETS observations, and (b) interactions between the LINEAR program and the Minor Planet Center (MPC). Fast movers (definite NEO candidates) and medium movers are all converted to MPC format and electronically mailed to the MPC. Medium movers are processed at a lower priority. The slow movers identified from two or three nights of observations are linked. This set of linked observations is assigned a temporary designation, converted to MPC format, and electronically transferred to the MPC.

To ease the processing burden on the MPC, we process and link the slow-moving observations from two or three nights on the same area of the sky. Each set of linked observations is assigned a temporary designation and converted to the MPC observation reporting format. The resultant large data files are electronically transferred to the MPC via the Internet.

Additional data processing tasks involve analyzing the performance of the LINEAR system. Raw observations are processed to extract the sky coverage for a particular night. A plotting program displays the sky coverage, color coded for the number of nights each region is revisited. Software automatically downloads MPC lists of NEOs, extracts LINEAR discoveries, and superimposes them on sky-coverage plots. With these tools, we can analyze the search pattern and observing strategy of a given lunar dark period (during new moon) and adjust our observation strategies for the next lunar dark period. Finally, the files of designations received from the MPC are processed, and a database of raw observations, temporary LINEAR designations, and MPC designations is updated and maintained.

In addition to providing provisional designations based on two nights of observations of newly discovered objects, the MPC also coordinates the process of numbering and naming of new discoveries for the International Astronomical Union. Asteroids may be numbered and formally included in the catalog after there is a sufficiently good orbit on the object to guarantee that it will not be lost. Observations must be collected over three or four oppositions, which occur about every sixteen months, to generate an orbit of sufficient quality to number the object. The credit for numbering the object and the right to name the asteroid are conferred to the observer who provides data over a span sufficient to guarantee that the asteroid can be recovered and correlated over the interval between oppositions. This is called a principal designation, which usually takes data over an interval of thirty days to achieve. LINEAR currently has naming rights to approximately 450 asteroids when they are eventually numbered, and is acquiring these rights at a rate of approximately 200 per month. The first LINEAR asteroid, numbered 7904, has been named Morrow in honor of Walter Morrow, the recently retired director of Lincoln Laboratory.

LINEAR Search Results

The initial LINEAR system was tested during March through July 1997 to determine its search effectiveness. Because of limited equipment availability at that time, a 1024 × 1024-pixel CCD was used rather than the full-scale GEODSS chip. Despite the smaller CCD chip, LINEAR productivity was high, and performance was comparable to search programs such as NEAT and Spacewatch. During this five-month trial period 3 new NEOs and 1367 main-belt asteroids were discovered and assigned MPC designations.

LINEAR began search trials with the large-format

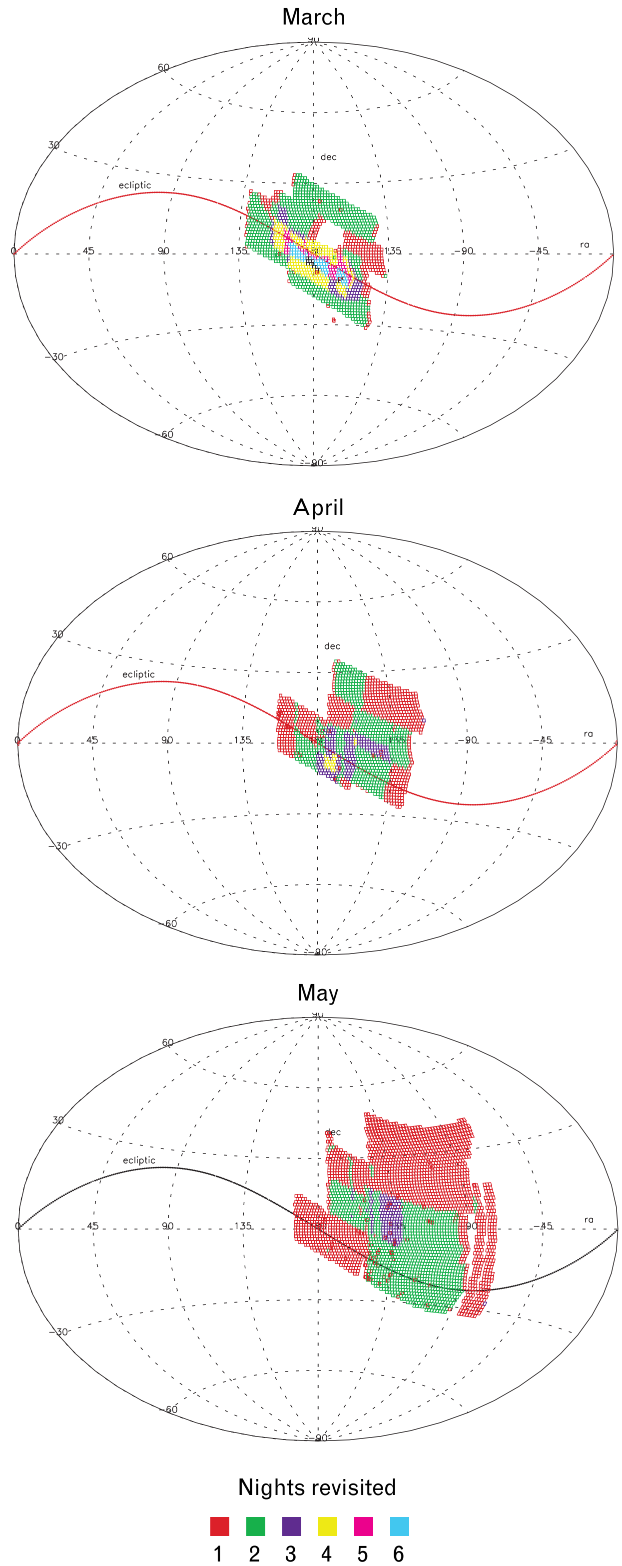


FIGURE 10. Equatorial plot of the sky covered by LINEAR during opposition in March, April, and May of 1998. The plots are color coded to indicate the number of times the sky area was covered during the month.

Table 1. Monthly Performance of LINEAR Program

Period	*Observations*	*Search Area (deg^2)*	*NEOs*	*Comets*
October '97	52,575	3060	9	0
March '98	151,035	9906	13	0
April '98	91,495	7124	8	1
May '98	51,068	12,124	14	4

1960 × 2560-pixel CCD chip in October 1997. LINEAR search operations were conducted during the half of the month when the moon was less illuminated to reduce the background noise and increase the sensitivity of the search. In the initial 10 nights of operations LINEAR generated 52,542 observations and detected 11 NEO candidates, of which 9 were confirmed and received new designations from the MPC. Two of the NEO candidates were lost in subsequent follow-up attempts by the worldwide network of astronomers who track new objects.

LINEAR resumed observations with the large CCD during the lunar dark period in March 1998. During that time, LINEAR produced over 150,000 observations and detected 22 NEO candidates, of which only 13 were confirmed and received designations. We believe one reason for the loss rate of NEO discoveries during this interval is that we overloaded the capacity of follow-up observers. During subsequent operations in April and May 1998, we invested more effort in following up our NEO discoveries to avoid this problem, and have had no losses for those two months. During the March 1998 lunar dark period, the MPC indicates that LINEAR provided over 90% of the worldwide total of asteroid observations. Figure 10 contains a plot of the sky coverage achieved during the March, April, and May 1998 observing intervals. Many of the areas near the ecliptic were covered multiple times. During the three-month interval displayed, the search planning methods that LINEAR used matured significantly, leading to coverage of a larger extent of the sky with less overlap beyond the two visits required to achieve MPC designations on the discovered objects.

Table 1 summarizes the LINEAR search observations with the large-format CCD, demonstrating that LINEAR has the capability to discover long-period comets. The comets are detected in the same process as asteroids and included on the MPC confirmation page. Figure 11 shows a histogram of the estimated sizes of the NEOs discovered. LINEAR is finding numerous asteroids larger than 1 km in diameter, the theoretical threshold diameter for worldwide climatic effects in a collision. Another metric of LINEAR performance comes from the MPC's list of potentially hazardous asteroids that can potentially approach Earth to within 5 million km and are at least 200 m in diameter [6]. As of 16 June 1998, this list has 123 entries of which LINEAR has discovered 12.

Figure 12 shows a histogram of all LINEAR asteroid detections, both known and newly designated, through the end of 1997. The histogram demonstrates that LINEAR can see beyond what is documented in the current catalog of asteroids. The *x*-axis

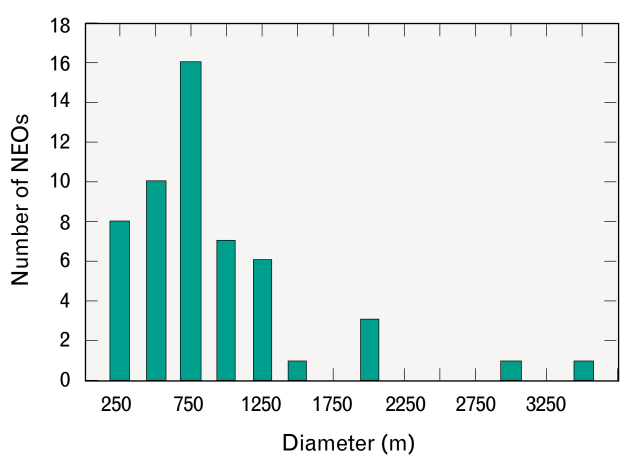


FIGURE 11. Histogram of the size distribution of NEOs discovered by LINEAR through March 1998.

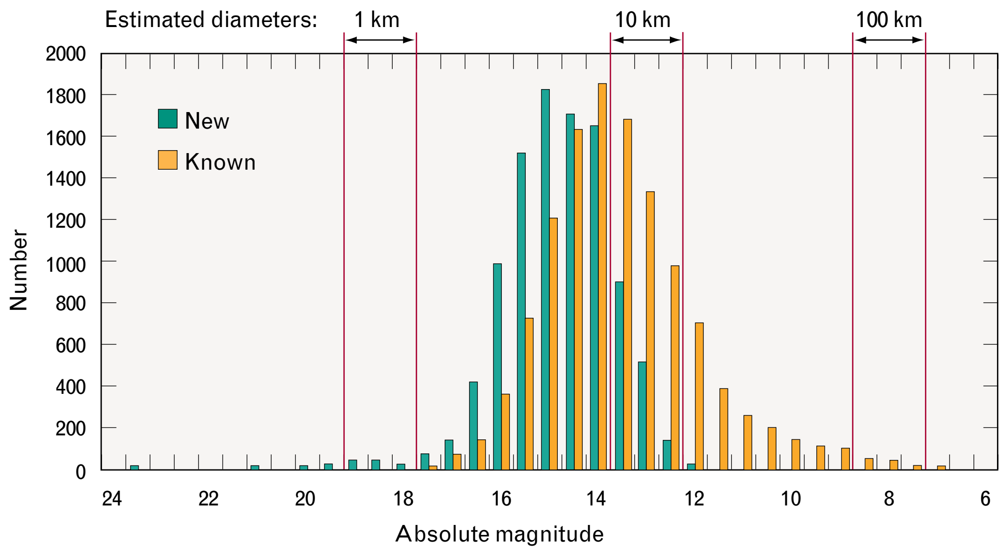


FIGURE 12. Histogram of asteroids detected by LINEAR through 1997, including new discoveries and known objects. The peak of the population discovered by LINEAR is approximately two visual magnitudes fainter than the peak for the known population.

of the figure shows both absolute magnitude (on the bottom) and the estimated diameter of asteroids detected (on the top). Diameter estimates are based on absolute magnitude by assuming an average surface reflectance. The peak of the population discovered by LINEAR is approximately two visual magnitudes fainter than the peak for the known population, representing a major advance in detection capability. Improved detection sensitivity allows LINEAR to characterize more quickly the population curve shown in Figure 2. This capability is required to catalog all NEOs down to 1 km.

Another metric for determining the contribution made by LINEAR is to compare its productivity with other major asteroid search programs. Table 2 compares three recent months of LINEAR results with the recent results of the Spacewatch and NEAT programs. Note that LINEAR's performance exceeds that of the other programs.

Further insight into the relative performance of the search programs may be derived from sky plots provided by the MPC. The MPC does not generally know what portion of the sky each search program has covered; however, it does track the distribution of the asteroid detections provided by each search program. Figure 13 contains the sky plots of the detections reported by major search programs, including Spacewatch, NEAT, ODAS (a joint effort between the Observatoire de la Côte D'Azur in Nice, France, and the Institute of Planetary Exploration in Berlin-Adlershof, Germany), and LINEAR for March, April, and May 1998 [7]. The LINEAR program dominated the sky over each of these months in both sky coverage and number of observations generated.

Table 2. Performance of Asteroid Search Programs

Program	*Period*	*Detections*	*Detections/Month*	*Discoveries/Month*	*NEOs/Month*
LINEAR	3/98–5/98	58,719	9573	3027	12
Spacewatch	1/95–12/96	69,308	2888	459	2
NEAT	10/95–3/98	23,061	824	53	1

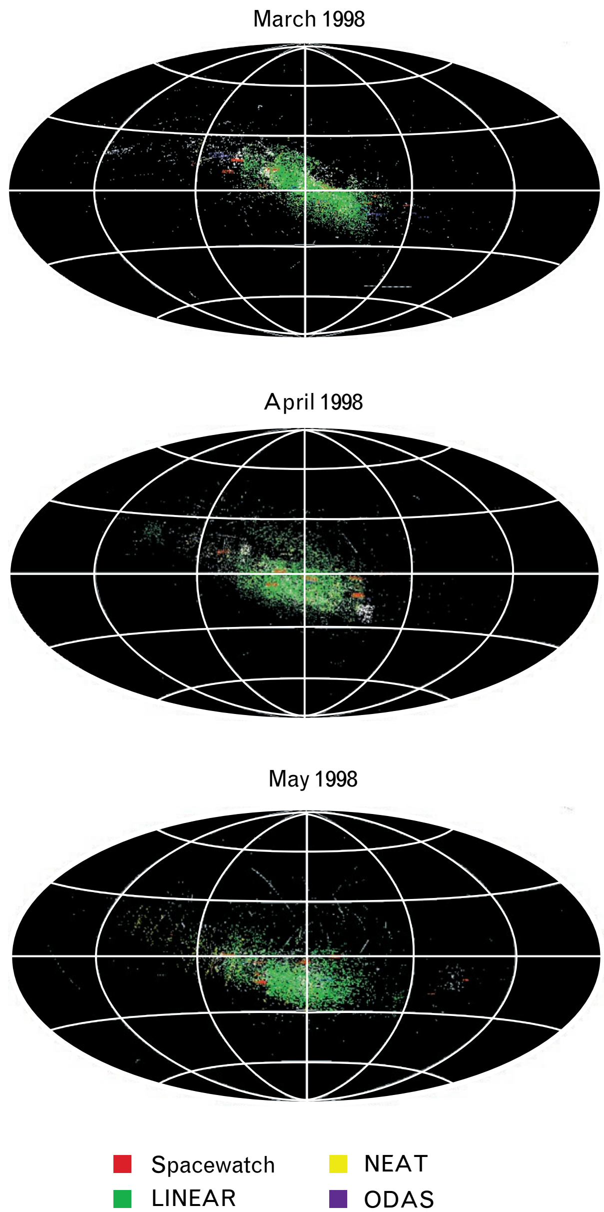


FIGURE 13. MPC sky plots showing detections of asteroids reported by the major search programs Spacewatch, LINEAR, NEAT, and ODAS (a joint effort between the Observatoire de la Côte D'Azur in Nice, France, and the Institute of Planetary Exploration in Berlin-Adlershof, Germany). The LINEAR program outperformed other search programs during the three-month period.

Summary

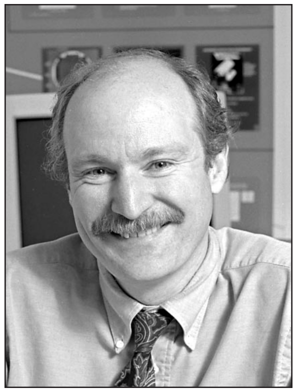
The LINEAR program has successfully demonstrated the application of U.S. Air Force space-surveillance technology to the search for NEOs, asteroids, and comets. Operational experience shows that the large-format 1960 × 2560-pixel CCD used by LINEAR for wide-area asteroid searches performs more efficiently than traditional CCDs used by other asteroid search programs. During three months of operations (March, April, and May 1998), LINEAR searched a total of 29,154 square degrees of sky to a limiting visual magnitude exceeding 19, and submitted over 293,000 observations of asteroids to the MPC. These data resulted in the discovery and designation of 53 new NEOs, 4 new comets, and over 10,000 main-belt asteroids.

Acknowledgments

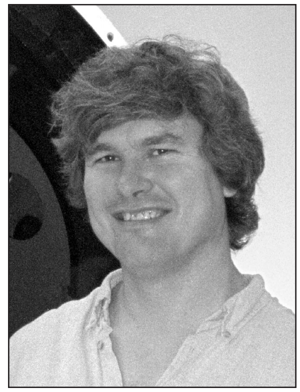
The authors would like to acknowledge and thank the following contributors to the work presented in this article: Eric Pearce, manager of the Lincoln Laboratory Experimental Test Site, where the observing is conducted; Mike Bezpalko, who helps with the observing; Peter Trujillo and Robert Duncan, who keep the site hardware and cameras in good working condition; and Gene Rork, who calculated the LINEAR detectability curves. The operations and development of the LINEAR program were funded by the U.S. Air Force.

REFERENCES

1. L.W. Alvarez, W. Alvarez, F. Asaro, and H.V. Michel, "Extraterrestrial Cause for the Cretaceous-Tertiary Extinction," *Science* **208,** 6 June 1980, pp. 1095–1108.
2. D. Morrison, R.P. Binzel, E. Bowell, C. Chapman, L. Friedman, T. Gehrels, E. Helin, B. Marsden, A. Maury, T. Morgan, K. Muinonen, S. Ostro, J. Pike, J. Rahe, R. Rajamohan, J. Rather, K. Russell, E. Shoemaker, A. Sokolsky, D. Steel, D. Tholen, J. Veverka, F. Vilas, and D. Yeomans, "The Spaceguard Survey: Report of the NASA International Near-Earth-Object Detection Workshop," NASA, Washington, 25 Jan. 1992.
3. T. Gehrels, "New Research by CCD Scanning for Comets and Asteroids," *NASA Technical Report,* 22 Sept. 1997, NASA-CR-205475.
4. E.F. Helin, S.H. Pravdo, D.L. Rabinowitz, and K.J. Lawrence, "Near-Earth Asteroid Tracking (NEAT) Program," *Ann. NY Acad. Sci.* **822,** 30 May 1997, pp. 6–25.
5. G. Stokes, R. Weber, F. Shelly, D. Beatty, H. Viggh, E. Rork, and B. Hayes, "Air Force Planetary Defense System: Initial Field Test Results," *Proc. Fifth Int. Conf. on Space '96* **1,** *June 1996*, pp. 46–53.
6. http://cfa-www.harvard.edu/iau/lists/Dangerous.html
7. Private communications, G. Williams.

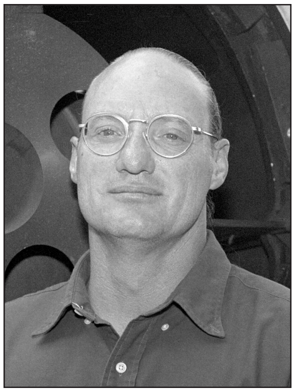


GRANT H. STOKES
is the associate leader of the Surveillance Techniques group, where he specializes in analysis, design, and operations of space-surveillance systems, including the Space-Based Visible (SBV) and LINEAR programs. The SBV system provides the first space-based space-surveillance capability to Space Command in Colorado Springs, Colorado. The SBV was initially operated as a technology demonstration for eighteen months and has now become a contributing sensor for Space Command. Before coming to Lincoln Laboratory in 1989, Grant worked as a senior scientist and operations manager at Geo-Centers Inc., a small 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 holds a B.A. degree in physics from Colorado College in Colorado Springs, and M.A. and Ph.D. degrees in physics from Princeton University, Princeton, New Jersey.



FRANK SHELLY
is an associate staff member of the Surveillance Techniques group, based at the Experimental Test Site 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 like weather systems, mount encoders, digital-to-analog converters, CCD cameras, and filter wheels. Frank helped develop the Transportable Optical System (TOS), which the U.S. Air Force operates in Spain. He joined Lincoln Laboratory in 1986 after studying computer science at the New Mexico Institute of Mining and Technology in Socorro.

HERBERT E.M. VIGGH
is a staff member of the Surveillance Techniques group, and is responsible for the software development, computer system, and data analysis of the LINEAR program in Lexington, Massachusetts. Herb acts as liaison with the Minor Planet Center in Cambridge, Massachusetts, submitting observations and receiving asteroid designations. Herb joined Lincoln Laboratory in 1992 after working on space robotics, mission planning for autonomous vehicles, multisensor data fusion, and airborne lidar-turbulence detection systems for Boeing Aircraft Corporation in Seattle, Washington. As a flight engineer, he tested flight management computers and airplane navigation systems on Boeing transports. He holds a B.S. degree in aeronautics and astronautics with an aviation option, and M.S. degrees in electrical engineering and computer science, and aeronautics and astronautics from MIT.



MATTHEW S. BLYTHE
works under contract for the Experimental Test Site near Socorro, New Mexico, through Manpower Inc. of Albuquerque, New Mexico. He plans and conducts observing sessions, then analyzes the observations. He also provides feedback about the software performance of the LINEAR system. Matt started working at ETS in 1989 after graduating from the New Mexico Institute of Mining and Technology in Socorro with a B.S. degree in physics with an electronics option.

JOSEPH S. STUART
is an assistant staff member in the Surveillance Techniques group, writing software to support asteroid detection and Earth imaging. He joined Lincoln Laboratory in 1993 after earning a B.S. degree in computer science at the University of Pennsylvania, in Philadelphia.