NASA Ames Space Science Division

Asteroid and Comet Impact Hazards

The Near-Earth Objects Survey Workgroup Report

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Eugene M. Shoemaker, Lowell Observatory (Chairman)

Alexander A. Boyarchuk, Russian Academy of Sciences

Gregory Canavan*, Los Alamos National Laboratory

Andrea Carusi, Chair of the IAU NEO Working Group

Marcello Coradini, ESA Headquarters

John Darrah, U.S. Air Force Space Command

Alan J. Harris, Jet Propulsion Laboratory

David Morrison, Ames Research Center

Michael J. Mumma, Goddard Space Flight Center

David L. Rabinowitz, Carnegie Institution of Washington

R. Rikhova, Russian Academy of Sciences

With Contributions from:

Clark R. Chapman, Planetary Science Institute

Brian G. Marsden, Smithsonian Astrophysical Observatory

Steven J. Ostro, Jet Propulsion Laboratory

Simon P. Worden, U.S. Air Force Space Command

Donald K. Yeomans, Jet Propulsion Laboratory

* Dr. Canavan must excuse himself from resource recommendations involving specific institutions.

Executive Summary

Executive Summary

Approximately 2,000 near-Earth objects (NEOs) larger than one km diameter revolve around the sun on short-period orbits that can occasionally intersect the orbit of the Earth. Only about 7% of this estimated population has been discovered. There is about one chance in a thousand that one of these undiscovered objects is destined to collide with Earth during the lifespan of the average American. Such a collision has the potential of injecting sufficient dark material into the atmosphere to cause a major loss of global crop production and consequent loss of human life.

NASA's charge to the NEO Survey Working Group was to develop a program plan to discover, characterize and catalog, within 10 years (to the extent practicable), the potentially threatening comets and asteroids larger than 1 km in diameter.

Advances in the last few years in the development of charge-coupled devices (CCDs) as detectors have led to substantial improvement in the projected capability to carry out a systematic survey of NEOs. In particular, large format, high quantum efficiency, fast readout CCDs have been developed under U.S. Air Force sponsored research. The efficiency of these detectors is now close to the theoretical limit. Use of these detectors on sufficiently large telescopes would enable rapid progress to be made in an NEO survey.

We have defined a program that responds immediately to the challenge of discovering potentially threatening NEOs. It would carry out a census of short-period comets and asteroids larger than 1 km in diameter and seriously address smaller NEOs and long-period comets, as well as develop a broad database of physical observations in order to evaluate the impact hazard. This program, based on further development of existing efforts within the U.S. civilian astronomical community, could meet restricted objectives (surveying the short-period NEO population) in ten years following an initial three-year development phase.

In order to proceed promptly, maximum use needs to be made of existing telescopes. In particular:

- we encourage collaboration of the U.S. Air Force. The Air Force facilities and technologies will enhance the undertaking. The Air Force's continued development of large array imaging cameras will be of value to all the participants;
- we encourage collaboration of the international community, including further development of programs underway in France, Australia,

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China, Canada, Russia and for the European Southern Observatory.

Recommended Program

The recommended program will accomplish the objective of discovering 60-70% of short-period NEOs larger than 1 km diameter within one decade (by the end of 2006, for funding beginning in FY96). It will also put into place the assets that will extend completeness above 90% in the following five years, and extend it both further and to smaller objects in subsequent years. Anticipated cooperation from the Air Force and international programs could shift the attainment of 90% completeness forward to 2006, and significantly augment capabilities for orbit determination and physical measurements.

The recommended program requires investment in search telescopes, detectors, and software to fully utilize current technology. Two dedicated telescopes of about 2-meter aperture are the core of the search system. One of these is already under construction. State-of-the-art CCD focal-plane arrays are required in both telescopes. Acquisition of computers and skilled personnel is required to bring the CCD systems into full operation within three years. One or two existing telescopes near 1-meter aperture, with appropriate advanced focal planes, can round out the survey facilities (capable of both survey work and astrometric follow-up for orbit determination). In addition, enhanced funding is necessary to obtain availability of roughly half time on a 3- to 4-meter class telescope for physical observations of a representative sample of threatening objects. Enhancement of the capability of the Minor Planet Center will be necessary to coordinate the program and handle the enormously increased discovery rates.

The level of funding required to carry out the recommended program is as follows:

Year 1	Year 2	Year 3	Year 4	Year 5
$4.3M	$4.3M	$4.7M	$6.2M	$4.5M

The total cost for 5 years is $24 million. This funding is for the NASA program; funding for participation of Air Force facilities in NEO surveys is not addressed in this report. Beyond the first 5 years, the annual costs drop down to operations costs of about $3.5 million per year.

It must be emphasized that, without an initial investment in large array CCDs with high-quantum efficiency, only moderate improvements will be made over the present rate of discovery of NEOs. Continuation of the present level of NASA supported NEO searches (about $1 million per year) will lead to discovery of about 25% of NEOs larger than 1 km in 10 years and defer 90% completeness to some time in the middle of the next century (assuming that the survey would be continued).

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Since its formation, the Earth has been subject to a continuing bombardment by cosmic debris in the form of asteroids and comets striking at speeds of tens of kilometers per second. While the atmosphere protects us from most of the smaller fragments, larger objects (roughly those bigger than 50 meters) are capable of reaching the lower atmosphere or the surface where they explode with an energy greater than that of any but the most powerful nuclear weapons. Impactors larger than a kilometer or so in diameter have the potential for still greater damage through global environmental effects; such impacts could place at risk much of the human population and endanger the survival of civilization. Geologic evidence suggests that occasional rare, very large impacts in the past have led to mass extinctions of living species. The widely observed impacts into Jupiter in July 1994 of the fragments of Comet Shoemaker-Levy 9 released energy measuring in the millions of megatons of TNT and generated fireballs and dark clouds on Jupiter about as large as the Earth. These events provided an object lesson on the effects of large impacts.

Recognizing the potential hazard of asteroidal and cometary impacts, the United States House of Representatives wrote in its NASA Multi-year Authorization Act of 1990: "The chances of the Earth being struck by a large asteroid are extremely small, but since the consequences of such a collision are extremely large, the Committee believes it is only prudent to assess the nature of the threat and prepare to deal with it. We have the technology to detect such asteroids and to prevent their collision with the Earth." The Committee directed NASA to study both the detection of potentially threatening asteroids and the technology for possible mitigation if an object were found on a collision course. These studies were carried out in 1991-92, and results were released in written form and discussed with the House Subcommittee on Space in a hearing held March 23, 1993.

Subsequent to that hearing, and reflecting widespread public interest in the impact of Comet Shoemaker-Levy 9 with Jupiter, the Committee on Science, Space, and Technology approved the following additional direction to NASA in July 1994: "To the extent practicable, the National Aeronautics and Space Administration, in coordination with the Department of Defense and the space agencies of other countries, shall identify and catalog within 10 years the orbital characteristics of all comets and asteroids that are greater than 1 km in diameter and are in an orbit around the Sun that crosses the orbit of the

Earth." The Committee further requested that the NASA Administrator should submit to Congress a Program Plan for accomplishing this survey.

The present report is a response to this request for a program plan to carry out a comprehensive ten-year survey of near-Earth asteroids and comets along the lines of the earlier recommendations of the Spaceguard Survey Working Group. The present working group was asked by NASA to assess the technical requirements for such a survey and propose a plan of action to implement it. This report summarizes the conclusions of that study.

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The 1992 proposal for an accelerated search for threatening asteroids in Earth-crossing orbits (The Spaceguard Survey: Report of the NASA International Near-Earth Detection Workshop, edited by D. Morrison) provided an analysis of the nature of the impact hazard and proposed an international telescopic survey to identify threatening objects. Its primary conclusions taken from the Executive Summary are given in Appendix I. Since the publication of the Spaceguard Survey Report, a number of international scientific meetings have been held on subjects related to the impact hazard, including the Space Science Colloquium on the Hazards of Impacts by Comets and Asteroids (Tucson, Arizona, January 1993), the Erice Seminar on Planetary Emergencies: Collision of an Asteroid or Comet with the Earth (Erice, Italy, May 1993), and the conference on Space Protection of the Earth SPE-94 (Chelyabinsk-70, Russia, September 1994). The International Astronomical Union has formed a Working Group on Near-Earth Objects (chaired by A. Carusi of Rome, Italy) to consider the issue and help coordinate international survey efforts. Several publications have appeared in the peer-reviewed scientific literature, including an analysis of the impact hazard (C.R. Chapman and D. Morrison in Nature, 1994). A comprehensive multi-author book covering a wide variety of issues associated with asteroid and comet impacts has been published (Hazards Due to Comets and Asteroids, edited by T. Gehrels, University of Arizona Press 1994). In addition, an unprecedented concentration of scientific and public attention focused on the impacts of Comet Shoemaker-Levy 9 with Jupiter in the summer of 1994.

As a result of these accelerating scientific and technical efforts, the nature of the impact hazard is better understood, and a variety of technical approaches to mitigating this hazard have been suggested. In general, the conclusions of the Spaceguard Survey Report have been confirmed and strengthened by these efforts.

III. Approach Of The Current Study

III. Approach Of The Current Study

While the objectives and strategy of the 1992 report remain valid, the technology for accomplishing those objectives has been improved substantially. The development of more sensitive detectors and faster electronics now appears to enable effective surveys with telescopes that are fewer in number and smaller than the 2 to 3 meter aperture discussed in the previous report. The current study applies these advances in detection technology to develop proposals for a less costly approach to implementing a near-Earth objects survey.

The purpose of this report is to outline a practical, cost-effective approach to implementing the United States elements of an international survey for Earth-crossing asteroids and comets. In accord with the Congressional request, the Survey plan is optimized to permit a complete survey, to the extent practicable, of the roughly 1000 to 2000 Earth-crossing objects larger than 1 km in diameter, although a great many smaller objects will also be detected and tracked.

The objective of a rapid survey for the larger Near Earth Objects (NEOs) is best achieved if existing or currently planned telescopes can be utilized. The Survey Working Group has therefore emphasized the use of existing assets from both NASA and the U.S. Air Force for implementing this survey. While this approach requires the combination of systems with different configurations and capabilities into the search network, it takes maximum advantage of past investments and substantially reduces both the cost and the time needed to implement the survey.

The proposed implementation approach must be flexible, since it involves the coordinated use of several different instruments which may become available at different times. The designs suggested for the NEO Survey telescopes, detectors, and signal-processing systems permit them to be used in a variety of observing modes, spanning a range in sky coverage and limiting magnitude. There is a trade-off between the area of sky that a telescope scans and the distance to which the telescope can detect objects of a given size. A telescope that monitors the whole sky will not find objects as far from Earth as one that searches a smaller area of the sky, using longer exposures. The optimum choice can be made for each instrument individually or for the network as a whole. As individual telescopes are added to the net, we expect the operating mode for all of the existing telescopes to be modified to optimize the efficiency of the entire operation. This flexible approach also permits us to anticipate future coordination

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with international partners without having to specify the exact nature of this collaboration at the outset.

Until recently, the best telescope for NEO discovery has been the 46-cm Schmidt telescope at Palomar Mt. This telescope regularly discovers 1 to 2 NEOs per month, and has done the most to characterize the threat from km-sized NEOs. Since 1990, however, the 90-cm Spacewatch Telescope of the University of Arizona, has been finding 2-5 NEOs per month, and is the first telescope to probe the entire population of objects ranging from about 10m to 10km. This telescope has proved the potential of CCD detectors and computer technology for NEO discovery, and established a bench-mark performance level.

With the new instruments and upgraded capabilities described in this report, individual telescopes with 1 to 2 meter apertures should be capable of increasing this discovery rate by at least a factor of ten, and we encourage the implementation of these improvements. However, the full power of the survey will be reached only when the telescopes are utilized as part of a coordinated network rather than as individual search efforts. The objective of this program is an integrated international survey system in which each instrument is assigned the tasks that it can do best in order to maximize the discovery rate of the entire survey ensemble.

IV. The Near-Earth Objects Population

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There are two broad categories of NEOs: comets and asteroids. Historically, asteroids and comets have been distinguished by astronomers on the basis of their telescopic appearance. If the object is star-like in appearance, it is called an asteroid. If it has a visible atmosphere or tail, it is a comet. This distinction reflects in part a difference in composition; asteroids are generally rocky or metallic objects without atmospheres, whereas comets are composed in part of volatiles (such as water ice) that evaporate when heated to produce a tenuous and transient atmosphere. However, a volatile-rich object will develop an atmosphere only if it is heated by the Sun, whereas a comet that is far from the Sun, or an old comet that has lost most of its volatile inventory and is insulated with a regolith deposit, also can look like an asteroid.

The near-Earth asteroids are categorized as Amors, Apollos, and Atens, according to whether their orbits lie outside that of the Earth, cross that of the Earth with period greater than 1 year, or cross that of the Earth with a period less than 1 year, respectively. Cometary objects are classed as short-period if their periods are less than 20 years, intermediate-period if their periods are between 20 and 200 years, and as long-period if their periods are greater than 200 years.

Even more relevant to this report is the definition of an Earth-crossing asteroid (ECA). These are the asteroids that have the potential to impact our planet. An ECA is defined as an asteroid moving on a trajectory that is capable of intersecting the capture cross-section of the Earth as a result of on-going long-range gravitational perturbations due to the Earth and other planets. In this case "long-range" refers to periods of tens of thousands of years. For any particular NEO, it will not be clear whether it is in fact an ECA until an accurate orbit is calculated. Further, as we are concerned here with the near-term hazard of collision with Earth, a survey for hazardous objects need consider only a subset of the ECAs, those that can pass within a specified distance of the Earth in the relatively near future (see Section VI).

In 1989 there were 90 known ECAs, while 128 ECAs were known at the time the Spaceguard Survey Report was written in 1992. Effective January 1, 1995, the number of known ECAs is about 250. The population of Earth-crossing asteroids can be approximated by several power laws, which reflect a steep increase in the number of ECAs as we go to smaller and smaller sizes; from such distributions one can estimate the total number of asteroids having diameters larger than values of particular interest. Based on analyses of the discovery statistics of ECAs and also the cratering record on the Moon (Rabinowitz *et al*., 1994), there are probably 1 to 2 thousand larger than 1 km diameter (the size for which this survey seeks completeness), 4 to 8 thousand larger than 500 m (a size representative of great potential damage from tsunamis), and 0.5 to 1.5 million larger than 50 m (the threshold for penetration of the lower atmosphere). Active comets can also cross the Earth's orbit with the potential for collision. At any given size, active short-period and intermediate-period comets contribute only an additional 1 percent or so to the total collision frequency, a value that is small compared to the estimated uncertainty in the ECA population. However, recent evidence indicates that inactive short- and intermediate-period comets may be about 10 to 20 times as numerous as the active, easily discovered comets (Shoemaker *et al*., 1994).

Although about 700 longer-period comets are known to have passed through the inner solar system during recorded history, their total population is difficult to characterize since the majority remain unobservable in the outermost regions of the solar system. From their orbital and size distributions, we estimate that the near-Earth flux of long-period comets is similar to the flux of active and inactive short- and intermediate-period comets. The total flux of Earth-crossing comets may be somewhere between 10 and 40 percent that of the Earth-crossing asteroid population.

The well-observed ECAs exhibit a diversity in infrared mineralogy approaching that in the rest of the asteroid population. The majority are expected to be similar to the dark C-class asteroids in general properties (presumably moderately low-density, colored black due to the presence of at least several percent of opaques). There are also a large number of S-class asteroids. (S's are thought to be either stony, chondrite-like objects, stony-iron objects, or a combination of both.) In addition, there are known examples of metallic bodies (probably like nickel-iron alloy meteorites) and rocky, monomineralic bodies. ECAs are often quite irregular in shape; they also tend to have rather rapid spins, but there is a great diversity in such properties. Radar images of several such objects (Castalia, Toutatis, Geographos) show that they have a wide diversity of shapes and possible structure. In the case of Castalia, two fragments appear to be merged to form a dumbbell-shaped double-lobed object.

It is particularly uncertain what the physical properties of comets (extinct or active) might be like. Only one comet has been studied in detail: Comet Halley, which was the target of several flyby spacecraft missions at the time of its last apparition in 1986. The nucleus of Halley is irregular and dark, with an average diameter of about 9 km. Like other comets, it is made of a combination of ices and dust, with much of the atmospheric outgassing near the Sun confined to discrete plumes or jet-like features ("jets"). The non-volatiles include both silicates and organic materials, while the primary ices (with percentages derived for Halley) are water (80%), carbon monoxide (7% - another 8% comes from organic dust, a distributed source in the coma), carbon dioxide (3.5%), plus smaller amounts of methyl alcohol, ammonia, hydrogen cyanide, and hydrogen sulfide. The physical configuration of comets is even less well understood than that of the small asteroids, and many comets have been observed to split under rather modest tidal and thermal forces. A direct estimate of density is derived from the tidal disruption of Comet Shoemaker-Levy 9, yielding a value near 0.5 g/cm^3.

For cataloging potential impactors, it is not essential to know a great deal about the physical nature of comets and asteroids. The most important properties are simply their mass and impact velocity, although it would make a difference if the projectile were double or multiple and easily came apart as it entered the atmosphere. However, a future program for intercepting and diverting an incoming comet or asteroid probably will require knowledge of the configuration, density, cohesion, and composition of these objects. For these reasons, in addition to their significance for basic science, spacecraft missions to comets and near-Earth asteroids will become essential for understanding the impact threat.

A program aimed at discovering potential Earth impactors will, by necessity, be focused on ECAs. Because of their larger orbits and longer periods of revolution, the discovery of Earth-crossing comets will require a much longer-term effort and presents a difficult challenge.

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V. Evaluation Of Survey Systems

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The evaluation of the performance of a given survey system depends primarily on only two parameters: the threshold brightness for detection (limiting magnitude), and the rate of sky coverage. Of much lesser importance are such factors as the geographic location of the observing site(s), the ability to detect rapidly moving objects compared to the sensitivity to stationary targets, and the detailed strategy used to follow up detections to obtain preliminary orbits. For the proposed NEO survey, we will show that the best strategy for maximizing the rate of discovery of NEOs is to cover the entire observable sky each month. An optimum search system should be designed to be capable of fast enough operation to achieve all-sky coverage, sacrificing limiting magnitude as necessary to achieve this goal. Thus we can, within the uncertainties of the models employed, reduce the problem to a single parameter: the limiting magnitude that a given system can deliver in the mode of covering the whole sky each month. The practical achievement of this mode has become possible with the present state of development of CCDs.

In this chapter, we will present the results of a survey simulation to show the level of completeness that can be expected from putative survey systems as a function of time (length of survey), area of sky covered per month (from which we derive the above conclusion for all-sky coverage), and size of NEO. We can then simply relate these results to specific systems through estimates of the limiting magnitude achievable with a given system. In Appendix III we give a more detailed report of the evaluation methods and results for specific systems. In this chapter, we summarize the search strategies and expected capabilities in more general terms.

Survey Systems

For the purpose of a quantitative discussion, we shall evaluate survey completeness for three rather specific systems. However it should be noted that results can easily be scaled to other systems that might be contemplated. The three systems are representative in general terms of systems of 0.5-m, 1-m, and 2-m aperture. Following is a brief description of each system.

1. The Lowell Observatory Near-Earth Object Survey (LONEOS) telescope is a modified Schmidt telescope of 0.58 m aperture, 1.11 m focal length (f/1.91), which is under construction at Lowell Observatory. "First light" is

expected during this year. Initially, it will be equipped with a two CCD chips with 2048 x 2048 pixels, 15 microns square, or a field format of 3 cm by 6 cm. Eventually, it is planned to use two butted 2048 x 4096 chips with 15 micron pixels, for a 6 cm square format, which yields an angular field of view 3.17 on a side, or an area of 10.1 square degrees. It is planned to use front-illuminated, unthinned CCDs with a quantum efficiency of ~25%. We estimate that this system can reach a limiting visual magnitude of 19.4 with 68 second exposures. In our evaluations, we consider the "full-up" system with (4096)2 pixels.

2. The USAF Space Command currently operates a network of 1-m, f/2 wide-field telescopes, the Groundbased Electro-Optical Deep Space Surveillance (GEODSS) system, for tracking Earth satellites. The GEODSS Upgrade Prototype System (GUPS), currently under development, will employ large format CCD detectors, which with only minor modifications and changes to the computer software, might be effectively employed for NEO surveys. The CCD detector under development at Lincoln Laboratory is a single chip of 1960 x 2560 pixels, 24 microns square, or a total format of 4.7 cm by 6.1 cm. In the GEODSS telescope, this yields an angular field of 1.23 by 1.61, or 1.98 square degrees. The chip is thinned, back-illuminated, with a quantum efficiency exceeding 75%. We estimate that this system can reach a limiting magnitude of 20.2 with 20 second exposures.
3. The Spacewatch (SW) Telescope on Kitt Peak, Arizona. The present (operating) system is a 0.9 m telescope of 4.6 m focal length (f/5) with a single CCD detector with 2048 x 2048 pixels of 24 microns, or a total format 4.9 cm on a side. The detector is thinned, back-illuminated, with a quantum efficiency of ~75%. SW has a demonstrated limiting visual magnitude of ~21.2 with a 147 second exposure covering a 0.57 square degree field. Since it is the only currently operating system, we have estimated the limiting magnitudes expected for the other systems by scaling from the demonstrated performance of SW.
4. A second telescope (SW-II) of 1.8m aperture and 4.9m focal length (f/2.7) is under construction. Initially, it will be equipped with a similar CCD detector, which will yield a field of view of 0.57 on a side. In a scanning mode with a 30 second integration time, this system should reach a limiting visual magnitude of 21.5. With this detector and exposure arrangement, SW-II cannot achieve all-sky coverage each month (to be discussed later). It could do so with a mosaic of 4 butted CCD chips, giving a field of view of 1.14 on a side, and rapid read-out electronics so that it could take individual exposures as short as 10 seconds. The telescope is mechanically and optically capable of accommodating this array and exposure rate. With 10 second exposures, the limiting visual magnitude would be about 20.9.

Survey Simulation

The approach taken was to generate a set of 1000 synthetic NEO orbital elements, matching the distribution statistics of the actual NEO swarm as best we can determine that from the present sample of known NEOs. We imposed one "unnatural" restriction: we included in the sample only orbits which pass within 0.05 astronomical unit of the Earth's orbit. As a general rule, asteroids whose orbits do not pass within 0.05 AU of the Earth's orbit pose no threat of collision on a time scale of a century, as the planetary perturbations necessary to reduce the miss distance to zero require longer than that to make such a change. Thus we have limited our sample to a subset of the actual distribution: the ones that actually pose a potential threat. Our results don't appear to be very much affected by this restriction, but it is reassuring to know that we have prejudiced the distribution in favor of the more hazardous objects.

Having created a set of synthetic orbit elements, we then generated a set of positions for each object, one for each lunation (new moon) for ten years, or 125 positions for each object. For each computed position, we also calculate the rate of motion on the sky and a relative magnitude which takes into account the distances from the Earth and Sun, and the solar phase angle (analogous to the "phase of the moon", which in a like way very much affects the brightness of the object).

To conduct a survey simulation, we "filter" the file of 125,000 positions to tabulate which objects are "discovered" and which are not. The various "filter" elements include limitations on the sky area viewed, either those imposed by the maximum area the putative system can cover or those naturally existing due to horizon limits, Sun or Moon in the sky, too close to the galactic plane, where detections are impossible due to background star confusion, and most important, object size/system limiting magnitude. On this latter point, we note that the system limiting magnitude and the absolute magnitude of objects are 100% correlated parameters. That is, a system capable of detecting objects 4 times fainter than another system will achieve the same level of completeness of NEOs at 1/2 the diameter as the other system. Thus in estimating completeness vs. size of NEOs, we needn't do independent evaluations for different limiting magnitudes. The same "completeness curve" applies for completeness vs. size at a given threshold magnitude as applies for completeness vs. threshold magnitude for a given size of NEO.

Observational Strategy

Even the basic *detection* of an asteroid requires multiple observations. The method used by the only operational system, Spacewatch, is to scan the same area of sky three times, separated by ~1 hour each. The images are compared to reveal any moving object, with the third scan as a confirmation against erroneous or confused images in either of the other two scans. It is anticipated that the systems described above would operate in a similar mode. Some economy could be achieved by storing a catalog of the sky from past (previous months or years) scans of the same area, so that only two new scans, to be compared against the archival catalog, would suffice. Thus the first step, detection and confirmation of a moving NEO, requires taking two or three scans of a given sky area, separated by an interval of time of the order of an hour or two. This results in a measurement of the instantaneous position in the sky and a rate of motion, which is sufficient for finding the object sometime later, for example the next night.

In order to obtain even a preliminary orbit for the object, further observations are needed. Present practice is to identify NEO candidates on the basis of anomalous rate of motion compared to main-belt asteroids, as determined on the first night of observation. For these objects, additional observations are needed, on at least two more nights, and preferably spaced over an interval of about a week. A one week "arc" is usually sufficient to make a preliminary estimate of the "minimum orbit intersection distance" (MOID) from the Earth and determine whether the object presents any potential hazard to the Earth on a timescale less than a century. A longer arc is necessary to consider the object reliably "cataloged", but with only a week arc the number needing further follow-up, on the strict basis of hazard alone, can be reduced to a small enough number to be accomplished with modest resources.

With highly automated systems, recording detections at much higher rates than present systems, it may become more efficient to just cover the sky often enough that the week-arc follow up occurs automatically, for everything. This has the advantage that all objects are followed up to the level of a preliminary orbit determination. Thus the few NEOs which chance to be mimicking main-belt motion at the time of detection are discriminated and become "discovered." To operate in this mode requires covering the search area about 4 times each month, rather than once plus targeted follow up.

In summary, "detection" consists of a sequence of two or three observations on a single night, which are usually sufficient to distinguish a main-belt object from an NEO and to find it again the next night. To "discover" the object, in terms of a preliminary orbit, requires two or three more observations over about a week, and represents about a doubling of resources over detection alone.

Survey Completeness vs. Area of Sky Coverage

For our first simulations, we specified the area of sky covered per month as the radius of a circle on the celestial sphere centered on the opposition point, which is generally the most productive area to search. In this experiment we made no restrictions for horizon or closeness to the galactic plane. For the detection threshold, which is a combination of telescope limiting magnitude and size of object, we chose limiting magnitudes appropriate for a single GEODSS telescope equipped with the Lincoln Laboratory GUPS CCD chip, with exposure times appropriate to allow coverage of the area of sky assumed in each case. For size of object, we took the brightness corresponding to a 1 km diameter object of albedo 0.15 (typical S class albedo), or equivalently, a 2 km object of albedo 0.04

(somewhat darker than average C, D, etc. objects). In Figure 1 we plot the rate of detections of NEOs for three assumed sky areas corresponding to circles of radius 34 □, 65□, and 137□ out from the opposition point. For the focal plane instrumentation assumed, these sky areas correspond to exposure times per single image of 100 sec, 30 sec, and 10 sec, respectively. With these exposure times, the specified sky areas can be covered three times (the redundancy required for detection and confirmation) in ~100 hours of observing time, which is the typical amount of time available from a given site in a month, allowing for weather and other types of interruptions. The 34 □ and 65□ sky areas are probably achievable from a ground-based site. 137 □ corresponds to covering the whole celestial sphere down to a solar elongation of only 43 □, clearly not possible from anywhere on the ground without serious losses from atmospheric extinction. The point of this figure, which is a very robust result and applies for any system we have evaluated, is that it is better to cover more sky and sacrifice limiting magnitude as necessary, until all available sky is being surveyed.

All-sky Surveys

Having established that the optimum strategy is always to cover all available sky each month, we concentrated on this mode of operation in the remaining analyses. We first evaluated how much sky is accessible and how many hours are available to cover it for each month of the year. The restrictions applied are:

1. The Sun must be more than 10¡ below the horizon.
2. The moon must be below the horizon.
3. The target area must be more than 25¡ above the horizon at some time during the night.
4. The target area must be more than 20¡ away from the galactic plane.

Subject to these conditions, we determined that, almost independent of station latitude, the maximum rate of sky coverage required is ~135 square degrees per hour in order to cover all of the sky once per month. Allowing for duty cycle losses, cloudy weather, and other down time, the rate of sky coverage should be ~200 square degrees per hour to cover the whole sky once per month. It is important to note here that any system intended to contribute seriously to the survey itself, rather than serve as a "test bed", should be designed to cover sky area at the above rate. Indeed, unless a separate system of astrometric follow-up is contemplated, the survey system needs to be capable of 2 or 3 times that rate to assure enough observations to derive preliminary orbits for the discovered objects.

In Figure 2 we plot the fraction completeness vs. time for each of the three systems described above. For both LONEOS and Spacewatch - II, we have assumed the "full-up" configurations described above which would be capable of all-sky coverage each month. These curves represent the fraction of objects detected, and do not allow for the necessary work of follow-up observations to determine orbits for detected objects, which will be discussed later in this chapter.

Completeness as a Function of Size of NEO or Limiting Magnitude of System

As noted above, the question of whether or not an NEO is detected, given that it passes within the surveyed area, is a function of only one parameter: brightness compared to the detection threshold of the survey system. Thus size and albedo of NEO and threshold limiting magnitude of the detection system all collectively constitute only a single variable. So we can derive a single "completeness curve" which can be used to describe completeness as a function of limiting magnitude of the survey system, for a given size and albedo of object, or equivalently, completeness as a function of size of body, for a system of specified threshold detection magnitude.

Figure 3 is a plot of that function derived from the simulated 10-year survey of 1000 objects. The vertical scale is simply the fraction of the 1000 objects "detected". The horizontal scales are either relative size of object, or threshold detection limit of the system. We have plotted the curve twice (dashed lines), offset by a factor of 2 in diameter (1.5 magnitudes brightness), which correspond the difference of approximately a factor of 4 in albedo between the brighter, "S-Class" asteroids and darker, "C-class" and related types. Among measured NEOs, the ratio of high to low albedo objects is approximately 10:1. However this is strongly affected by the fact that dark objects of a given size are much more difficult to detect. Thus we suspect the bias-corrected ratio is closer to half each, at a given size. The solid line curve in Figure 3 is an equally weighted average of the two dashed curves, and represents the completeness curve for an NEO population consisting of equal numbers of high and low albedo objects. We will use this curve for further analyses.

In Fig. 4, we have plotted the completeness curve to represent completeness vs. diameter of NEO, for various values of system limiting magnitude. In Fig. 5, we present the completeness curve, this time scaled vs. limiting magnitude of the system, for various diameters of NEOs. In addition to the three systems discussed above, we have included curves for the current Palomar 46-cm Schmidt photographic system and for the suggested "Spaceguard Survey" system (see Appendix I) of 2-3m telescopes capable of surveying to a threshold magnitude of 22. From these plots, it appears that a system reaching limiting magnitude 20 can achieve about 80% completeness of NEOs down to a size of 1 km diameter in a 10-year survey.

Strategies for Preliminary Orbit Determination

One can contemplate two strategies to determine orbits rather than merely detect objects. One way is to do targeted follow-up observations, either by assigning the observations to a second telescope or by taking time from the discovery survey to make these observations. A second mode is to cover the whole sky so often that repeated detections of the same object are sufficient to yield orbit solutions from the regular survey observations. Figure 6 is a comparison of these two follow-up strategies, which we now describe.

Presently, surveys are done in the first mode, of targeted follow-up. To make the problem tractable, it is necessary to discriminate NEOs from the much more abundant main-belt (MB) objects based on motion in the sky, before an orbit is known. Thus there is a "blind spot" of slow sky motion where an NEO can mimic a MB object and thus not be discriminated. As we go to surveys reaching to fainter magnitude, discoveries will be made at greater distances, thus at slower average motion, and the "blind spot" becomes a more significant loss factor. To evaluate this mode of follow-up, we have computed a second completeness curve, this time filtering out objects which, even though they may be in an observable part of the sky at a given time, are exhibiting main-belt-like motion, and thus would not be "noticed". From past experience (e.g. Spacewatch, Palomar photographic), the "overhead" of follow-up of past discoveries appears to be a task of the same magnitude as the survey itself. Thus a survey telescope may be occupied about half time taking follow-up observations and half surveying new sky. Or if two telescopes are available, one could scan while the other does follow-up. In either case, the "cost" is a factor of two in exposure time that could be devoted to survey-only, which translates to ~0.4 magnitude in threshold detection. So we shift the "targeted follow-up" curve 0.4 magnitudes to the right.

The second possible follow-up mode consists of simply scanning the sky more often, so that enough positions are obtained of each object to derive a preliminary orbit of every object detected. Thus even those exhibiting normal MB motion are discriminated. For the same threshold magnitude, this technique would obviously discover more objects. However, it is likely that operation in this mode would require covering the sky many times per month, perhaps 4, to assure that at least three observations, each separated by several days, would be obtained of a given object. Thus the "cost" is a factor of 4 in exposure time, or ~0.8 magnitude. So we shift the other curve in Figure 6, 0.8 magnitude to the right.

The result is that the two curves cross one another, so the strategy of targeted follow-up is superior except for the very largest objects. On the other hand, it is the very largest objects which are most important. A pedantic reliance on anomalous motion leads to a worrisome result that no survey, no matter how sensitive, can achieve &GT 90% completeness in 10 years. But the largest objects are also brighter, and very much less numerous, than smaller objects. Furthermore, any large object mimicking main-belt motion will be there the next month for repeat coverage. Thus a hybrid strategy should be possible which could closely approximate the higher level of the two curves over the entire range. In any case, the problem of following up to the point of preliminary orbit determination is roughly a "factor-of-two" complication over bare detection only.

Returning briefly to Figs. 4 and 5, We have associated "LONEOS" with a limiting magnitude of 19, whereas we estimate it is capable of reaching 19.4 in an all-sky survey mode with 68 second exposures. Thus the limiting magnitude of 19.0 is about correct if that telescope is tasked with doing its own targeted follow-up, consuming half its time. The limiting magnitude of 20 associated with GEODSS is about the expected performance of one GEODSS telescope, full time surveying. Thus in truth, this curve represents the capability of two GEODSS telescopes, one surveying and a second one doing follow-up, or some similar combination. The magnitude limit of 21 associated with SW-II is the limit expected for single-coverage of all sky, so again, to achieve this level of performance would require a second 2m telescope, or perhaps a highly automated version of SW-I could keep up with the task. Finally, the limit of 22 associated with "Spaceguard" is in a sense "by definition." In the Spaceguard Report (see Appendix I) a requirement was defined to achieve nearly all-sky surveying to limiting magnitude 22. That requirement was then estimated to correspond to a system of about five 2-to-3 m telescopes equipped with CCD arrays. We concur with that scale of instrumentation required to achieve all-sky coverage to magnitude 22.

Conclusion

If one asks the question, what is the likely largest size of any remaining undetected object (that is, where completeness equals one over the number of objects of that size expected), the answer is about 3 km for the evaluated systems, after 10 years. Pushing this limit down to ~1 km would require a Herculean effort. Thus we must accept some level of incompleteness. The systems evaluated can yield completeness in the range 80-90% or better, especially if all are used in concert. This level of completeness should reduce the threat from collision by an undetected NEA to less than that posed by impacts from long-period comets, so in that context, we can declare these systems capable of achieving the Spaceguard goal of reducing the hazard of asteroid collision by an unknown object to below that from comets.

The most important lesson which emerges from this analysis is that the best survey strategy is to cover the entire accessible sky every month, sacrificing whatever magnitude limit is necessary to accomplish this. A very positive result is that if that strategy is followed, adopting reasonable and even conservative limit on sky observability, it is possible to obtain reasonable completeness in ten years, including objects which never quite reach out to the orbit of the Earth and hence never come to opposition. Thus the ability to observe closer to the sun or to remove horizon limitations is not a sufficient justification in itself to move to a space-based survey system.

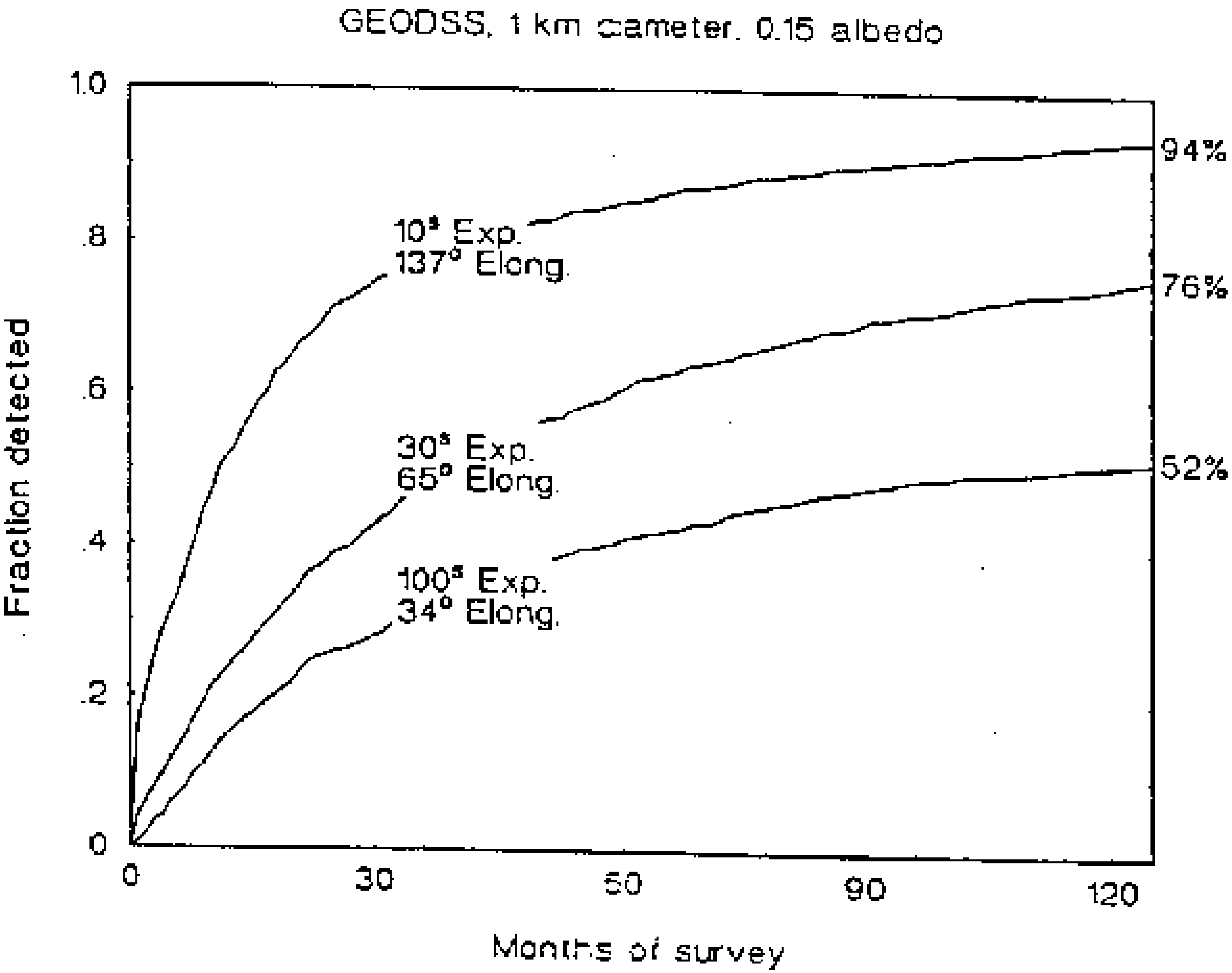

Figure 1. Rate of discovery vs. time for one GEODSS telescope. Each curve represents a different choiceof exposure time, and consequently limiting magnitude, and results in a different area of sky per month that can be covered. The curves represent the discovery rate for ~1 km diameter objects of moderate albedo (0.15), or ~2 km diameter objects of low albedo (0.04).

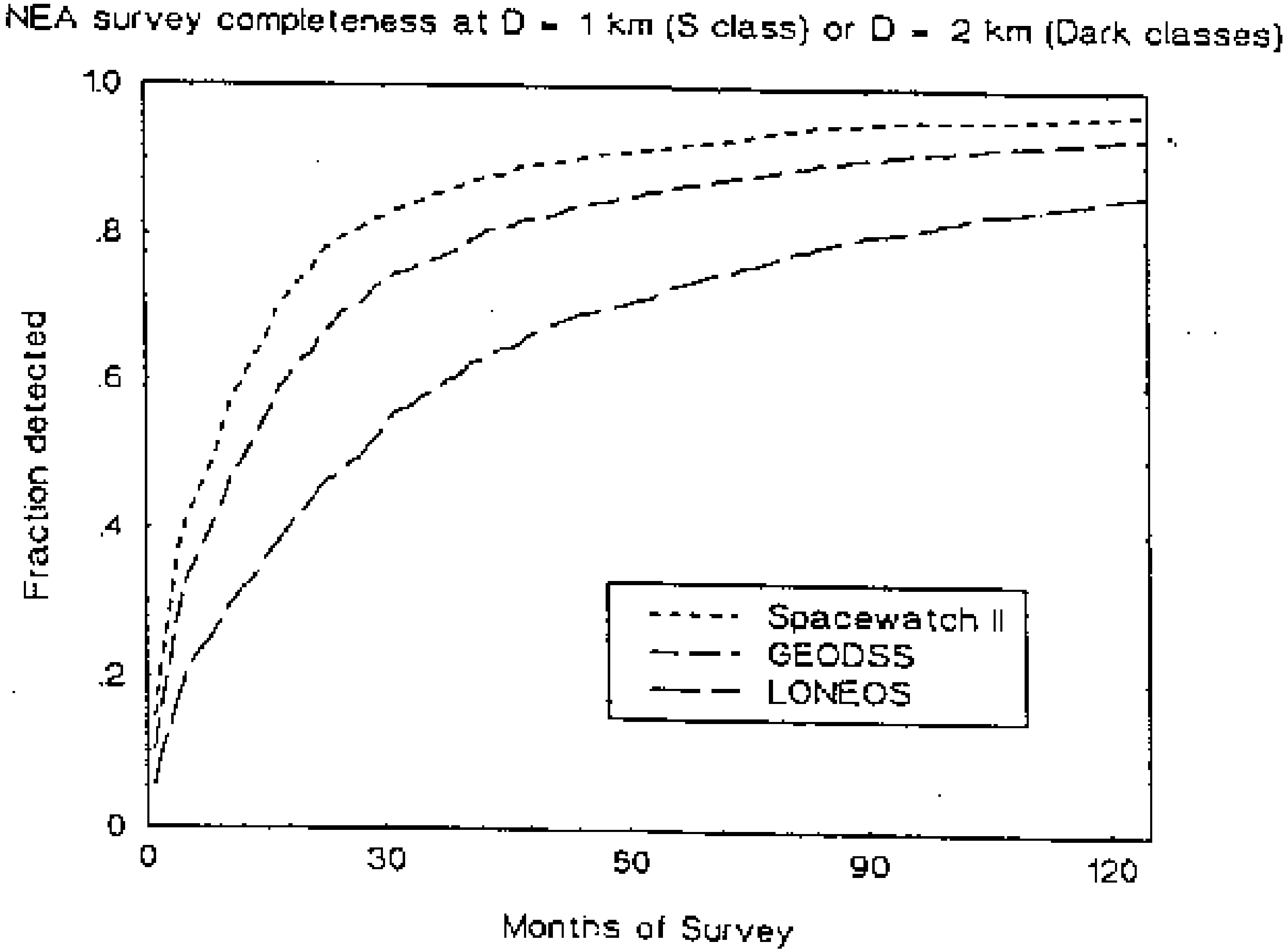

Figure 2. Rate of discovery vs. time for each of the three systems evaluated, assuming that the rateof sky coverage is chosen such that all available sky area is covered each month. The curves represent the discovery rate for ~1 km diameter objects of moderate albedo (0.15), or ~2 km diameter objects of low albedo (0.04).

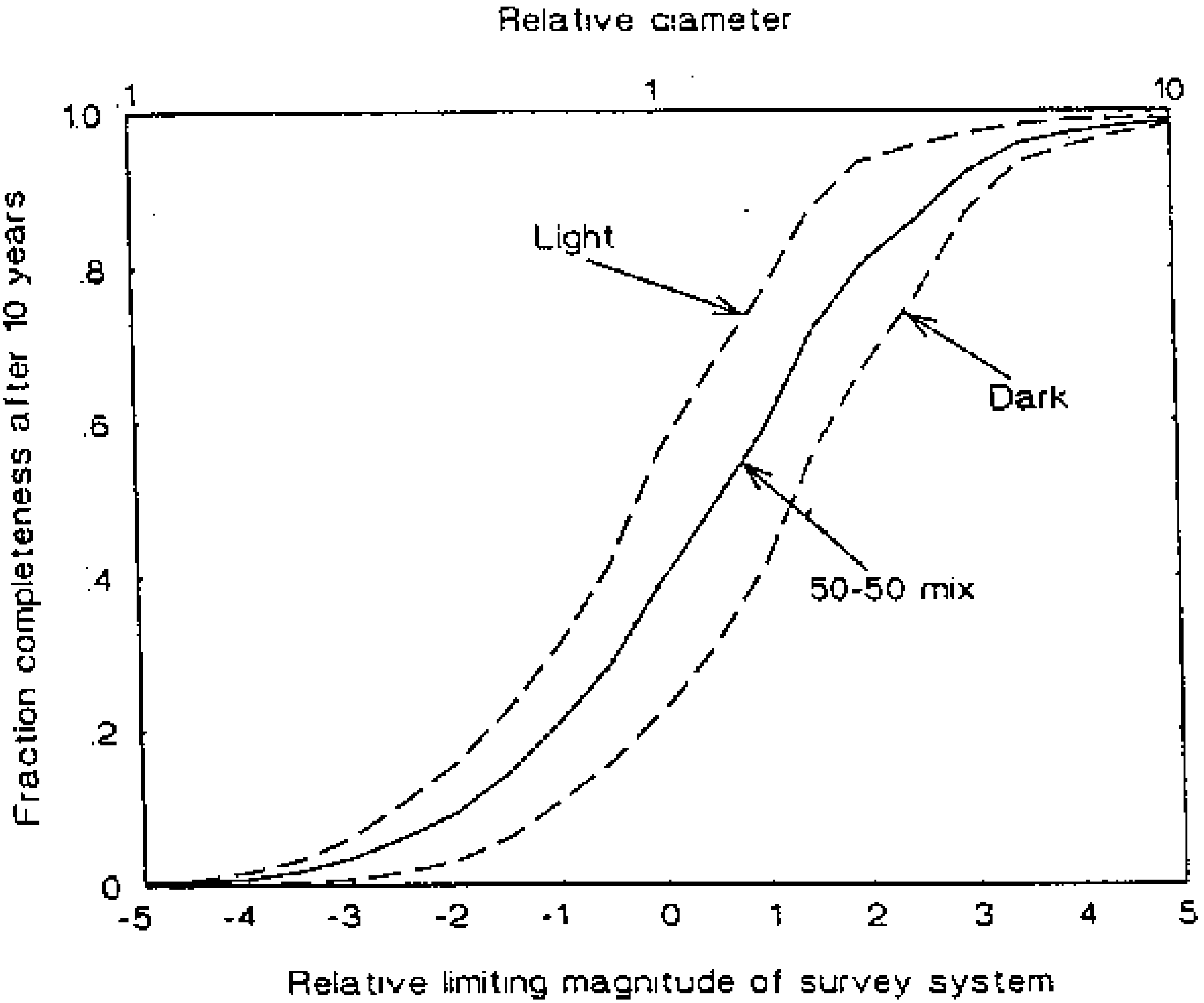

Figure 3. Completeness as a function of limiting magnitude of survey systems. Light refers to a population with albedo equal to average S-type (light) asteroids and dark refers to asteroids with albedo equal to average C-type (dark) asteroids.

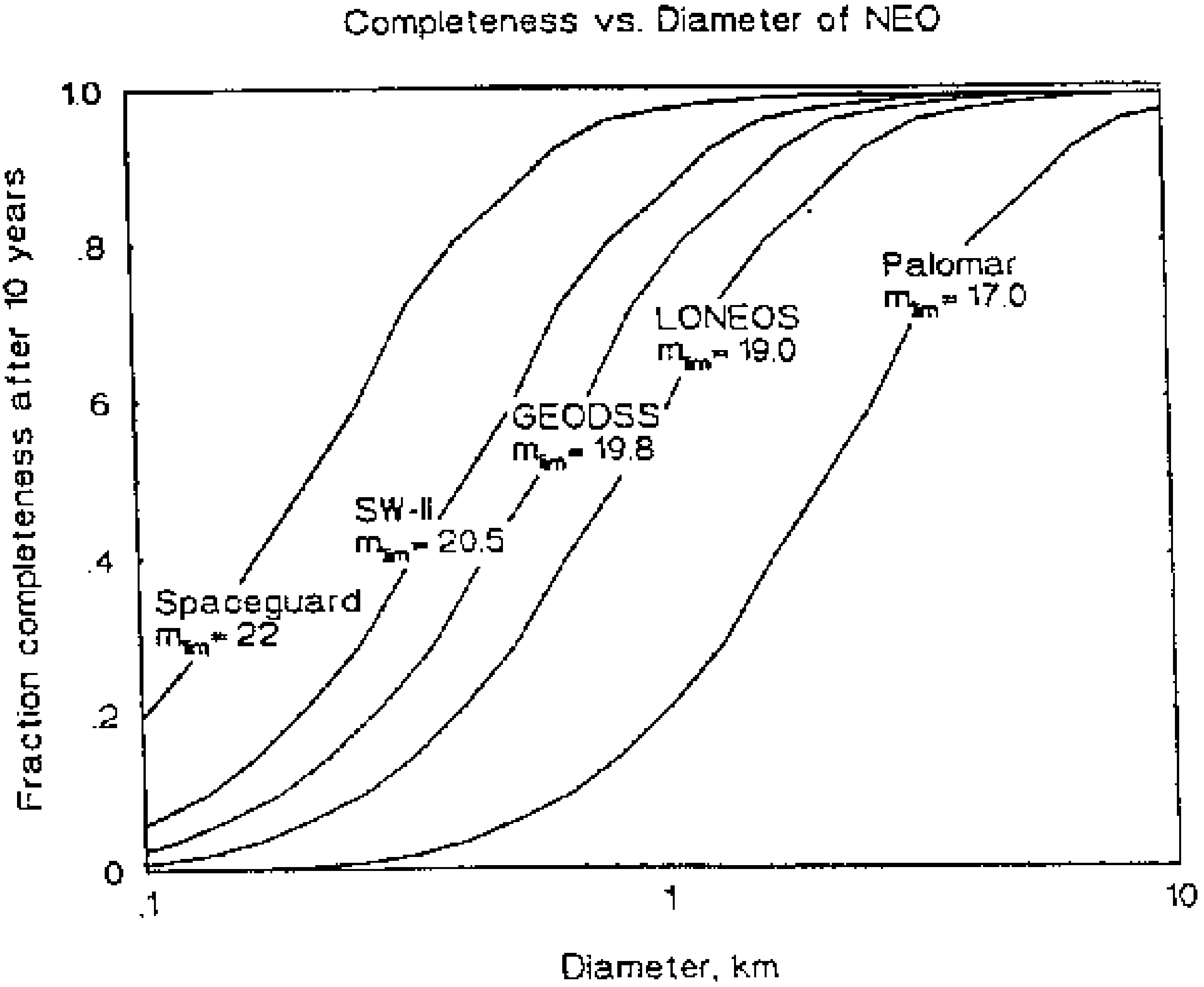

Figure 4. Completeness as a function of asteroid diameter for five survey systems described in text

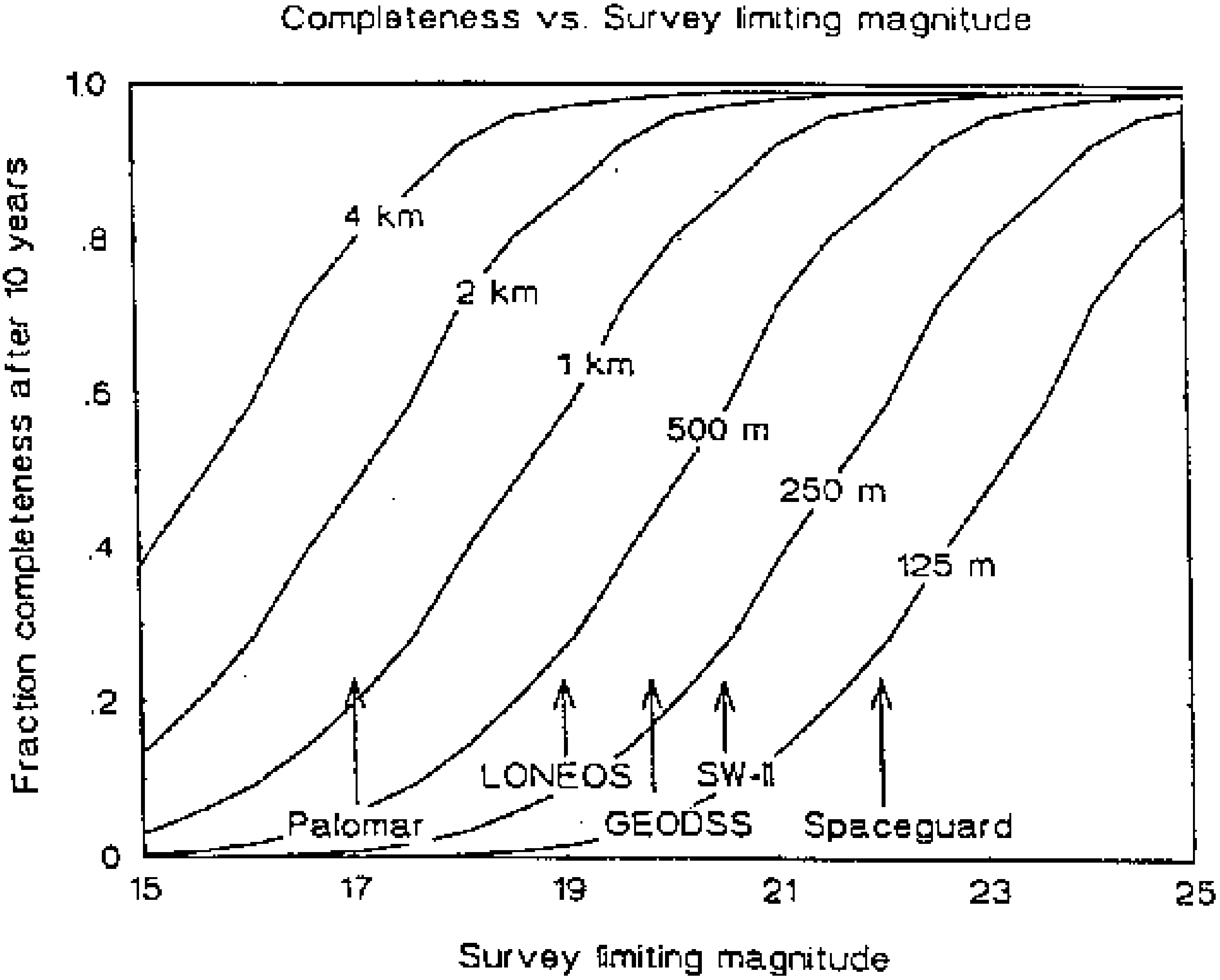

Figure 5. Completeness as a function of limiting magnitude of survey telescopes.

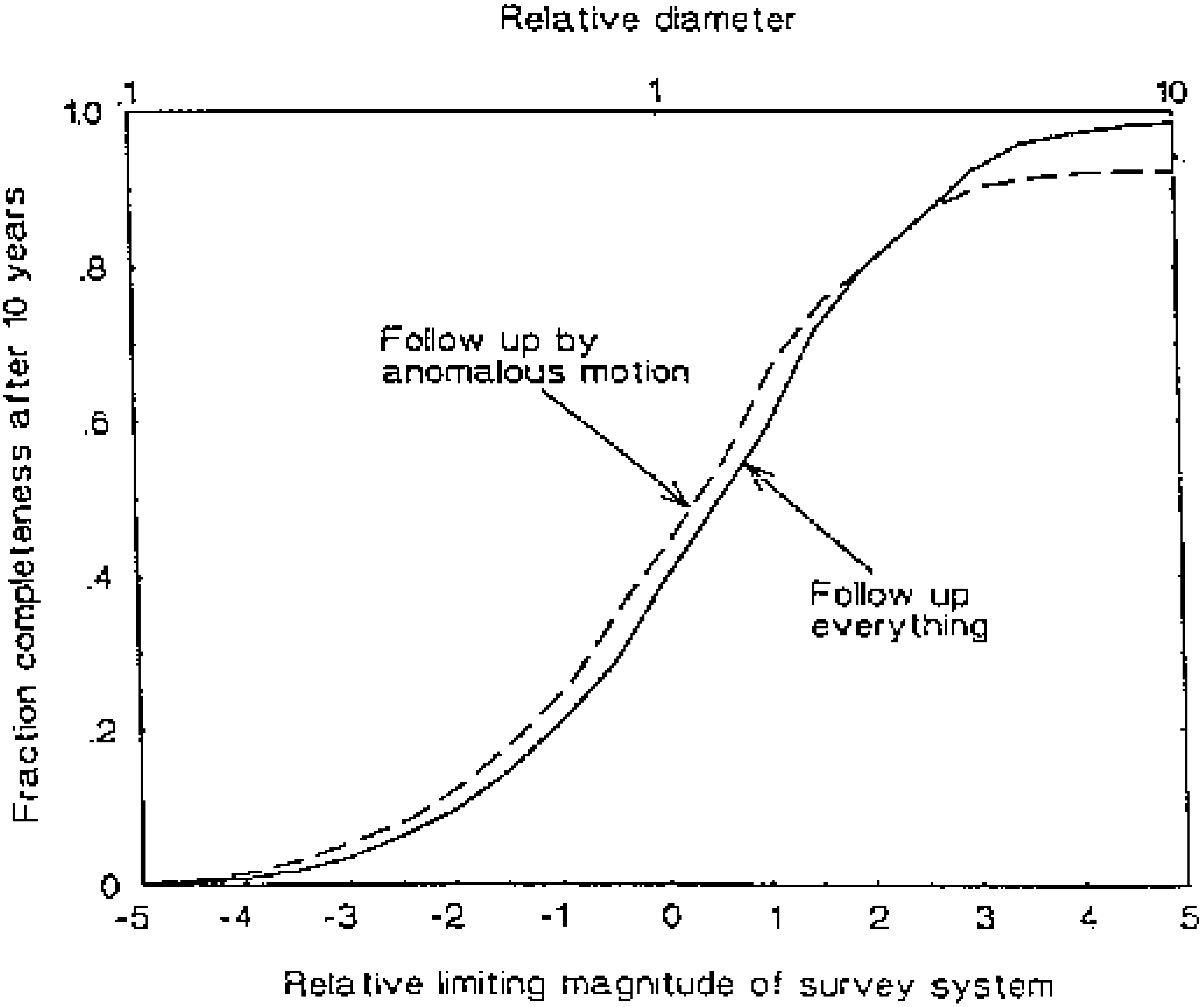

Figure 6. Completeness as a function of limiting magnitude of survey systems with two differentstrategies for preliminary orbit determination (see text).

NASA Ames Space Science Division

Asteroid and Comet Impact Hazards

VI. Precise Orbit Determination and Physical Observations

VI. Precise Orbit Determination and Physical Observations

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Additional observations following the discovery of Earth-approaching objects are required to achieve a more complete understanding of the NEO population and to assess their threat of impact on Earth. First, the orbital elements of a potentially threatening object must be obtained with sufficient accuracy to ensure recovery on its next approach to Earth, and also to determine the probability of impact at a future date. Any later attempt to mitigate the threat will depend critically on the accuracy of the observations and either the length of the observed arc during the discovery apparition, the use of radar range information, or the recognition of observations obtained on prior apparitions. Second, a sample of the discovered bodies should be classified by reflectance and spectral type in order to assess the completeness of the survey as a function of size and composition. Otherwise we will not know how many asteroids have been missed, nor the risk we would face of an impact from these undiscovered bodies. This information will be useful for planning potential measures to mitigate the threat from such objects, though such considerations are beyond the scope of this study.

Astrometric Observations

Because NEOs are often discovered at a time when they pass just close enough for detection, they often become fainter with time. After a few weeks, and sometimes only a few days, they can not be re-observed with the same telescope that made the discovery unless longer integration times are used. Half of the kilometer-sized NEOs that will be detected in an all sky survey will be visible for no more than one lunation (Table 1). Unfortunately, this observation window is too short to determine with sufficient certainty the orbit of a potentially threatening NEO from optical observations alone. Many NEOs determined to be in Earth crossing orbits could not be ruled out as threats by such limited observations. Also, the position of such an object could not be predicted with sufficient accuracy to find it again a few years later. If the telescopes that conduct the survey are large enough (~2m), they will have enough light-gathering power to cover the whole sky each month with short integrations (~10s), and still have time left over for further astrometric observations of potentially hazardous NEOs discovered in previous months. However, if meter-class telescopes are used, they will require longer integrations to achieve the same limiting magnitude, and will not have time left over for this extended astrometric follow-up. Also, they may not have the pixel resolution needed to determine orbits of adequate precision for future recovery and hazard prediction. In that case, additional telescopes of 1-m aperture or larger will be required for astrometric follow-up.

Physical Observations

There is both a need and an opportunity to make physical observations of a subset of NEOs discovered by the NEO Survey. In its barest form, the Survey would identify an enormous number of objects in Earth-approaching orbits, characterized by their orbital properties and their optical magnitudes. However, in order to identify the NEOs that would be potentially hazardous to Earth, sampling of the population's physical properties is essential. The mass-frequency relation of the NEO population must be defined in order to reach a specified level of completeness for a threat defined by impact energy. Asteroid albedos are known to differ by a factor of ~30; some constituent materials of NEOs differ even more. Without adequate information about albedos, inferred masses (and hence impact energies) could differ by more than a factor of 100. Moreover, the population of meter-to km scale objects could differ greatly from that of the larger objects. Therefore, cataloguing NEO orbital properties to some limiting magnitude does not meet the minimal goals of the NEO Survey. Sampling of associated masses (i.e by determination of diameters and albedos) is also required.

A survey of NEOs made for the purpose of raising our level of understanding about impact hazards has broader goals than merely obtaining a partial or complete census of objects of particular sizes. It should seek to obtain data about physical properties that will help us understand the impact hazard more generally. For example, it is reasonable to expect that NEOs with different origins will fragment in different ways. Extinct comet nuclei with tensile strengths ~100 to 1000 dynes/cm$^{\square}$ will fragment easily, while metallic bodies such as are represented by nickel-iron meteorites with tensile strengths exceeding 10$^{\square}$ dynes/cm$^{\square}$ will not fragment easily. The fragile, cometary bodies may therefore dominate the population of NEOs smaller than some transition size (~1 meter to 1 kilometer). Since comets originate in the outer solar system, such objects might also be expected to dominate NEOs with higher impact velocities. Thus an understanding of NEO mineralogy will be a factor in our understanding of impact hazard versus size. Ideally, the statistical completeness of the survey would be assessed for each mineralogical class, and this would require knowledge of the mineralogical type and size for as many NEOs as practicable.

If the survey is conducted with meter-sized telescopes, there is further impetus to make sample observations that determine the diameter and albedo distributions of the NEOs. Searches by meter-sized telescopes will have magnitude limits in the range V=20-21. As a result, completeness over a 10 year period drops off rapidly in the size range for which we are hoping to raise completeness to a maximum. Kilometer-sized, dark NEOs would be sampled only to a completeness of ~60% (Section VI). However, this estimate is critically dependent on the assumed albedo distributions. For example, we currently have measured albedos for only ~40 NEOs, and these are biased by observational selection. The assumption in Section VI that the ratio of dark (C type) to light (S type) albedos is ~1 could be off by a factor of 2, and this ratio may depend on the size of the NEOs. Hence, meter-sized telescopes might sample bright, km-sized NEOs to completeness level of only 75%, if there are twice as many dark objects as bright ones at 1 km diameter. We would not know the true limit unless we made enough physical observations to know the albedo distribution.

Requirements for Optical Telescopes

Physical observations must be made when an NEO is brightest (usually near the time of discovery). For the purposes of physical characterization, the minimum telescope aperture for spectroscopy and light curve measurements is 2m. Such telescopes are capable of recording visible light spectra with high signal to noise (high enough for crude spectral classification) down to V□17. Although most discoveries will be fainter (V□20), a large enough fraction (~6%) will be discovered with V &LT 17 to provide a representative sample. Light curve measurements and filter photometry with the same telescopes will allow the spectral characterization of fainter discoveries (V~20). These same telescopes could be used for both astrometric and physical follow-up.

For the purposes of albedo measurements and unambiguous mineralogical classification, however, a 2m telescope is not large enough. Albedo measurements require a combination of intensity measurements at both optical and thermal infrared wavelengths, while classification of mineralogy requires low resolution (l/d□ □100 - 1000) spectrophotometry, particularly in the 1-5 µm region. Such measurements are possible using large format infrared and visible-light detector arrays. These arrays can acquire the needed spectrum over a wide spectral range simultaneously, at the required resolution, by using cross-dispersed diffraction gratings. It is possible to design a single instrument that acquires thermal infrared, near infrared, and visible spectra simultaneously, by using several array detectors. This permits very efficient data collection and greatly reduces the limiting magnitudes.

Despite these modern advances in array technology, telescopes with apertures several times larger than the survey telescopes will be needed for mineralogical classification and albedo determination. For equal signal to noise ratio, the product of telescope area and integration time (on-chip) must be larger by R (= l/d □), assuming the detection sensitivity is limited by read noise. The on-chip integration time during discovery is typically 10 seconds and this can be easily increased to several minutes or more during the follow-up observations, when the NEO is tracked. The telescope diameter then must be ~3 to 10 times larger than the discovery telescope. For example, the 3-m IRTF in Hawaii is required to make infrared measurements (J, H, K wavelengths) for an object with V &LT 17, but is limited to V &LT 15 for infrared spectroscopy. A 3-meter class telescope is a minimum requirement.

In summary, the survey telescopes alone will not provide an adequate data base for assessing the impact hazard to the Earth. Two dedicated 2-m telescopes for combined survey and extended astrometric follow-up and/or a dedicated 3-m class telescope will be needed for follow-up astrometric and physical observations.

Radar Observations

Radar is the most powerful groundbased technique for post-discovery reconnaissance of NEOs and is likely to play a central role in identification of possibly threatening objects during the foreseeable future.

Delay-Doppler measurements are orthogonal to optical angle measurements and typically have a fractional precision between 10 and 10, and consequently are invaluable for refining orbits and prediction ephemerides. A single radar detection secures the orbit well enough to prevent "loss" of the object, shrinking the object's instantaneous positional uncertainties by orders of magnitude with respect to an optical-only orbit, obviating the need for extensive optical follow-up and greatly improving the accuracy of long-term trajectory predictions. During the past decade, observations of newly discovered objects have revealed range errors from ~100 km to ~100,000 km in pre-radar range predictions. The availability of radar measurements could be the difference between knowing that an object will pass "within several Earth-Moon distances of Earth" in a few decades and knowing that it will "hit the Earth."

The same measurements also provide otherwise unavailable information about the target's physical properties, including size, shape, rotation, multiplicity, and surface characteristics. Measurements of the distribution of echo power in time delay (range) and Doppler frequency (radial velocity) constitute two-dimensional images that provide spatial resolution as fine as 10 meters. With adequate orientational coverage, such images can be used to construct geologically detailed three-dimensional models, to define the rotation state precisely, and to constrain the object's internal density distribution. Moreover, radar wavelengths are sensitive to near-surface bulk density and structural scales larger than a few centimeters. For comets, radar waves can see through optically opaque comas and can also reveal large-particle clouds. The value of a radar observation increases in proportion to the echo strength.

A signal-to-noise ratio (SNR) as large as 20 is usually adequate for detection and marginal resolution of the echoes. SNRs greater than 100 let one achieve enough resolution to be able to make simple statements about shape. With SNRs approaching 1000, the data permit detailed constraints on dimensions, and with SNRs at least as large as ~3000 one can make images that clearly show surface features. Crudely, one can expect the number of useful pixels in a dataset to be of the same order as the SNR. The observation time required to achieve any given SNR increases with the eighth power of the distance. Even a modest-SNR radar observation can dramatically shrink the cost and risk of a spacecraft mission to a near-Earth object, by reducing or eliminating the need for on-board optical navigation and by providing advance characterization of the target. The highest-SNR radar investigations can be as informative as the cheapest NEO flybys under consideration.

The world's two primary facilities used for planetary radar astronomy are the NAIC Arecibo Observatory in Puerto Rico and the NASA Goldstone Solar System Radar (part of the Deep Space Network) in California. Arecibo is being upgraded and by 1996 will be more than 20 times as sensitive as Goldstone, see twice as far, and cover three times as much volume as Goldstone. The more fully steerable Goldstone instrument, with a solid angle window twice the size of Arecibo's and an hour-angle window at least several times wider than Arecibo's for any given target, will serve a complementary role, especially for newly discovered objects. Table 2 lists the radar-astrometric range limits expected for Arecibo and Goldstone by 1996.

Discovery apparition geometry often is exceptionally favorable to radar reconnaissance, but such windows rarely last more than a week or two. The optical-astrometric time base needed to secure a newly discovered NEO's orbit (and to identify the date of subsequent radar opportunities) is generally at least several months. That is, the radar-targeting decision usually must be made long before the orbit estimate is good enough to guarantee recovery or to identify future close approaches accurately. Minimal reconnaissance of a new NEO requires at least one block of time, probably at least two hours long, on one of a handful of possible dates, to be scheduled with extremely short notice (typically on the order of a few days to a few weeks). However, Arecibo is primarily a national center operated primarily for visitors engaged in passive radio astronomy and ionospheric physics, and Goldstone's primary responsibility is spacecraft telemetry. At each site, the total usage for all radar astronomy has averaged less than 5%; an increase to 10% is unlikely under current institional constraints. Moreover, each site has limited tolerance for frequent disruption of schedules to accommodate new targets of opportunity. Current anticipations are that only those newly discovered NEOs with the very highest SNRs and/or very long advance notice (probably 5 to 15 objects per year) can be observed at Arecibo, even if each target is observed only on one date. Roughly 90% of the opportunities to observe new NEOs from Arecibo will probably be missed. A dedicated NEO radar facility would cost more than $100M; we deem recommendation of such an expenditure inadvisable at present, although it is desirable to initiate a preliminary engineering/cost study to define the capability and optimum design of a dedicated NEO radar as a function of cost.

On the other hand, it is highly desirable ensure the vitality of current NEO radar observing programs. It also is desirable to optimize the use of Arecibo for response to NEO radar opportunities by reducing the time between identification of a radar opportunity and the initial detection of the target from several days to several hours, and by taking other steps to minimize disruption of telescope and personnel schedules. In principle, the following six actions can triple the number of useful radar observations of newly discovered NEOs, at a total cost of less than $500K per year:

1. Expand current capabilities for On-Site Orbit-Determination. The JPL OSOD program has been in use for Goldstone ECA radar observations for a year. Simplify its user interface and install it at Arecibo.
2. Connect Arecibo and Goldstone to electronic communications lines with the widest possible bandwidth.
3. Implement remote and absentee observing protocols at both sites.
4. Provide support for two full-time technical assistants, one each at Arecibo and JPL.
5. Augment Arecibo's operational support to provide enough transmitter fuel for dedication of 5% of the telescope time to NEO radar.
6. Urge that both NAIC and the DSN adopt flexible policies for optimizing response to target-of-opportunity situations.

Table 1. Cumulative fraction of NEOs that cannot be re-detected vs. time (t) after discovery. This table shows the cumulative fraction of NEOs that cannot be re-detected as a function of time, t, after discovery. V=20 is assumed, but the fractions are nearly the same for V=22. 50% of the discoveries are visible for no longer than 18 days. Since the moon is dark enough for complete sky coverage only 10 nights in each month, 18 days is typically the time an NEO must be observable if observations are to cover more than one lunation. It is thus likely that 50% of the discovered NEOs will be observable for fewer than 10 days.

t (days)	cumulative fraction
0	0.000
1	0.000
2	0.037
3	0.067
4	0.093
5	0.140
6	0.188
7	0.225
8	0.258
9	0.286
10	0.318
11	0.344
12	0.375
13	0.407
14	0.426
15	0.446
16	0.458
17	0.472
18	0.504
19	0.530
20	0.549
21	0.559
22	0.578
23	0.587
24	0.611
25	0.627
26	0.642
27	0.655
28	0.682
29	0.696
30	0.726
40	0.847
50	0.946
60	0.981
70	0.988

80	0.993
90	0.996
100	1.000

VII. Cooperation Between Air Force and NASA

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Introduction

The Department of Defense has the responsibility for protecting the United States against catastrophic losses. Those are generally thought to be military threats, but the possibility of such losses from impacts by celestial bodies is also recognized. As the primary space arm of the DoD, the USAF and Air Force Space Command are evaluating the need and steps for defending the planet from such unlikely but devastating events. Air Force Space Command already maintains a sophisticated array of ground-based sensors for monitoring the space debris that represent a hazard to space operations and an extensive array of space-based sensors that can and have detected the impact of NEOs on the Earth's atmosphere and helped to diagnose their composition. Air Force Space Command is now in the process of evaluating whether those sensors should be improved and shared for the defense of the planet. That evaluation is taking place at the policy and technology levels. The former should be completed this year; the latter should be completed by technology developments and field tests next year. If the results of both evaluations are positive, the Air Force and DoD would be in a position to address this important mission, which it would do in a manner that would fully integrate the results and capabilities of civil and international efforts.

The following section describes the capability of the current AF sensors, the technology programs for their improvement, the plans for testing them, and the options for integrating them into existing DoD sensor nets. The following section describes the steps that should and could be undertaken to efficiently integrate civil and DoD detection efforts.

Background

The Air Force has a space serveillance system which includes both optical and radar facilities, associated communications and processing which it uses to maintain the orbits of approximately 7,000 objects which are orbiting the Earth from very low altitude to geosynchronous and somewhat beyond. The Air Force maintains for the national and international community a catalog that is used by the Defense Department, the intelligence community, the civil community and the commercial community. We currently use approximately 50,000 observations a day to maintain the on-orbit catalog of all man-made objects down to 5-10 cm in diameter.

Example Activities of Potential Interest to NEO Search

Optical systems consist of the Ground-based Optical Deep Space Surveillance (GEODSS) System, plus the large telescopes on Mt. Haleakali, Maui. The GEODSS main telescope characteristics are described in Figure 7. These telescopes have low F numbers and large fields of view which are a fundamental advantage for NEO search because they were designed as search instruments. These telescopes appear to be quite suited for the search of asteroids down to sizes on the order of 100 meters in diameter and at ranges out to approximately 1 AU (see Figure 8).

The Air Force has a research and development program at Lincoln Laboratory to develop a new advanced CCD imager for GEODSS. Its properties are described in Figure 9. The GEODSS main telescope and the new Lincoln camera will be in a testing mode until late spring or early summer 1995. The Air Force's experimental test site (ETS) is near Socorro, NM. Our current estimate is that the one GEODSS main telescope at ETS with the new camera should have the capability of increasing the current world wide discovery rate of Earth-crossing asteroids by a factor of ten (search coverage approximately 6,000 square degrees per month at limiting visual magnitude of 22). The Air Force currently has six GEODSS main telescopes that are not part of the current space surveillance operations.

The Air Force's GEODSS Upgrade Prototype System (GUPS) is focused on demonstration of new technologies with a plan of incorporating new technologies in the operational GEODSS. GUPS is a fully transportable GEODSS site, which would be an advantage in quickly establishing a new site. GUPS is managed by Air Force Electronic Systems Center and has a three year development schedule ending 9/96. There are extensive demonstrations to be performed during the program at the ETS. GUPS is shown in Figure 10.

The Air Force's Phillips Laboratory is developing a 3.7 meter telescope at Maui known as AEOS. Our analysis suggests that if AEOS is used as a follow-up sensor it is capable of developing a characterization matrix for each newly discovered Earth-crossing object (light curve, spectral characterization, albedo) as well as improving the quality of the orbit for each catalogued object up to approximately 120,000 objects per year, which is the maximum expected from the upgraded detection suite.

In summary, the advances in computer and focal plane technologies since 1976 have motivated the attempts to improve the GEODSS system. The Lincoln large-area CCD camera, coupled to a 40-inch GEODSS telescope, will be field-proven by approximately 1 April 95 at the ETS. The GUPS will be turned over to the Air Force in very late 1996 at the ETS. The GEODSS sensor upgrades (Ebiscon to large CCD) may start in FY'1998, but no sooner. The search for NEOs is not an entirely new mission for there seems the Air Force's ETS has in the past detected new asteroids; for example 2460 MIT Lincoln, 3343 Nedzel, and 3403 Tammy.

Near Term Cooperative Efforts

We are proposing to pursue within resources a proof of concept capability that will evaluate the usefulness of GEODSS with the new CCD camera for near-Earth object searches. We expect such proof of concept work could start late spring/early summer 1995 with a proposed asteroid tracking demonstration in September 1995 and regular observing schedule proposed to start October 1995. This would be a research and development activity at the GEODSS ETS optimizing software and interaction with other site tasking. The Air Force proposes to hold periodic meetings with the scientific community to discuss the results and provided data to the scientific community over the next two to three years.

Air Force Space Command (AFSPC) has asked Los Alamos National Laboratory (LANL) to study the physics of signatures of asteroids impacting Earth's atmosphere as seen by Defense Department's space sensors, evaluating the uselfulness of DoD space sensor data on composition of asteroids and measuring the flux of smaller asteroids passing very near Earth. Classified and unclassified workshops on these topics are planned for the summer of 1995. AFSPC's Chief Scientist will be hosting workshops in a number of areas for invited experts from the scientific community. The first workshop on 12-13 May 1994 covered all aspects of the threat, detection, and defense. Subsequent workshops will be more focused. The following three planned workshops will be co-hosted by Dr. Shoemaker:

A. Evaluating the risk to the planet

B. Evaluating the role of *in situ* and fly-by missions to future defense, and

C. Evaluating the technical means of defense

> (note: The planned international meeting at Lawrence Livermore National Laboratory during the last week of May 1995 may meet this need).

Future Decision Making

Air Force Space Command has been tasked by the Air Force Chief of Staff to do a Mission Area Assessment for defense of the planet. The time scale for Air Force evaluation in decision making is likely one to two years. The Air Force Scientific Advisory Board will have an ad hoc study in calendar year 1995 to review space surveillance/space debris/asteroid warning. Thus, the Air Force should be able to make firm decisions about significant commitments in this mission area, although that will not happen in the very short time scale prior to this report.

```
------------------------------------------------------------------------------------------------------------------
CONFIGURATION           Folded Prime Focus
APERTURE DIAMETER (in): 4.0
EFF, CLEAR APERTURE (m2):       0.46
FOCAL LENGTH (in):      8.6
F NUMBER:       2.15
FLAT FOCAL PLANE DIAMETER (mm): 8.0
SPECTRAL BAND:  0.35-0.9 mm
IMAGE QUALITY:          80% of energy from solar pointsource encircled in 2 arc sec diameter
ENCODER ACCURACY (arc sec rms): 1.5
ENCODER RESOLUTION (arc sec):   0.36
----------------------------------------------------------------------------------------------
```

Figure 7. GEODSS Main Telescope Characteristics

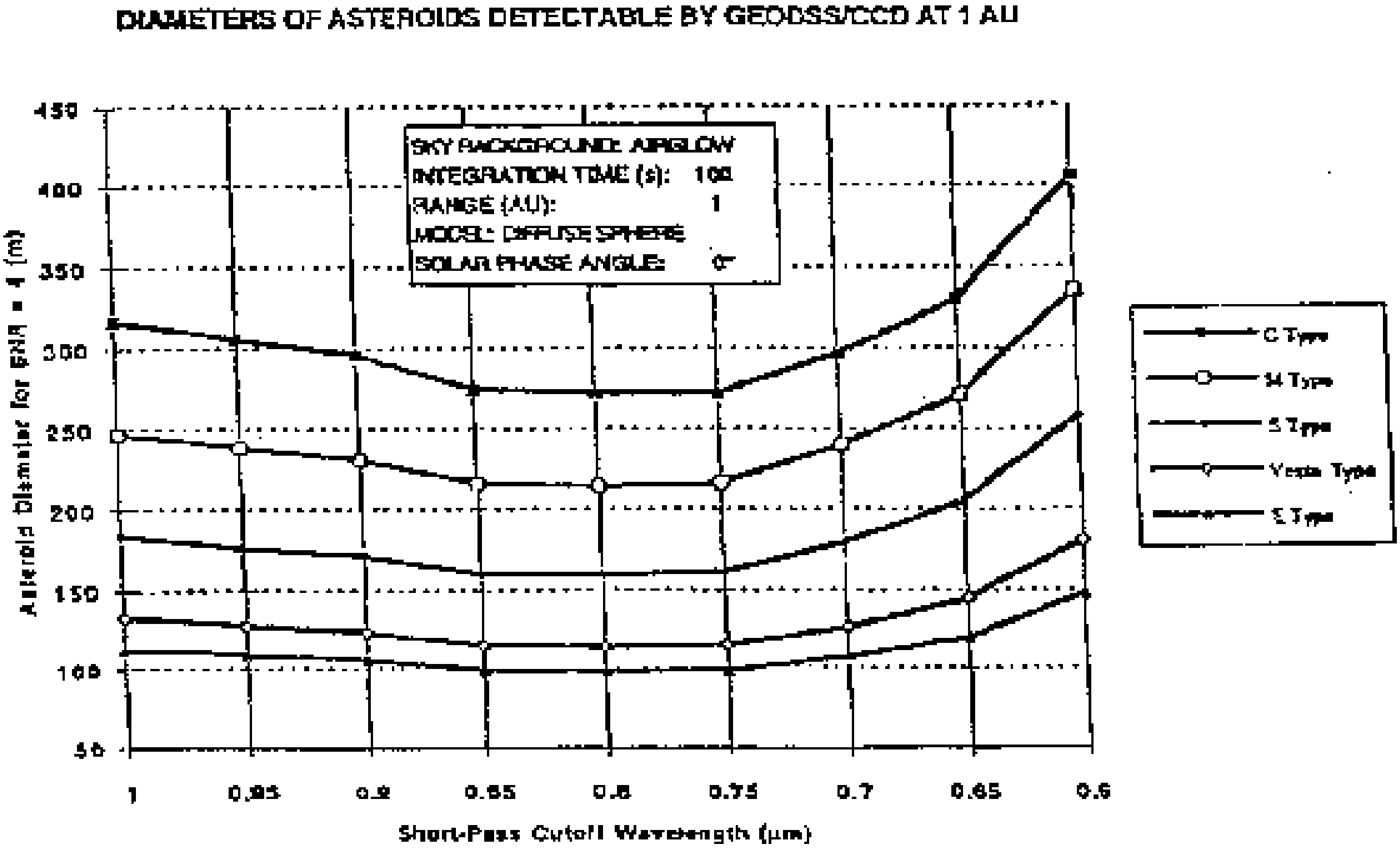
DIAMETERS OF ASTEROIDS DETECTABLE BY GEODSS/CCD AT 1 AU
SKY BACKGROUND: AIRGLOW
INTEGRATION TIME (s): 100
RANGE (AU): 1
MODEL: DIFFUSE SPHERE
SOLAR PHASE ANGLE: 0°
C Type
M Type
S Type
Vesta Type
E Type
Asteroid Diameter for SNR = 4 (m)
450
400
350
300
250
200
150
100
50
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
Short-Pass Cutoff Wavelength (µm)

Figure 8.

```
 ------------------------------------------------------------------------------------------------------------------------
 LINCOLN CCD IMAGER FOR GEODSS

         PIXELS: 2560 X 1960
         PIXEL WIDTH:    24 mm
         READOUT METHOD: FRAME-TRANSFER
         SPECIAL FEATURE:        SEPARATE 32 x 32 PIXEL CCD PHOTOMETER
         FOCAL PLANE AREA:       61.4 x 47.0 mm FOR LARGE CCD
                 0.77 « 0.77 mm FOR PHOTOMETER
         # READOUT PORTS:        8 FOR LARGE CCD, 1 FOR PHOTOMETER
         HIGHEST DATA RATE:      2 MHz
         HIGHEST FRAME RATE:     10/s  FOR LARGE CCD (2x2 Bin)
                 1000/s FOR PHOTOMETER (No Bin)
         READOUT NOISE AT HIGHEST RATE:  †10 ELECTRONS RMS FOR LARGE CCD, †6 ELECTRONS RMS FOR PHOTOMETER
         †SOLAR QUANTUM EFFICIENCY :     65% (BACK-ILLUMINATED)
         RESPONSIVITY VARIATION: †2% RMS
         DARK CURRENT AT -50¡ C: †24 ELECTRONS/PIXEL/s
         DARK CURRENT VARIATION: †10%RMS
         CHARGE TRANSFER INEFFICIENCY:   †1.0E-5, 1620 electrons, -40¡C
         FULL WELL CAPACITY:      500,000 ELECTRONS PER 2 x 2 BINNED PIXEL
         %PIXELS AFFECTED BY POCKETS:    †0.2%, ALL ISOLATED
         %PIXELS WITH BRIGHT DEFECTS;    †0.15%, ALL ISOLATED
         FLATNESS:       ± 10 mm P-P
 ------------------------------------------------------------------------------------------------------------------------------
```

Figure 9. Lincoln CCD Imager Characteristics

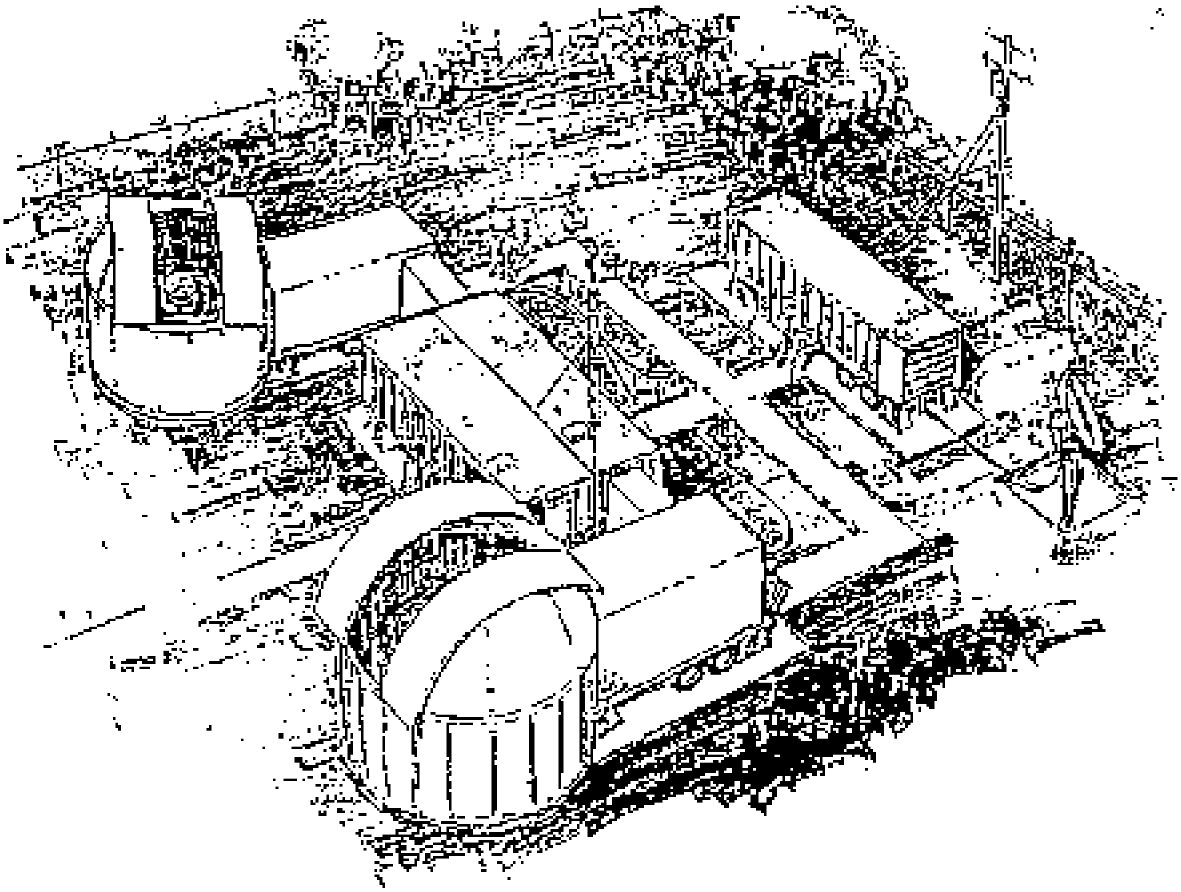

Figure 10. GEODSS Upgrade Prototype System

VIII. International Cooperation

VIII. International Cooperation

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The discovery of asteroids and comets and the determination of their orbits has been, by long-standing tradition, an international effort. By agreements through the International Astronomical Union, the maintenance and publication of ephemerides of all numbered minor planets has been the responsibility of the Institute for Theoretical Astronomy (ITA) at St. Petersburg, Russia. The ITA has supported a long-range program of astrometry to upgrade the orbits of known asteroids. The center for receiving observations of newly discovered as well as established asteroids and comets has been the Minor Planet Center, now located at the Smithsonian Astrophysical Observatory at Cambridge Massachusetts. This center collates the incoming observations, assigns designations, calculates preliminary and improved orbits, determines when a minor planet becomes numberable, and publishes the results on a monthly basis in the Minor Planet Circulars (MPCs). The work of observers and orbit calculators throughout the world are published in the MPCs. Most of the immediate dissemination of information on NEOs is nowadays via the Minor Planet Center's MPECs (Minor Planet Electronic Circulars), although initial cometary information is communicated via the IAU Central Bureau for Astronomical Telegrams (IAU Circulars), also located at the Smithsonian Astrophysical Observatory. This system has served to coordinate the existing international effort of discovery of asteroids and comets extremely well, including all work to date on NEOs.

There is a continuing high level of international interest in dedicated NEO surveys. One of the strongest on-going efforts is the Anglo-Australian Near-Earth Asteroid Survey (AANEAS). Located at Siding Spring, New South Wales, AANEAS utilizes several telescopes (Steel, 1995). AANEAS not only reports numerous discoveries of NEOs but also provides crucial follow-up astrometry and recovery of NEOs found elsewhere, particularly when observations are needed in the southern sky. Another important program of follow-up astrometry is being carried out in Canada.

A new observing system, utilizing an array of CCDs at the focal surface of a 1-m Schmidt telescope is being developed at C·te d'Azure, France. This system, which will be dedicated primarily to NEO search, will substantially improve the coverage of the sky needed in NEO surveys.

In Japan, where amateur observers have made significant contributions to discovery and astrometric observations of NEOs, Syuzo Isobe (1994) of the

National Astronomical Observatory of Japan has proposed that a network of telescopes belonging to cities and amateurs be equipped with CCD detectors to provide critical astrometric observations of discovered NEOs and to assist in the NEO search. A suitable CCD system is being tested; as many as 47 telescopes with apertures larger than 50 cm potentially could participate in this network.

A working group of the International Astronomical Union, chaired by Andrea Carusi of Italy, has been established to help formulate an international program of surveying for NEOs. Investigators and observatories in Europe are potential participants, and a plan is being developed for use of a 1-m Schmidt telescope at the European Southern Observatory in Chile in NEO search. In China, funds have been allocated for a 1-m telescope dedicated to an NEO survey.

As the hazard of NEO impact is global, the systematic survey for NEOs should be an international effort. Appropriate institutional mechanisms are already in place, at the ITA and the Minor Planet Center to coordinate international participation. It is expected that strong support of an NEO Survey in the United States by NASA and the Air Force will help foster support by other nations of the systematic survey work abroad.

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IX. Coordination of Observing Program

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The proposed NEO survey will provide a flexible and cost-effective approach to meeting the objective of discovering and cataloging NEOs (both Earth-crossing asteroids and short-period comets) with the goal of complete coverage of objects 1 km or more in diameter. By upgrading and coordinating existing telescopes (either presently operational or under development), the survey reduces start-up costs and accelerates the time-table for NEO discovery.

Flexibility of operation should allow the most effective use of any particular configuration of survey instruments that may be operational at any given time. If only a single telescope is on-line, then it can be operated in a way that will, for example, maximize the discovery rate for 1-km or larger NEOs by scanning rather rapidly over a large sky area centered on the opposition point. If a second identical or similar telescope is added, the two can be used together to scan complementary sky areas, increasing the total area covered as well as probing to fainter objects by lengthening exposure. In a similar way, the observations of different telescopes with dissimilar operating characteristics can be optimized. The objective of such an approach is to maximize the total number of discoveries of the target objects by eliminating redundant discoveries and optimizing the use of each instrument to take advantage of its particular capabilities. Cooperation replaces competition, to the advantage of all the parties.

With an adaptable system, it is not necessary to specify detailed instrument requirements in advance. Within a range of operating parameters (aperture, focal length, scan rate, number of pixels, etc.), any telescope and detector system can contribute to the overall NEO survey. It is possible for new partners to join in the NEO survey effort at any time, as they bring their own individual systems to an operating state. This adaptability is especially attractive for an international system, since each partner can decide independently the nature of any new systems to be developed and the degree to which such systems must be specially configured for NEO survey work. While we envision a survey that consists initially of a small number of existing U.S. telescopes that can be brought into operation quickly, we anticipate that the survey will grow into an international effort as other partners choose to join.

As more telescopes become available to the NEO survey, the complementarity of their operations can be increased. In the early stages, with only 2 or 3 systems operating, it may be most efficient to have each system perform its own confirmation and follow-up, sharing information with others but operating in a manner not too different from that of current NEO surveys. At this stage, the primary coordination requirement will be to ensure that the surveys are complementary and not redundant. But as the network expands, it might become more efficient for some instruments to concentrate on discovery, and others to concentrate on follow-up. It will not be efficient to interrupt the operations of any one telescope for follow-up once the discovery rate increases by an order of magnitude above current values.

The cross-over into a truly interdependent and fully coordinated system is the most important operational hurdle for the maturity of the survey. It will require a fundamental change of attitude, with a high level of communication and trust among different observers. A coordinating center will need to be established, possibly to be co-located with the central organization for data analysis and orbit computation. This center will provide the day-to-day technical coordination of the effort consistent with guidelines to be established by the consortium of survey partners, who will meet from time to time as a steering group to review the performance of the system.

X. NEO Computational and Data Centers

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As the discovery rate of near-Earth objects accelerates, there will be an increased need for the close coordination of the various observing sites to optimize the efficiency of the entire discovery program. An integral part of this cooperative effort will be the efficient processing of astrometric data, the computation of orbits and ephemerides, and the rapid dissemination of these data products to the observing communities. An optimized discovery program for near-Earth objects will rely upon extremely close cooperation between the community of observers and those concerned with modeling the past and future motions of the entire population of the solar system's small bodies. Once a moving object is detected, telescopic observers will need to be aware of any previously discovered objects in their fields of view to distinguish new discoveries from those objects that have been previously observed. In addition, a central repository, or repositories, will be required to catalog for each object, the discovery data, the follow-up astrometric data, updated orbits, and any data that could be used to physically characterize the particular object. These activities will be the responsibility of the NEO computational and data centers.

The objectives of the NEO computational and data centers are to:

1. For all asteroid and comet discoveries, immediately distribute observations to other data centers. The centers would then coordinate activities so that NEOs are immediately identified and observers are notified of the identifications
2. Provide discovery and follow-up observers with rapid response orbits, ephemerides, error analyses, and optimal future observing opportunities.
3. Coordinate the follow-up optical and radar observation programs that will obtain astrometric observations and the data used to physically characterize new objects.
4. Search existing observation files for pre-discovery astrometric data that might extend the observation interval for orbit determination work. In addition, center personnel should encourage the examination of unmeasured plates for pre-discovery observations.
5. Archive astrometric observations, orbits, ephemerides, error analyses, and the data used to describe the object's physical characteristics.

6. Determine whether each NEO will become a potential threat to Earth in the future.

During the establishment of the NEO computational and data centers, care must be taken to ensure that each center is using common planetary ephemerides, archives, and data files and that each center's software is cross-checked against similar software at other centers.

Processing astrometric observations and determining orbits can be separated into two types of activity that are basically distinct. The first type involves the recognition of all the observations that belong to individual objects, while the second involves the handling of objects of special interest.

Separating Observations of Individual Objects

The initial processing of astrometric data and cataloging these data by object is an activity that is already underway at the Minor Planet Center in Cambridge Massachusetts. The current activities of the Minor Planet Center could be extended to meet the demands of the NEO survey described in this report. As such, it is instructive to begin with a summary of the Minor Planet Center's current activities.

Astrometric observations are currently received by the Minor Planet Center at a rate that averages several hundred per day. In a typical year there are observations of several comets, several tens of near-Earth asteroids and several thousand asteroids generally. Several tens of observatories distributed around the world are involved in this effort. A good rule of thumb is that near-Earth asteroids amount to 1 percent of the total number of observations. For near-Earth objects, two observing programs currently account for about 55 percent of the data, two more programs add another 10 percent, and amateur astronomers collectively contribute rather more than 20 percent. For the most part, it has been expected that observers will arrange their work so that the same sky fields are covered on two neighboring nights and that on reporting their astrometric data, they will properly label the positions that belong to the same objects. On receiving material of this type, the Minor Planet Center first identifies numbered asteroids, other asteroids previously observed at multiple oppositions (or for several months during a single opposition), and asteroids that have been already discovered and observed on two nights at the current opposition. The remaining two-night sets of observations are then designated as new discoveries, after which more sophisticated techniques are used to attempt identification with asteroids observed only imperfectly in the past; orbits are determined, and advice is given to the observers as to whether further observations at the current opposition might be beneficial for securing its orbit. Such communications are also made when errors--most frequently timing errors--are detected in the data. Single-night observations may also be included in the identification process, although discoverers are usually not credited without a second night of observations.

While observers have been encouraged to make observations for two-nights and to participate in a two-way communication to maximize the usefulness of their observing programs, the Minor Planet Center has also recently worked with extensive sets of single night observations from the Spacewatch program with a minimum of communication -- except for the month-by-month publication (in printed and electronic form) of the orbital information and astrometric data sets. In a recent experiment, a month's supply of observations at a daily rate of 500 were completely processed by one person using one computer in 1.5 days. It is estimated that the current staff and facilities of the Minor Planet Center could accommodate an order of magnitude increase in observational throughput if no hardware or software maintenance were required, the observations are submitted in a businesslike manner without further communication with the observers, and if the quantity of the formal published data were sharply reduced.

With a fully operational NEO survey, we estimate that the increase in volume of observations reaching the Minor Planet Center will be two orders of magnitude more than the current volume. This increase will also mean that the number of near-Earth objects detected in the future will be comparable to the current discoveries of the main-belt objects.

Attending to Objects of Particular Interest

Those asteroids and comets that are potentially Earth-approaching can be automatically recognized in the complete data set and isolated for further study. A simple test can easily be conducted to determine whether or not a particular object's orbit could possibly bring it within close proximity to the Earth. If this is the case, an effort should be undertaken to determine the likelihood of the object actually making a close Earth approach (for example, within the distance of the Moon) in the foreseeable future. The immediate prediction of actual close Earth approaches is necessary to identify potential threats and optimal opportunities for ground-based characterization of the objects by ground-based photometric, spectroscopic, and radar techniques. During close Earth approaches, the astrometric data (optical and radar) used to refine the orbital solutions are extremely powerful in driving down ephemeris uncertainties. In addition, predicted close Earth approaches are important in identifying future opportunities for spacecraft intercepts because, during these close approaches, potential mission targets will have greatly reduced ephemeris uncertainties, short communication distances, and excellent opportunities for ground-based observations to complement the in situ spacecraft data.

For the near-Earth objects of special interest as future radar targets, for future space missions, and for those objects expected to make future close Earth approaches, personnel at the Jet Propulsion Laboratory (JPL) have carried out, or coordinated, the necessary astrometric observing programs, orbit updates, error analyses and predictions for close approach circumstances. For these special objects, the necessary astrometric data are either sent directly to JPL, then relayed to the Minor Planet Center (MPC) or sent first to the MPC and immediately relayed to JPL. In either case, the astrometric data for these objects are resident in files at both the MPC and JPL.

For those near-Earth objects that are identified as having the potential to closely approach the Earth, the following steps would be undertaken:

1. Additional optical astrometric data (and radar data if possible) would be solicited to refine the orbit, and forward numerical integrations and error analyses would be made to identify the times and distances (and associated errors) for future close Earth approaches.
2. For those objects that are predicted to make close Earth approaches within a few tens of years and are identified as either potential threats to Earth or suitable spacecraft mission targets, special ground-based observing programs would be established as follows:
    1. Optical astrometric observations would be taken and reduced with respect to accurate reference star positions such as those contained in the Hipparcos and Tycho reference star catalogues.
    2. If possible, radar astrometric data would be taken to further refine the object's orbit and to reduce the future ephemeris uncertainties.
    3. Photometric, spectroscopic, and radar observations would be taken to physically characterize the object's size, shape, albedo, spin state, and infer its chemical composition and mass.

- As more and more astrometric data are received, the orbit would be continually improved and forward integrations would be run to refine the predicted times and circumstances of coming close-Earth approaches. For each new orbit, error analyses and impact probabilities would be computed to define the object's position and position uncertainties for future close Earth approaches.

NASA Ames Space Science Division

Asteroid and Comet Impact Hazards

XI. The Broader Significance of NEOs

XI. The Broader Significance of NEOs

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The NEO survey recommended here constitutes a fiscally sensible first step in assessing and reducing the risk of a globally catastrophic asteroid or comet collision with Earth. The most likely, and certainly the most desirable outcome of the survey, will be that none of the discovered NEOs will turn out to be hazardous during at least the next century. Regardless of the outcome, the survey will identify tens of thousands of small worlds that, at least for a century, are not on collision course with Earth.

The potential promise of these "friendly" NEOs is highly significant for a variety of reasons, most of which stem from their closeness to Earth and their accessibility. The NEO population includes the cheapest targets of human and robotic exploration beyond the Earth-Moon system. In fact, many of the objects likely to be discovered will be accessible with very low delta V (i.e., less than required to land on the Moon and for only those with small orbital eccentricities) and low roundtrip mission times (6 months or less). These represent by far the easiest targets for human exploration (far easier than landing on the Moon - no landing module required, minimal delta V for rendezvous and escape).

Therefore, expeditions to NEOs are logical next steps in an evolutionary program of human exploration of the solar system: The NEOs are humanity's stepping stones to Mars and ultimately deeper space. Of course, any economically viable vision of space exploration will place the highest immediate priority on inexpensive robotic including multiple flyby, rendezvous, and sample return. High-speed intercept of numerous NEOs by microsatellites also appears feasible and cost-effective.

The rationale for telescopic and robotic reconnaissance of NEOs is multifaceted. Pieces of NEOs that have fallen to Earth as meteorites show a wide diversity of composition. Most contain at least some free metal (iron-nickel alloy and small portions of platinum-group metals and gold) and chemically-bound oxygen. Many contain organic chemicals and water of hydration. The NEOs thus constitute key space resources with considerable potential in the future exploration of space. In principal, NEO minerals could be used to provide oxygen, water, biomass, and fuel to help sustain human colonies. Many NEOs may be loosely bound aggregates that would facilitate construction of a human habitat within a shell of material to secure shielding from potentially lethal high-energy particles. In this light, NEOs may ultimately become the first long term human outposts beyond the Earth-Moon system.

Meanwhile, it is desirable to begin to build up a base of knowledge for deflecting or destroying a threatening object; thorough understanding of the internal structure of NEOs will require robotic exploration and may require geophysical reconnaissance by humans. Fortunately, the likely sizes of accessible NEOs are well suited to the capabilities of human explorers.

The recent discovery that we exist in an asteroid swarm has enormous long term consequences, and its historical importance may someday be seen to rank with Columbus's discovery of the New World. Collisions with NEOs have played a prominent role in the geological and biological evolution of Earth, and one way or another, NEOs probably will play a role in the long term future of human civilization. Our knowledge of the NEO population (and of its influence on the origin and evolution of Earth and life) is in its infancy, and detailed information about individual objects is extremely sparse. However, a science of NEOs has emerged, and can be expected to mature in parallel with the discovery and exploration of the NEO population.

It is thought that the NEO population is derived from a great range of sources -- primitive asteroids, differentiated asteroids, and extinct comets. Probably they include everything from returning fragments of Earth-Venus planetesimals to Uranus-Neptune planetesimals and Kuiper belt objects. Because of their frequent close passes by the terrestrial planets, the dynamical evolution of NEOs is extremely complex. Definition of the orbits of a sufficiently large sample of NEOs is likely to elucidate mechanisms for their delivery into Earth-crossing orbits and should also refine statistical assessments of collision probabilities. This work is coupled to determination of cratering rates and the chronology of evolution of the terrestrial planets. It also should constrain ideas about delivery of volatiles to Earth and the terrestrial planets and the influence of this process on the early history of life.

During the past few decades, NASA's discovery and exploration of other worlds has captured the imagination of a generation of young people who decided to embark on careers in science and engineering. These achievements of America's space program have truly elevated the human spirit. History tells us that the need to explore is built into the human psyche. Most would agree that an exciting, yet affordable, domestic space program can help to ensure the vitality of our society as we begin the next millennium. All indications from telescopic observations are that many NEOs are unlike any objects yet seen by spacecraft, extraordinarily strange places that pose unique challenges for investigations by robots and humans.

Accordingly we recommend that NASA view the NEO survey as part of a broad-based program of NEO research focused on robotic and human exploration objectives. NASA should embrace discovery and exploration of Earth-crossing asteroids as a cornerstone of the space program, as a fiscally responsible initiative with virtually enormous guaranteed return.

The United States could celebrate the dawn of the Third Millennium by declaring its intention to land humans on an asteroid to conduct intensive scientific exploration and to return them safely to Earth in the first decade of the next century.

Note Added in Press by Near-Earth Objects Survey Working Group on 30 June 1995: This study was conducted under severe time restrictions, thus it was not possible to consider certain aspects that would otherwise have been explored more thoroughly. In particular, the Working Group did not consider surveys from space. Proper study of space-based surveys would have required more resources and time than were available to the Working Group, and are therefore deferred to a future study.

Likewise, it must be stated that the plan outlined in this report does not fully address the hazards posed by comets, especially long-period ones and dormant nuclei. This matter deserves further study, both in terms of the level of hazard posed and in effective means of detection of such objects.

This report deals primarily with scientific and technical issues related to near-term assessment of the impact hazard, within the constraints imposed by a severe fiscal environment. However, in this section we briefly consider certain other aspects of near-Earth objects, primarily from the perspective of future exploration and exploitation. The Study Group presents these as interesting possibilities with varying degrees of practicality, ranging from `presently economically and technically feasible' in the case of robotic exploration to `provocative and interesting' in the case of resource extraction. Clearly, the most significant dividend from near-term exploration of near-Earth objects will be improved understanding of the roles played by such objects in the origin and evolution of our planetary system, and their influence on humans and other living organisms.

XII. Suggested Five-Year Budget for NASA Support of NEO Survey

XII. Suggested Five-Year Budget for NASA Support of NEO Survey

The level of funding required to carry out the recommended program is as follows:

Years from Beginning of Funding

	Year 1	Year 2	Year 3	Year 4	Year 5
Optical Survey					
Equipment	2.5	0.5	0.2	1.2	1.0
Development & Operations	1.0	1.0	1.3	1.5	1.7
New 2-m Telescope	0.3	2.0	2.0	2.0	0.1
Data Centers	0.2	0.2	0.4	0.5	0.6
Physical Observations	0.3	0.6	0.8	1.0	1.1
TOTAL	4.3	4.3	4.7	6.2	4.5

The total cost for five years is $24 million. Beyond the first 5 years, the annual costs drop down to operational costs of about $3.5 million per year. Major investments are needed in advanced focal-plane arrays, supporting computers, and one new dedicated 2-meter telescope in the first five years. The survey cannot come close to meeting a goal of 90% completeness down to 1 km diameter NEOs without such an investment.

Along with the acquisition of the necessary equipment, substantial development of computer programs to handle the data flow from large format CCDs and the maintenance and augmentation of skilled observing teams is required. The costs of operation of the observing facilities will increase as these facilities become fully instrumented.

A huge increase in the number of discovered asteroids will require support for centers that receive the positional observations, collate and coordinate observations, and complete preliminary and final orbits. The level of support needed will increase as the discovery rate ramps up to a plateau in about five years.

We recommend that physical observations of NEOs be increased from the present modest level of effort as the rate of discovery ramps up. Both optical (including infrared) and radar observations are needed. To obtain a good understanding of a representative sample of NEOs, an appropriate level of effort would be about $1.1 million per year, when discovery rate reaches a plateau.

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Impact Hazard.

The greatest risk from cosmic impacts is associated with objects large enough to disturb the Earth's climate on a global scale by injecting large quantities of dust into the atmosphere. Such an event would depress temperatures around the globe, leading to massive loss of food crops and possible breakdown of society. Various studies have suggested that the minimum mass impacting body to produce such global consequences is several billions of tons. The corresponding threshold diameter for Earth-crossing asteroids or comets is between 1 and 2 km. Smaller objects (down to tens of meters diameter) can cause severe local damage but pose no global threat.

Search Strategy.

Current technology permits us to discover and track nearly all asteroids and short-period comets larger than 1 km in diameter (estimated population about 2000) that are potential Earth-impactors. These objects are readily detected with moderate-size ground-based telescopes. What is required is a systematic survey that effectively monitors a large volume of space around our planet and detects these objects as their orbits repeatedly carry them through this volume of space. In addition, long-period comets could be detected with advance warning of several months before impact, using the same telescopes used for the asteroid survey.

Spaceguard Survey Network

The survey involves a coordinated international network of specialized ground-based telescopes for discovery, confirmation, and follow-up observations, monitoring about 6000 square degrees of sky per month with automated signal processing and detection systems that recognize asteroids and comets from their motion against the background stars. The telescopes should reach astronomical magnitude 22. For purposes of the Spaceguard Survey Report, we focus on a network of six 2.5-m aperture, f/2 prime focus reflecting telescopes, each with four 2048x2048 CCD detectors in the focal plane.

Follow-up and Coordination

In addition to discovery and confirmation, the Spaceguard Survey program will require follow-up observations to refine orbits, determine the size of newly-discovered objects, and establish the physical properties of the asteroid and comet population. Observations with large planetary radars are an especially effective tool for the rapid determination of accurate orbits. The survey program also requires rapid international electronic communications and a central organization for coordination of observing programs and maintenance of a database of discovered objects and their orbits.

Expected Survey Results

Numerical modeling of the nominal survey indicates that about 500 Earth-crossing asteroids will be discovered each month. Over a period of 25 years we will identify more than 90 percent larger than 1 km in diameter. The advantage of this survey approach is that it achieves the greatest level of completeness for the largest and most dangerous objects; however, if continued for a long time, it will provide the foundation for assessing the risk posed by smaller objects as well. Continued monitoring of the sky will also be needed to provide an alert for potentially dangerous long-period comets.

Conclusions:

The Spaceguard Survey is an essential step toward a program that can reduce the risk associated with an unforeseen cosmic impact by more than 75 percent over the next 25 years.

Appendix II

NEO Survey Workgroup Report

History of Discovery and Observations of NEOs

The recognition of Earth-crossing comets occurred during the founding period of modern science in the 17th century. Edmond Halley, who carried out the first systematic determination of comet orbits, found that the orbits overlapped the orbit of the Earth. He recognized immediately that comets could collide with the Earth. Over the course of the intervening centuries, hundreds of Earth-crossing comets have been discovered. Awareness of the possibility of comet impact with Earth was heightened by the near miss of Comet Lexell in 1770, which passed within three million km of the Earth. Pierre Simon de LaPlace, among others, speculated on the consequences of comet impact for mankind. However, this awareness faded during the 19th century, owing, perhaps, to a widespread opinion that comets were entirely diffuse objects and, therefore, not threatening. This misconception was decisively challenged in 1950 by Fred Whipple, who showed that the diffuse coma of a comet must originate from a solid nucleus. Whipple's conclusion has since been confirmed by infrared and radar studies of comet nuclei and by imaging of the nucleus of Halley's comet from flyby spacecraft. Impact of the nuclei of Shoemaker-Levy 9 on Jupiter in 1994 provided a direct demonstration of the effects of cometary collision with a planet.

The first discovered Earth-approaching asteroid was (433) Eros, found in 1898 by G. Witt at Berlin. (1862) Apollo, discovered by K. Reinmuth at Heidelberg in 1932, was the first recognized Earth-crossing asteroid, although (887) Alinda, found by M. Wolf at Heidelberg in 1918, is now recognized as an Earth crosser. Two more Apollos, (2101) Adonis and 1937 UB (Hermes) were discovered in the 1930's. On the basis of these early discoveries, the population and impact rate of Earth-crossing asteroids larger than 1 km in diameter was correctly inferred by Watson (1941). By 1972, a total of 13 recognized Earth crossers had been discovered, chiefly in the course of stellar proper-motion surveys and a broad survey of the sky with the 1.2-m Schmidt telescope at Palomar Observatory. Four of these objects that were considered lost have been recovered and are now numbered asteroids.

In 1973, the first dedicated survey for near-Earth asteroids was initiated by Helin and Shoemaker (1979) at Palomar Observatory, California. This survey used the 46-cm Schmidt telescope for photographing a region near opposition (the direction opposite from the Sun) each month. A second survey with the Palomar 46-cm

Schmidt, started by E. M. Shoemaker and C. S. Shoemaker in 1983 and continued through 1994, photographed a much broader region of the sky on a monthly basis. A parallel effort on the same telescope was carried out by Helin. T. Gehrels began a development effort to utilize CCD detectors to scan the sky for NEOs in 1981. By 1989, a 2048 x 2048 pixel CCD was installed in the Spacewatch telescope at Kitt Peak, Arizona, and the Gehrels team began discovering a substantial number of near-Earth asteroids with this system. A fruitful photographic search program in the southern hemisphere was begun in 1990 at Siding Spring Observatory, New South Wales, under the direction of D. I. Steel. This program uses plates taken with a 1.2-m Schmidt for NEO detection and two other telescopes for follow-up. In addition to the dedicated surveys, summarized by Carusi *et al*. (1994), discoveries of NEOs have been reported from many other observatories world-wide, including amateur observatories in Japan. Significantly increased attention has been given to Earth-approaching asteroids since the beginning of the first systematic survey effort at Palomar. About 250 Earth-crossing asteroids have been discovered to date from the combined effort of all observers.

Photometric, spectrophotometric, infrared observations all made with optical telescopes, and radar observations are the entire basis for our understanding of the sizes, shapes, rotation states and mineral composition of the near-Earth asteroids. Observations of (433) Eros and the Apollo asteroid (1685) Toro were carried out in 1972. The discovery at Palomar of (2062) Aten, in 1976, initiated a period in which physical observations of many near-Earth asteroids were obtained during the discovery apparition. The first radar detection of an NEO was made of the Apollo asteroid (1566) Icarus in 1968 by R. M. Goldstein; since 1975, radar observations have been made of numerous NEOs by S. J. Ostro and his colleagues. To date, physical observations of one type or another have been obtained for more than 80 near-Earth asteroids (Chapman, *et al*.1994)

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NASA Ames Space Science Division

Asteroid and Comet Impact Hazards

Appendix III

NEO Survey Workgroup Report

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Evaluation of CCD Systems for Near-Earth Object Surveys

Alan W. Harris*

A commonly stated goal to address the hazard of a possible impact of a Near-Earth Object (NEO) with the Earth is to conduct a nearly complete survey of all NEOs larger than ~1 km within a time of ~10 years. Current photographic surveys have a completion time scale of more than a century. Several automated systems using CCD detectors and computer searching algorithms promise much better performance. In this paper, we consider three such systems which are in various stages of development to evaluate how well they can meet the above stated goal. The systems are *Spacewatch II*, a 1.8 m telescope currently under construction to be installed on Kitt Peak, Arizona; *LONEOS* (Lowell Observatory Near-Earth Object Survey), a 0.6 m Schmidt telescope system under construction at Lowell Observatory, Arizona, and the *GEODSS* (Groundbased Electro-Optical Deep Space Surveillance) system of 1m telescopes currently operated by the USAF for tracking Earth satellites.

To evaluate these systems, we generated a synthetic set of monthly positions of 1000 NEOs chosen to mimic the expected distribution of real objects, and estimated the fraction which could be detected by each of these systems under expected levels of performance for an interval of 10 years. A general result from these simulations is that the best strategy is to cover the entire accessible sky every month, rather than cover a smaller area to a fainter threshold brightness. We find that each of these systems could potentially achieve a level of completeness in the range of 80% or more, for all objects larger than 1 km. For a variety of practical reasons, it may require a system of two or more telescopes to actually achieve this level of completeness, including reliable orbit determination of the objects detected.

INTRODUCTION

In recent years, it has become evident that the Earth is moving through a swarm of asteroids and comets in orbits which come very close to the Earth's, and that these objects, collectively referred to as Near-Earth Objects (NEOs) pose a hazard to life, if one were to impact the Earth. Compared to other natural disasters such as floods, earthquakes, volcanic eruptions, etc., impacts by asteroids or comets are far less frequent, but potentially the most severe of natural disasters[1]. Thus a prudent first step in addressing this hazard is to catalog most such objects large enough to cause global disaster (objects of diameter > 1 km) in the relatively near future. Present surveys, most notably that done at Palomar Observatory using a photographic Schmidt telescope of 18" aperture, would require more than a century to reach a substantial level of completeness of the 1 - 2 thousand such objects estimated to exist.

Several telescope systems are under development which could substantially increase the rate of coverage, and offer the possibility to obtain a fairly complete inventory on the time scale of a decade. In this paper, we evaluate three such systems:

1. The Spacewatch (SW) Telescope on Kitt Peak, Arizona. The present (operating) system is a 1.2 m telescope with a single CCD detector. A second telescope (SW-II) of 1.8 m aperture is under construction. Since SW-I is the only currently operating system, we use its demonstrated performance to scale capabilities of the other planned systems. For SW II, we consider briefly the system in its start-up configuration, but more thoroughly with more capable focal plane instrumentation, comparable to that contemplated for the other systems evaluated. We call this system "Super-Spacewatch II".
2. The Lowell Observatory Near-Earth Object Survey (LONEOS) telescope is a modified Schmidt telescope of 0.58 m aperture, which is under construction at Lowell Observatory. "First light" is expected during this year. As with SW-II, we evaluate the system capability as it will be when upgraded to its full capability, rather than the initial "testbed" system.
3. The USAF Space Command currently operates a network of 1 m, f/2 wide-field telescopes, the Groundbased Electro-Optical Deep Space Surveillance (GEODSS) system, for tracking Earth satellites. Current plans call for upgrading these telescopes to operate with large format CCD detectors, which with only minor modifications and changes to the computer software, might be effectively employed for NEO surveys.

The evaluation of the various planned or possible survey systems requires several steps. First, we evaluate the limiting magnitude expected for a given system, as a function of rate of motion in the sky. A moving object will record as a streak, and thus the limiting magnitude decreases with increasing motion. In addition, we define the rate of sky coverage. For most planned systems, this is variable. Covering larger sky area per month requires decreasing exposure time, so we define the limiting magnitudes for several rates of sky coverage. In order to estimate the effectiveness of a given system and coverage strategy, we generated a synthetic sample of 1000 NEO orbital elements, randomly chosen to fit expected distributions of orbital elements of actual objects. We then generated "predictions" of position, motion, and magnitude for each object for each of 125 lunations (10 years). The final step in the evaluation is to "filter" the set of 125,000 positions according to the sky area coverage and magnitude limits of each given system to estimate the fraction "discovered" by a given system. It should be emphasized that this algorithm defines "discovery" as a detection. Since several passes (detections) are required to confirm a moving object, a crude rate of motion is implicitly included, but full orbit determination is not. This could be accomplished employing a follow-up telescope, taking some time from the survey mode to do follow-ups, or by simply surveying at several times the rate of sky coverage so that multi-day arcs are obtained of each object in the survey area.

LIMITING MAGNITUDE

The limiting visual magnitude for an untrailed image, m_1, is scaled from the empirical limit derived for Spacewatch[2]:

$$m_1 = 22.3 + 1.25 \log\left(\frac{AQt}{a(SNR)^2_{\mathrm{lim}}}\right)$$

A is the effective light collecting area of the telescope, that is, the area of the primary mirror, less obstructed area, times the transmission factor of the optics. The above relation yields a limiting magnitude ~0.8 less than the theoretical limit based on photon statistics, as noted by Rabinowitz, and also confirmed by the theoretical magnitude threshold computed by Tennyson [3] for GEODSS. We adopt the above formula for the limit for all systems evaluated, but recognize that this is conservative, with ~0.5 magnitude or more improvement being theoretically possible.

In Table 1 and Figure 1, we evaluate the limiting magnitude vs. rate of motion of an object in the sky for the current Spacewatch, Spacewatch II, LONEOS and GEODSS, scaling from the above relation. We also tabulate and plot the performance of the original Spacewatch, as given by Rabinowitz2, which was used for scaling to the other systems.

Q is the quantum efficiency of the CCD detector. For unthinned, front-illuminated detectors (Original Spacewatch and LONEOS) we have taken this to be an average of 0.25 over the spectral band 0.50 to 0.85 m. For thinned, anti-reflection coated, back-illuminated detectors (Current Spacewatch, Spacewatch II and GEODSS), we have taken *Q* to have an average value of 0.75 over the spectral band 0.45 to 0.80 m.

t is the integration time. For sidereal scanning (with the telescope clamped down, as with Spacewatch) this is fixed by the drift rate. Scanning can also be accomplished at a faster rate by driving the telescope in declination and clocking the CCD chip at a faster rate, *e.g.* Spacewatch II or LONEOS. In the "stare mode", with the telescope tracking at sidereal rate, the exposure time may be chosen to be almost any value. Any of the evaluated systems can operate in this mode. It is planned as the only mode for GEODSS.

a is the sky area (in arcsec^2) which contains the image of a point source. Generally this is the area of a square array of pixels needed to span the image width plus some margin. for the Spacewatch cameras, it is 3x3 pixels; for LONEOS and GEODSS it is 2x2 pixels.

$(S/N)_{\mathrm{lim}}$ is the limiting signal-to-noise level that is deemed detectable. We take this to be 4 for all systems evaluated, except for Spacewatch, where Rabinowitz uses a value of 6.

$r_1 = \sqrt{a}/t$ is the rate of motion in the sky at which a point image trails by the width of the image during the exposure time t. For GEODSS, the planned mode of operation is to take ~10 short exposures for each set position, and then co-add them with all possible offsets to eliminate trailing. Thus in effect, , where t is the total integration time of the ten exposures. The limiting magnitude for a short trailed image of an object moving at rate r &GT r_1 is:

$$m_{\mathrm{lim}} = m_1 - 1.25 \log (r / r_1).$$

r_2 is the rate of motion at which the trail becomes too long to reconstruct as a single signal. This limit occurs for a variety of reasons, including limitations of computer capability, long trails crossing confusing images, or just the physical dimensions of the CCD chip. We take r_2 to correspond to a trail length of 100 pixels for all systems. For r &GT $r_2$2, the limiting magnitude is given by:

$$m_{\mathrm{lim}} = m_2 - 2.5 \log (r / r_2),$$

where $m_2 = m_1 - 1.25 \log (r_2 / r_1)$ is the limiting magnitude at the rate r_2.

The present Spacewatch system uses a strategy of three passes over the same area of sky to achieve detections. The three passes are necessary to eliminate false images and chance coincidences from genuine objects. Spacewatch II and LONEOS will employ the same strategy. It is expected that GEODSS can achieve reliable detections with only two passes, since the 10 sub-exposures in each pass can serve to eliminate false images (cosmic ray hits, for example) and establish rough rates of motion which must correlate between passes to be counted as real detections.

RATE OF SKY COVERAGE AND AVAILABLE SKY AREA

The rate of sky coverage is just the FOV of the instrument, divided by the exposure time, divided by the number of passes per area (3, or 2 for GEODSS). Roughly speaking, there are ~150 hours of darkness (dusk to dawn, and moon below the horizon) per month. Assuming weather, duty cycle losses, etc. can be held to less than 1/3, the annually averaged time available is about 100 hours per month, so the rate of sky coverage per month is ~100 times the rate per hour. For

Spacewatch I and II and LONEOS, we assume one telescope dedicated full time. For GEODSS, one can contemplate less than full time dedication, or more than one telescope. Thus the rates of sky coverage might be adjusted accordingly. Note that 10,000 sq. deg. corresponds to a circle of ~60 radius.

After some initial evaluations, to be discussed later, it became clear that the generally best strategy is to cover all available sky each month. Thus we evaluated that matter in some detail. In addition to limitations due to darkness and horizon, it is not practical to observe too close to the galactic plane, because the number of confusing stars becomes so great that images of asteroids have an increasing probability of being obscured by such stars. This limit is of course magnitude dependent: the fainter the limiting magnitude, the farther from the galactic plane one must stay. In the range of the systems evaluated, m_{lim} ~ 19-21, the limiting galactic latitude is ~20. We also required that objects be >25 above, and the sun be >10 below, the horizon. Imposing these limits, we calculated, as a function of station latitude, the total available sky area, the number of hours of darkness each month, and the ratio of the two, which is the required rate of sky coverage (Figure 2). From these calculations, we conclude that a net rate of sky coverage of ~130 sq. deg./hour is necessary to cover all available sky each month. Since the total available sky area is correlated with the length of the night, the required scan rate is not as variable throughout the year as the length of night.

SURVEY SIMULATION

In order to evaluate the effectiveness of each of the systems for carrying out an inventory of NEOs, we simulated a 10 year survey in the following way. We first generated a set of 1000 orbital elements, chosen to match the statistical distributions expected of NEOs. For eccentricity and inclination, we used two-dimensional Maxwellian distributions with dispersions chosen to match those of known NEAs: RMS (e) = 0.54 and RMS (i) = 21°. In the case of eccentricity, we had to truncate the distribution at 0.95, since one or two members of the distribution tended to be >1.0 if unconstrained. For semi-major axis, we used a uniform distribution, subject to the following limitations: the perihelion must be less than 1.05 AU [$a(1-e) < 1.05$]; and the aphelion must be greater than 0.95 AU but less than 4.8 AU [$0.95 < a(1+e) < 4.8$]. Thus all orbits are capable of approaching within 0.05 AU of the Earth's orbit, but are not capable of crossing Jupiter's orbit. In making this exclusion, we may be removing from the sample "dead comet" nuclei in Earth and Jupiter crossing orbits. There are presently no such objects in our NEA catalogs. If they exist, they are no more difficult to detect than other low-albedo NEAs, except for the fact that they come close enough to be discovered less frequently. But by the same token, they have an exactly proportionate lower probability of collision with the Earth, so they are just as easy to detect in proportion to the risk associated with them. Thus we feel that the simulation with this limitation is valid. We can also note that in the sample generated according to the above constraints, we did obtain a number of orbits which have aphelia *inside* the orbit of the Earth, *i.e.* in the range 0.95-1.0 AU. These are the interior equivalents to Amor asteroids, and are theoretically expected. To date, none have been detected, but that is likely do to the fact that present searches are mostly confined to less than 90° from the opposition point, where such bodies can never be found. Such a body could, however be perturbed by the Earth or Venus into an Earth-crossing orbit in a relatively short time period, thus constituting an impact hazard. Thus we consider it prudent to include a hypothetical population of such bodies to be sure that our survey designs are capable of detecting them. Figure 3 is a a set of plots of *a vs. e vs. i* for the set of 1000 elements.

Having chosen *a*, *e* and *i* for each object, we then assigned values of the argument of ascending node and mean anomaly at epoch to be uniformly distributed over 360°. The argument of perihelion was chosen uniformly within a range of values which brought to orbit within 0.05 AU of the Earth. In other words, we required that each orbit in the sample be such that the NEOs can *currently* pass within 0.05 AU of the Earth. This eliminates from the sample objects which are currently (over a period of centuries) not in hazardous orbits, even if they do cross a heliocentric distance of 1 AU (but far out of the plane of the Earth's orbit).

Having now defined the element set, we generated "predictions" for each object for each lunation for 10 years. This turns out to be 125 lunations, and of course covers two or more complete orbits for all objects in the sample. Each "prediction" includes position in the sky, rate of motion, and a magnitude factor which includes inverse-square-law effect for earth and sun distances, and the effect of solar phase angle. Thus in performing a survey simulation, one simply adds the magnitude parameter to an assumed absolute magnitude (H) corresponding to an object of a given diameter and albedo, and compares that to the magnitude threshold of the system being evaluated, to determine if the object is "detected", given that it is in the survey area of the sky. By selecting different limiting magnitudes (which is equivalent to different H values of the asteroids), one can "filter" the set of positions and magnitudes to obtain detection statistics for a given system for a range of sizes and/or albedos of NEOs.

SURVEY COMPLETENESS VS. AREA OF SKY COVERAGE

For our first simulations, we specified the area of sky covered per month as the radius of a circle on the celestial sphere centered on the opposition point, which is the most productive area to search. In this experiment we made no restrictions for horizon or closeness to the galactic plane. In Figure 4, we plot the completeness as a function of time for three areas of sky coverage for GEODSS. The magnitude limit was chosen appropriate for 1 km objects of albedo 0.15

(typical S class albedo), or 2 km objects of albedo 0.04 (somewhat darker than average C, D, etc. objects). The limiting magnitude was adjusted to allow for the differences for each of the exposure times required to obtain the sky coverage specified. In Fig. 4, the two curves for 30 and 100 second exposures are probably realistic in that those amounts of sky coverage can easily be obtained within the constraints of horizon limitations, etc. The third curve may be a bit unrealistic in that it implies coverage of the entire celestial sphere to within 43 ° of the direction of the sun. This might be achievable from space, but not from any one ground site. It is clear from these results that the best strategy is to trade magnitude threshold for sky area, all the way to an extreme not actually achievable from the ground. The best strategy is always to maximize sky coverage each month. We have carried out similar evaluations for the other systems considered, with always the same result. This becomes especially clear for the larger systems with fainter limiting magnitude. Such telescopes see essentially everything >1 km in diameter, if it passes into the field of view. So the completeness is mostly just a measure of the phase space covered by the system.

SURVEYS ASSUMING MAXIMUM-AREA COVERAGE

Having established that the best strategy is to cover as much sky area as possible each month, we developed a simulation in which it is implicitly assumed that all sky accessible from a given site is covered each month, to a specific limiting magnitude (as a function of rate of motion). For each system, the magnitude limit was selected appropriate for a rate of sky coverage that would result in covering the whole sky each month from a given site. Figure 5 is a plot of completeness *vs*. time for each of the three systems evaluated. For LONEOS, this plot is for 68 second exposures, with the magnitude and rate parameters shown in Table 1 and Figure 1. For GEODSS, all-sky coverage corresponds to ~20 sec. exposures, with limits which fall between those for 10 and 30 sec. exposures. For Spacewatch, all-sky coverage cannot be achieved with the single-chip focal plane presently being constructed. However, the telescope is optically and mechanically capable of accommodating a 4-chip mosaic, which with an improved read-out rate to allow efficient 10-sec exposures, could be upgraded to have the capability to cover the whole available sky each month. Such an upgraded system is entirely feasible and is comparable to the "full-up" systems contemplated for the other telescopes. We can see in Figure 5 that all three of the evaluated systems can detect most NEOs >1 km diameter (light) or >2 km diameter (dark) in the ten year period of the survey simulation.

COMPLETENESS AS A FUNCTION OF SIZE OF NEO

We next adjusted the limiting magnitudes to evaluate the systems over a range of sizes. The range covered was 0.125 km - 4 km for light objects (albedo 0.15), or 0.25 - 8 km for dark objects (albedo 0.04). Figure 6 is a plot of these results. Note that completeness falls off seriously below 1 km (2 km for dark) for LONEOS and GEODSS. SW-II maintains considerably better completeness down to 0.5 km (light) or 1 km (dark).

We can average the results for light and dark objects, weighted by the relative abundance of each type, to obtain an estimate of completeness for all objects as a function of size. We note that there are ~10 times more high albedo objects than dark ones among the known sample. But since dark objects must be about twice the diameter to have the same intrinsic brightness and hence detectability as light objects, and since objects of a given size are relatively ~5 times more abundant than objects twice the diameter, in the same population, the bias-corrected abundance of light and dark objects in the NEO population is probably about 50-50. Adopting this ratio, we plot in Figure 7 the completeness *vs*. size achieved by each system, after 10 years of surveying.

As one final step, we note that in all that has gone before, we discuss only completeness at a given size. We can integrate the completeness, weighting by the expected relative abundance of objects as a function of size, to obtain a completeness for all objects larger than a specified size. In Figure 8, we plot completeness of all objects larger than a given size, as a function of the lower-limit size, for the three systems evaluated. We have assumed a single power-law population in the range 0.25 km - 4 km of:

where $N(>D)$ is the number of bodies D. The power law index -2 is a compromise average value in the range of interest.

Follow-up strategies

One can contemplate two strategies to catalog orbits rather than merely detect objects. One way is to do targeted follow-up observations, either by assigning the observations to a second telescope or by taking time from the discovery survey to make these observations. A second mode is to cover the whole sky so often that repeated detections of the same object are sufficient to yield orbit solutions from the regular survey observations.

Presently, surveys are done in the first mode, of targeted follow-up. To make the problem tractable, it is necessary to discriminate NEAs from the much more abundant main-belt (MB) objects based on motion in the sky, before an orbit is known. Thus there is a "blind spot" of slow sky motion where an NEA can mimic a MB object and thus not be discriminated. As we go to surveys reaching to fainter magnitude, discoveries will be made at greater distances, thus at slower average motion, and the "blind spot" becomes a more significant loss factor. To evaluate the two modes of obtaining orbits, we have assumed the use of a second identical telescope. For purposes of this aspect of the study, we have used GEODSS performance characteristics, but similar results could be derived for other systems.

To explore the "targeted follow-up" mode, we ran a simulation of 5000 main belt asteroids, predicted at 25 monthly positions, and tabulated the rate of motion statistics as a function of position in the sky. From these data, we determined the size of "box" in motion coordinates that is so heavily contaminated by main-belt objects that discrimination on the basis of motion alone would not be possible. We selected the box size such that we estimate that of any objects found with motions lying outside the box, about half or more would be NEAs. Thus the follow-up telescope would not be tasked with following up more than twice as many objects as turned out to be NEAs. We then re-ran the simulation, with the same limiting magnitude (20 sec. exposures) as before, but with objects scored as "not detected" if their motion in the sky fell inside the "blind spot" for that position in the sky.

We explored the alternate method of follow-up, that of simply covering the sky more often, by reducing the limiting magnitude of the survey by 0.5 magnitude. This is the reduction in threshold that results in reducing the exposure time by a factor of ~2.5. In this scenario, both telescopes "plow the skies" at 2.5 times the previous rate, hence the two telescopes cover the entire available sky about 5 times per month. We estimate that this should be enough to yield orbits on most objects detected on most passes. Figure 9 is a summary of the completeness vs. size of body for these two strategies. It should be noted that the curve for "no follow-up is not directly comparable with the other two, as it assumes only one telescope, while the other two assume two telescopes. So the "cost" of follow-up is somewhat greater than one might infer from these plots. However, the other two curves should be fairly valid measures of the two allocation strategies of equal resources. Note that the "targeted follow-up" strategy is superior for smaller size bodies, while the "multiple coverage" strategy is superior for the larger bodies. Indeed, the curves "saturate" at the largest size range: essentially everything that enters the field of view is detected. This is about 99% of the entire sample, after 10 years. However, because of the "blind spot" that is a necessary consequence of the "targeted follow-up" strategy, 7% of the objects are "detected", nut never "recognized", because they never chance to exhibit anomalous motion, no matter how bright they may be. Thus a 10-year search using targeted follow-up can never be more than 92% complete, no matter how faint the detection threshold may be.

CONCLUSIONS

If one asks the question, what is the likely largest size of any remaining undetected object (that is, where completeness equals one over the number of objects of that size expected), the answer is about 3 km for the evaluated systems, after 10 years. Pushing this limit down to ~1 km would require a Herculean effort. Thus we must accept some level of incompleteness. The systems evaluated can yield completeness in the range 80-90% or better, especially if all are used in concert. This level of completeness should reduce the threat from collision by an undetected NEA to less than that posed by impacts from LP comets, so in that context, we can declare these systems capable of achieving the Spaceguard goal of reducing the hazard of asteroid collision by an unknown object to below that from comets.

The most important lesson which emerges from this exercise is that the best survey strategy is to cover the entire accessible sky every month, sacrificing whatever magnitude limit is necessary to accomplish this. A very positive result is that if that strategy is followed, adopting reasonable and even conservative limits on sky observability, it is possible to obtain reasonable completeness in ten years, including objects which never quite reach out to the orbit of the Earth and hence never come to opposition. Thus the ability to observe closer to the sun or to remove horizon limitations is not a sufficient justification in itself to move to a space-based survey system.

ACKNOWLEDGEMENT

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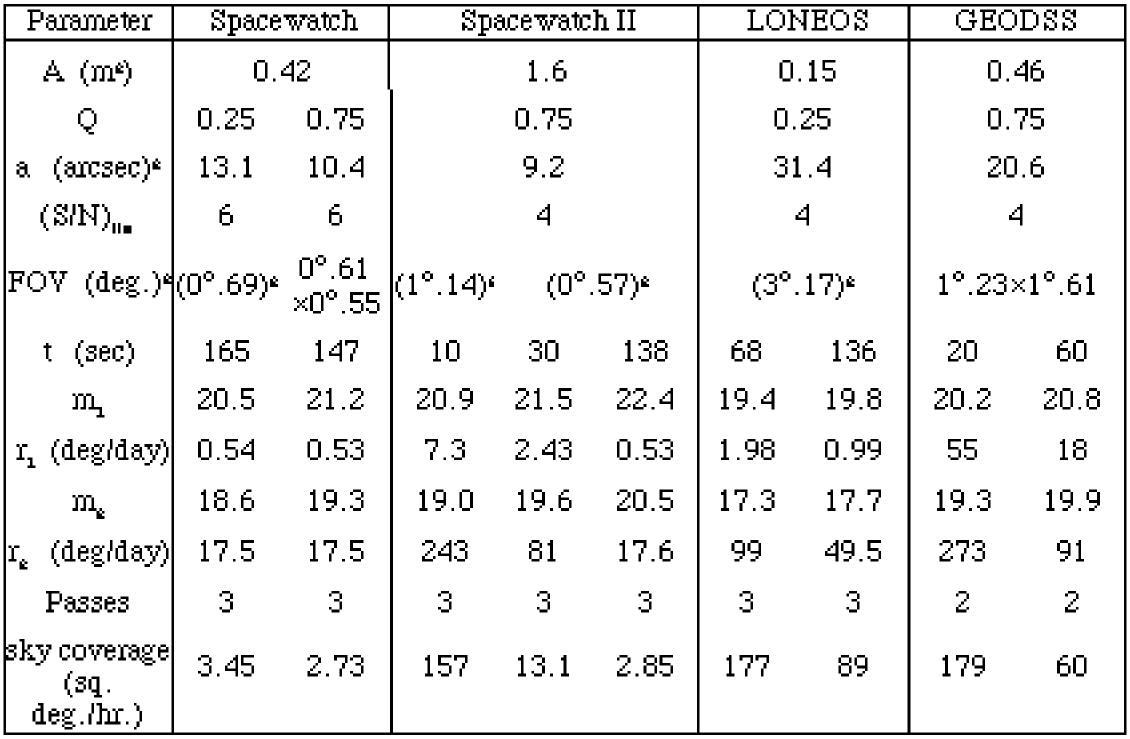
Table 1. Parameter values used for system evaluations



Parameter	Spacewatch		Spacewatch II			LONEOS		GEODSS	
A (m^2)	0.42		1.6			0.15		0.46	
Q	0.25	0.75	0.75			0.25		0.75	
a $(arcsec)^2$	13.1	10.4	9.2			31.4		20.6	
$(S/N)_{min}$	6	6	4			4		4	
FOV $(deg.)^2$	$(0°.69)^2$	0°.61 ×0°.55	$(1°.14)^2$	$(0°.57)^2$		$(3°.17)^2$		1°.23×1°.61	
t (sec)	165	147	10	30	138	68	136	20	60
m_1	20.5	21.2	20.9	21.5	22.4	19.4	19.8	20.2	20.8
r_1 (deg/day)	0.54	0.53	7.3	2.43	0.53	1.98	0.99	55	18
m_2	18.6	19.3	19.0	19.6	20.5	17.3	17.7	19.3	19.9
r_2 (deg/day)	17.5	17.5	243	81	17.6	99	49.5	273	91
Passes	3	3	3	3	3	3	3	2	2
sky coverage (sq. deg./hr.)	3.45	2.73	157	13.1	2.85	177	89	179	60

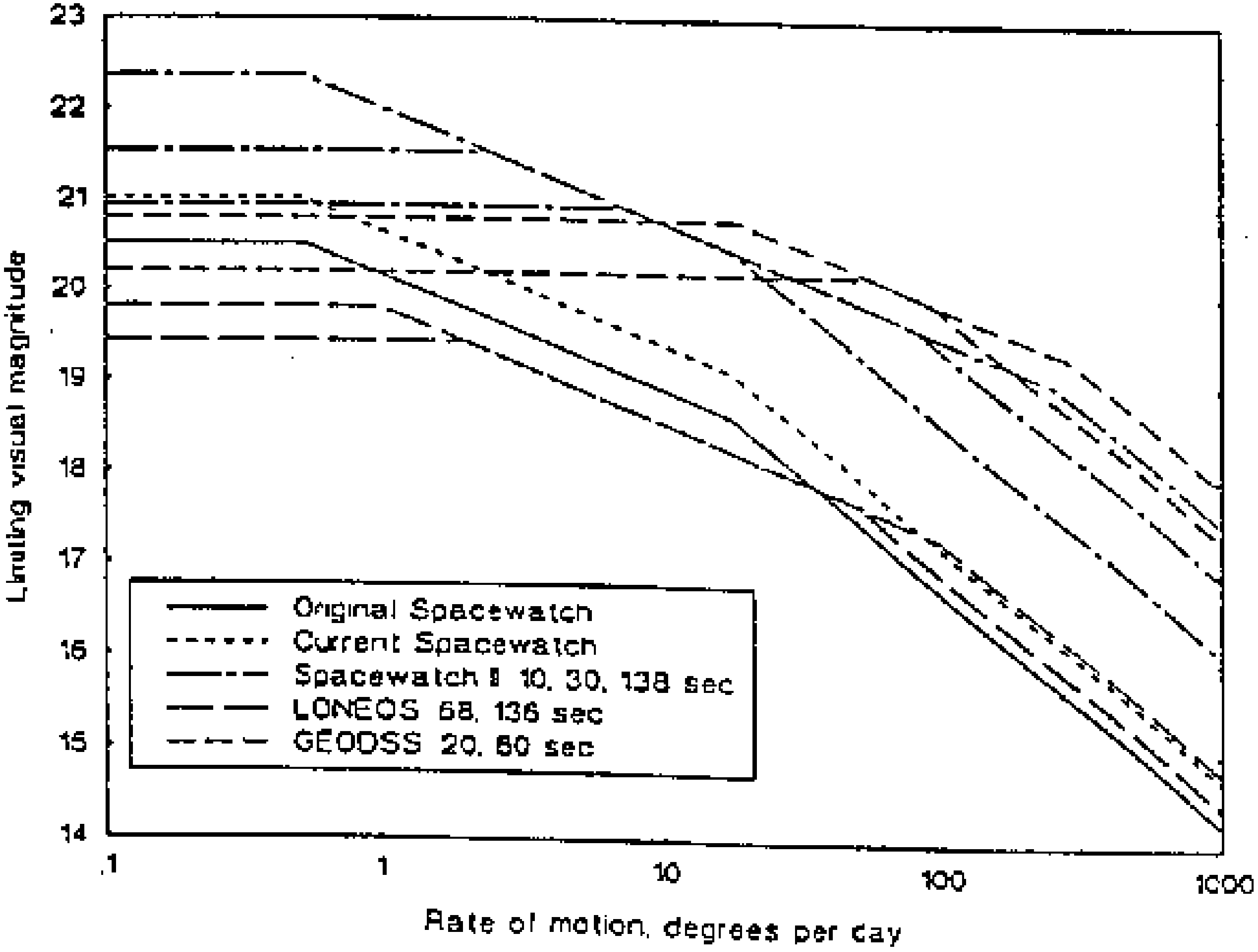


Figure 1. Limiting visual magnitude vs. rate of motion in the sky for evaluated systems

Figure 2

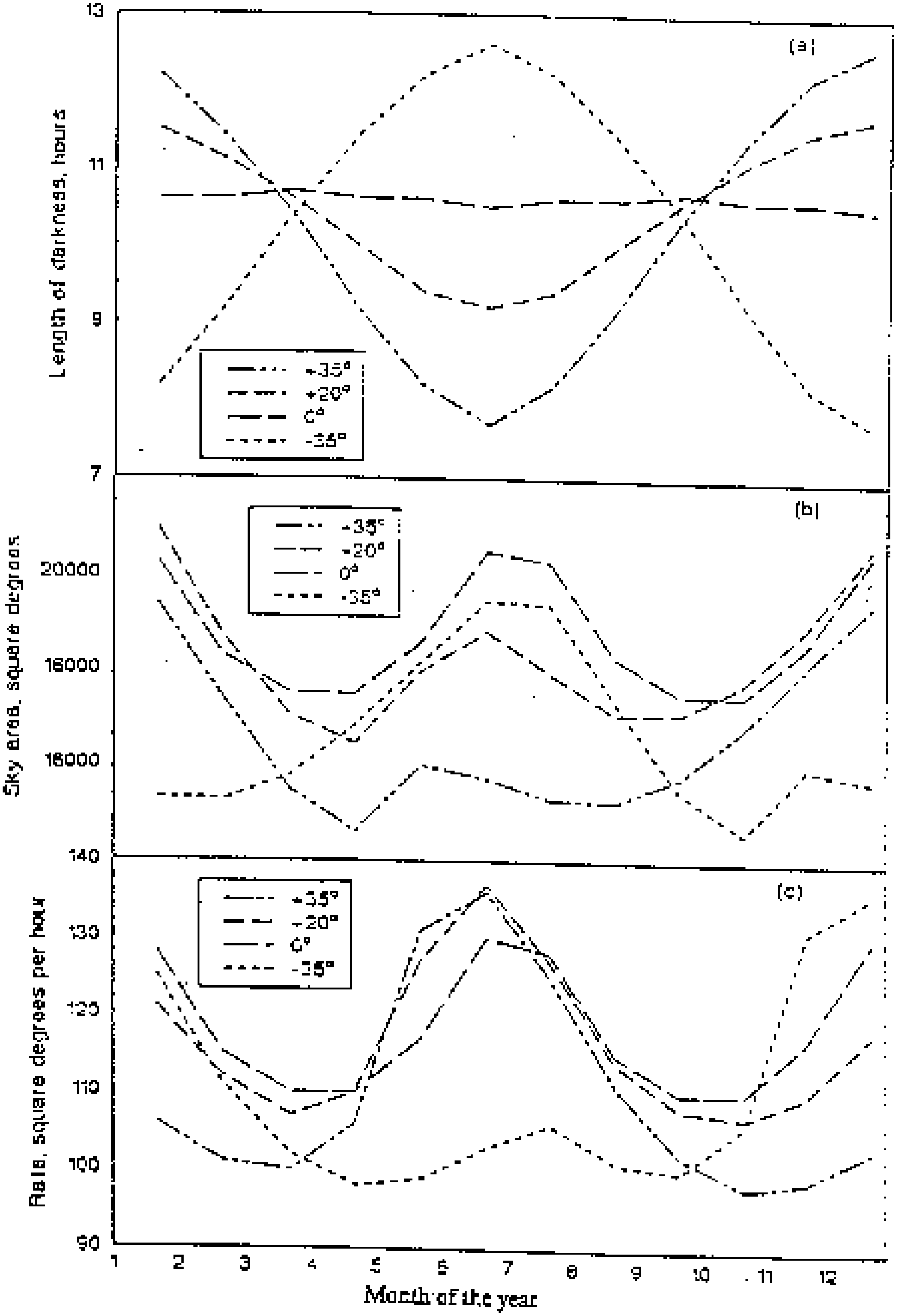
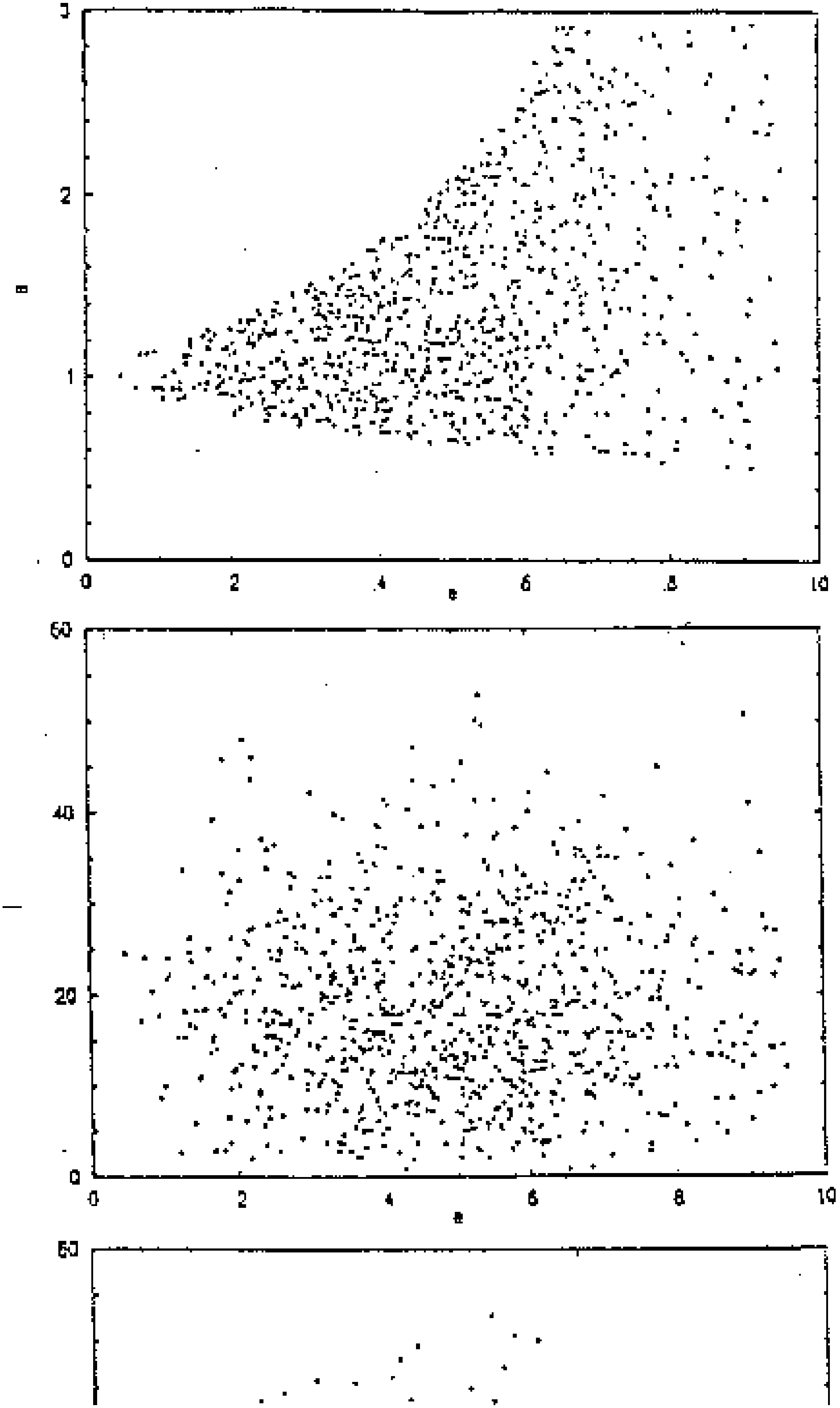


Figure 2. (a) Duration of darkness vs. month of the year; (b) net sky area visible all night (less area near galactic plane, >25^0 above horizon) vs. month of the year; (c) rate of sky coverage necessary to cover whole sky once per half-month, vs. month of the year.

Figure 3



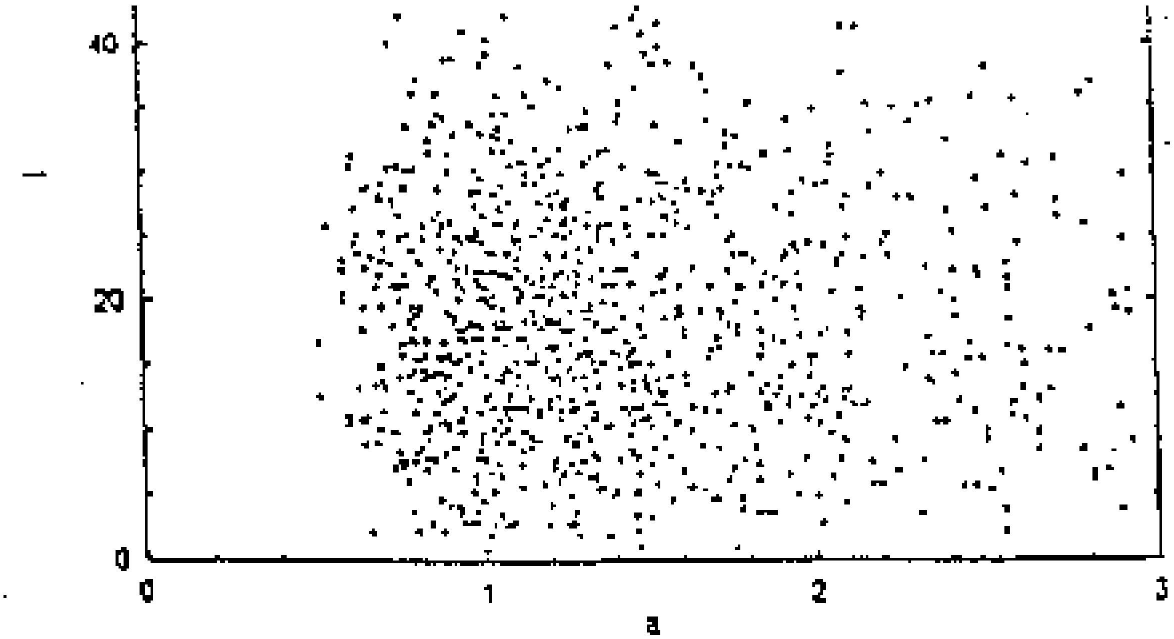


Figure 3. Plots of *a vs. e*, *i vs. e*, and *i vs. a* for 1000 synthetically generated orbital elements used for the survey simulations. *e* and *i* are distributed as two-dimensional Maxwellian distributions with RMS dispersions chosen to match the observed distribution of known NEAs: <*e*> = 0.54, <*i*> = 21°. To obtain values of *a*, we first made a random (uniformly distributed) choice in the range from 0.5 AU to 2.9 AU. If the randomly selected value of *e* brought the orbit inside the range 0.95 - 1.05 AU somewhere in the orbit, the orbit was retained. If not, the orbit was rejected, as one which cannot get close enough to the Earth to be a hazardous object. The upper limit of *a* was selected such that objects are not both Earth and Jupiter approaching.

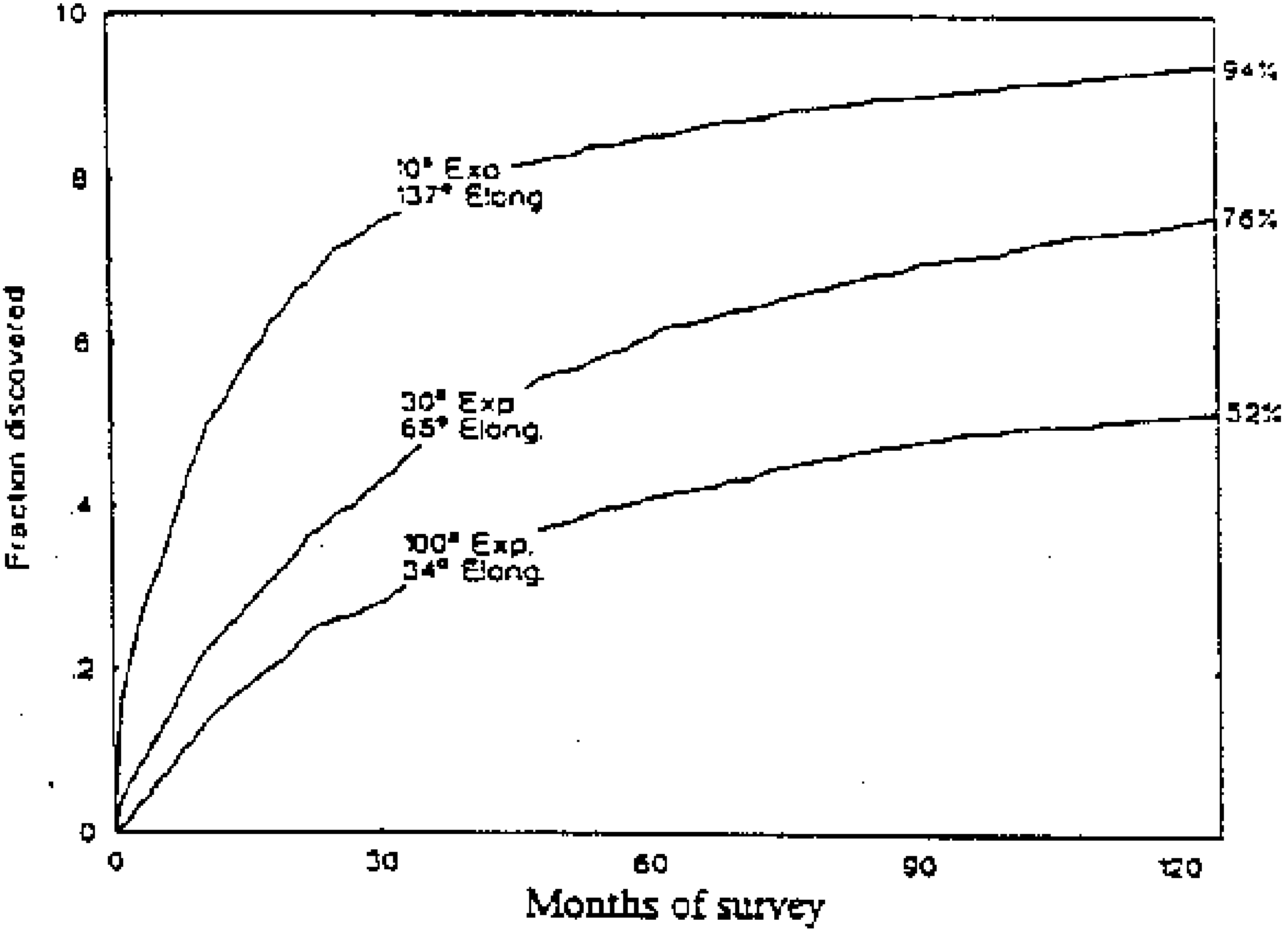


Figure 4. Rate of discoveries vs. time for one GEODSS telescope. Each curve represents a different choice of exposure time, and consequently limiting magnitude (*cf*. Table 1), and results in a different area of sky per month that can be covered. The curves represent the discovery rate for ~1 km diameter objects of moderate albedo (0.15), or ~2 km diameter objects of low albedo (0.04).

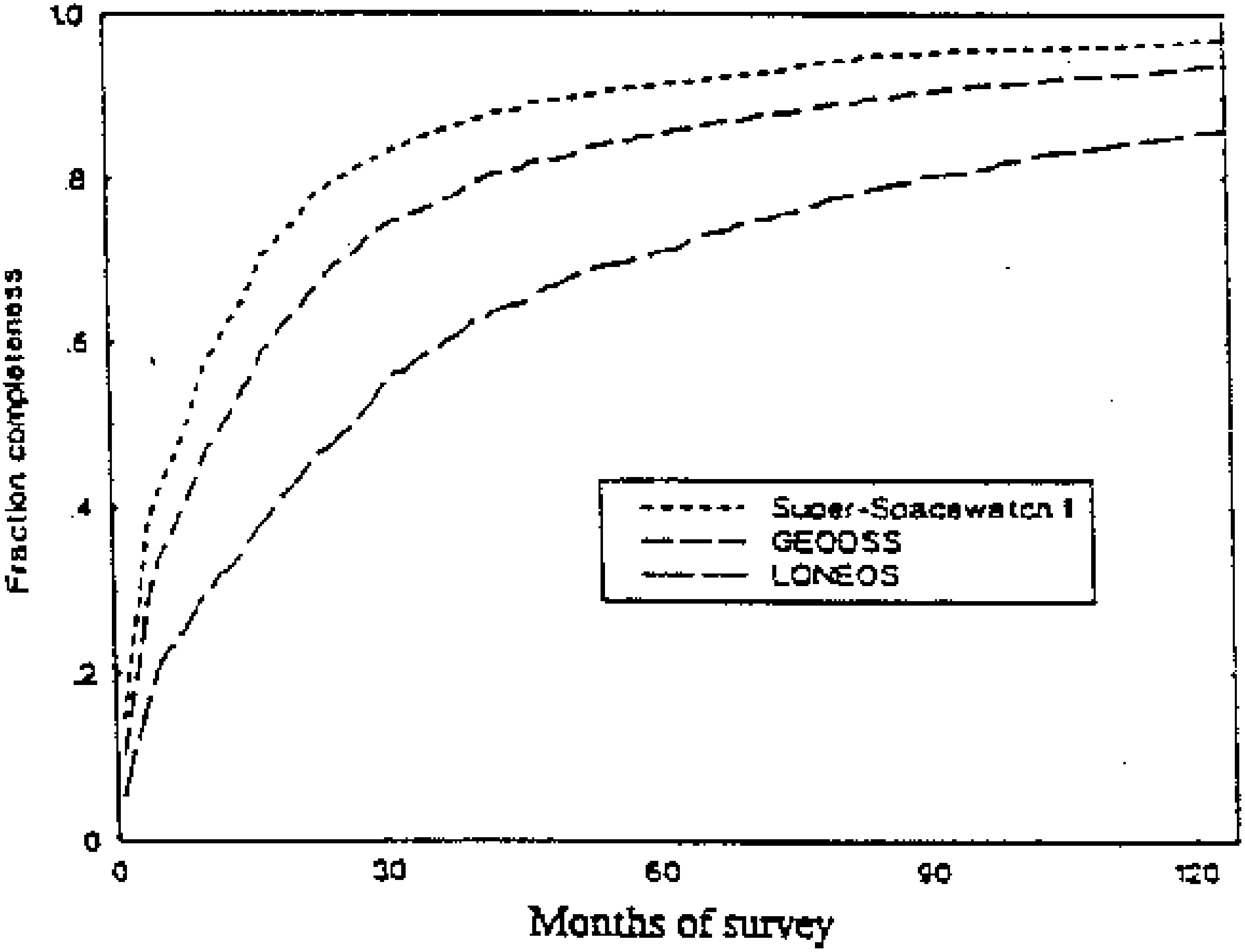


Figure 5. Rate of discoveries vs. time for each of the three systems evaluated, assuming that the rate of sky coverage is chosen such that all available sky area is covered each month. The curves represent the discovery rate for ~1 km diameter objects of moderate albedo (0.15), or ~2 km diameter objects of low albedo (0.04).

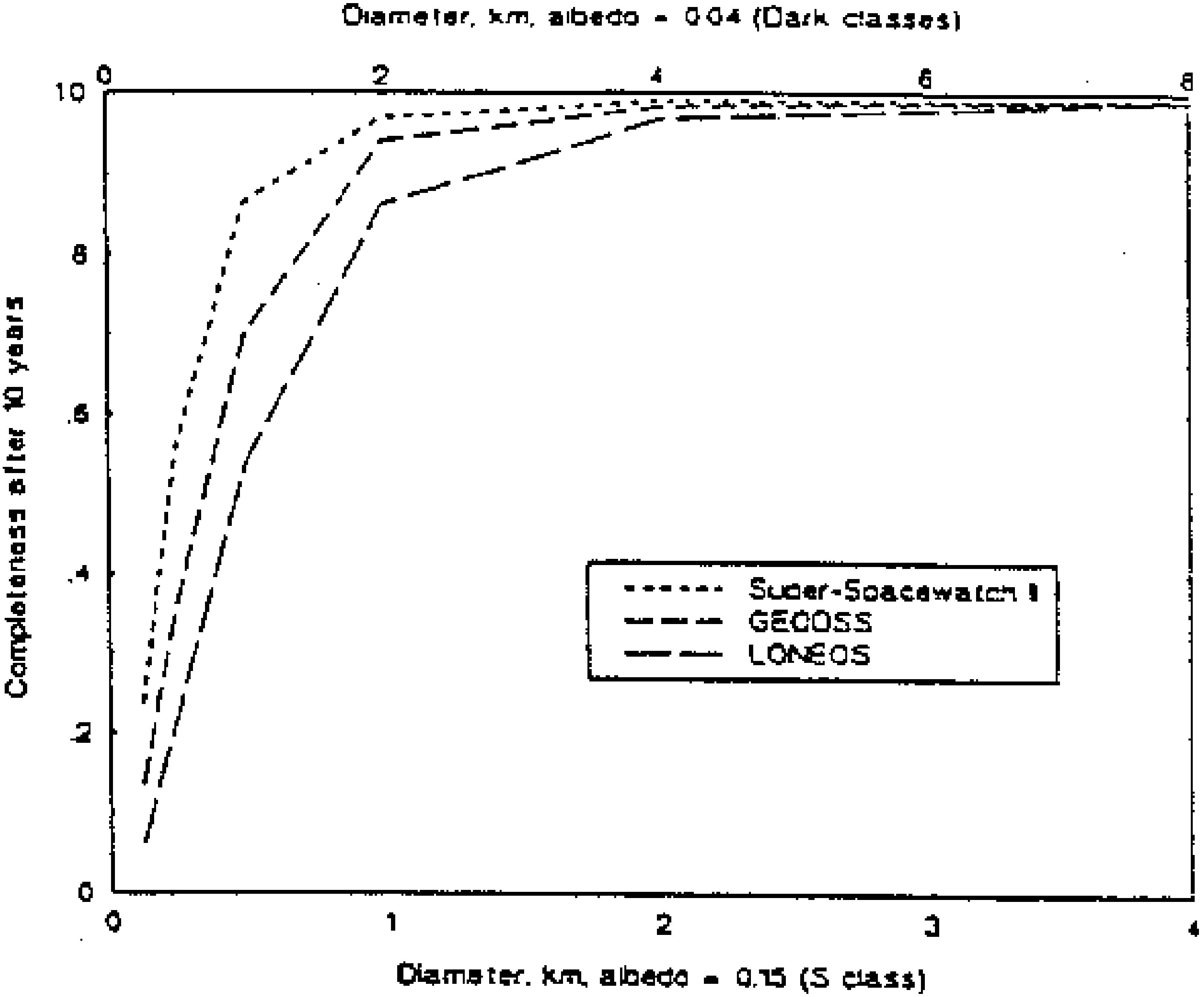


Figure 6. Completeness of detections after 10 years for each of the evaluated systems, *vs*. size of object. The scale for low albedo objects is given across the top of the plot, and that for higher albedo objects is given across the bottom.

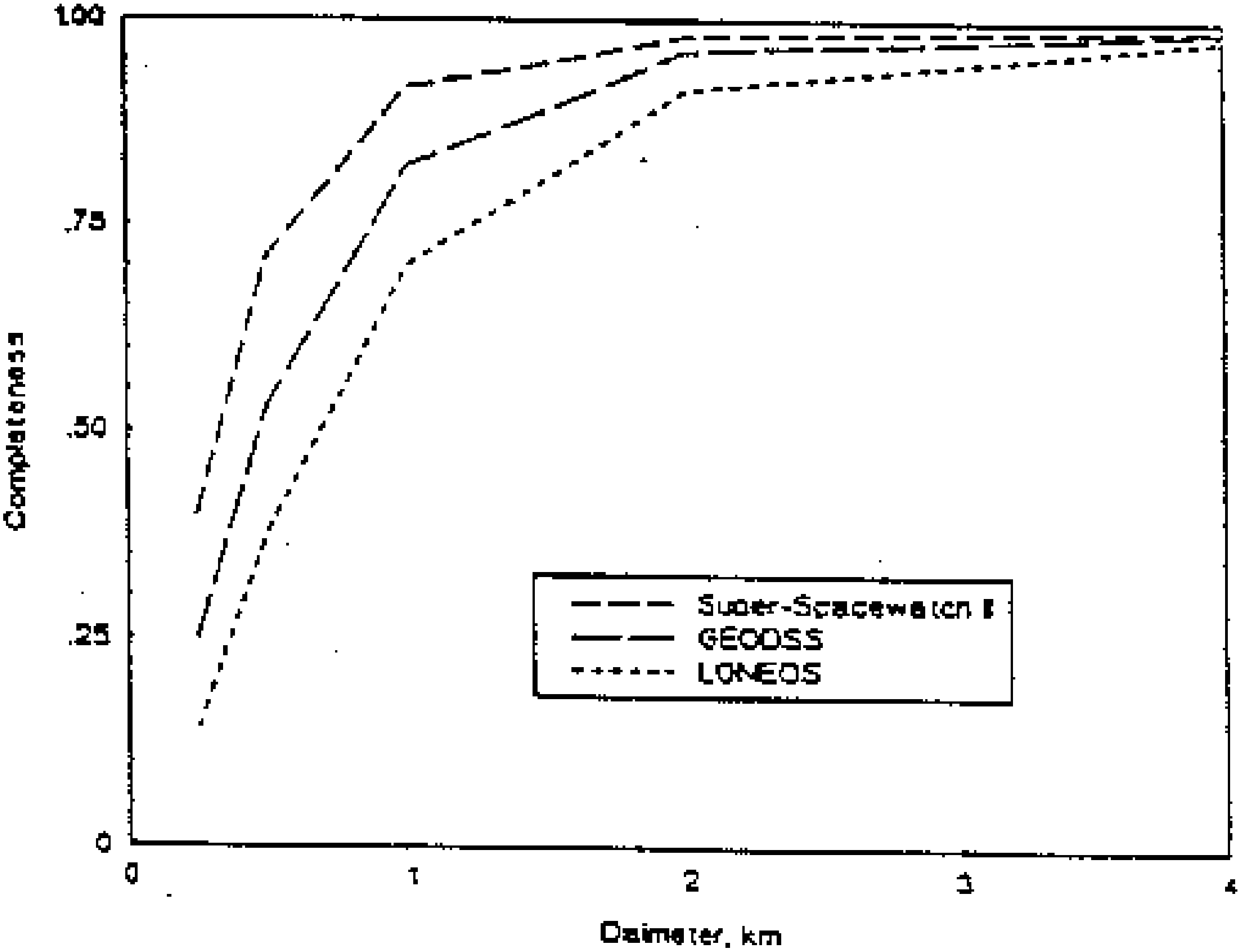


Figure 7. Completeness of detections after 10 years for each of the evaluated systems, *vs*. size of object, assuming a 50-50 mix of light and dark class objects at any given size.

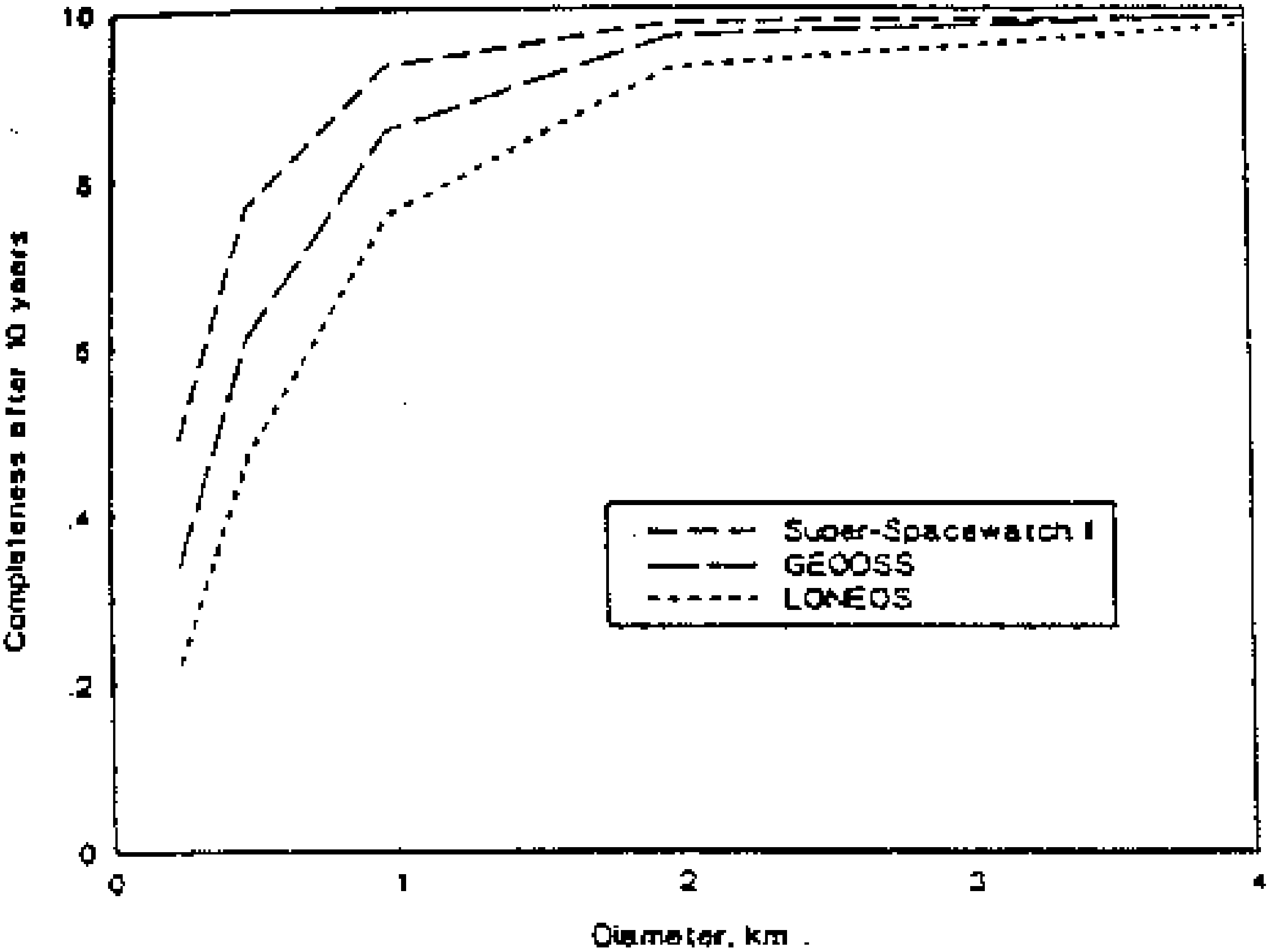


Figure 8. Completeness of detections after 10 years for each of the evaluated systems, all objects *larger* than a given size. As with Fig. 7, a 50-50 mix of light and dark objects is assumed.

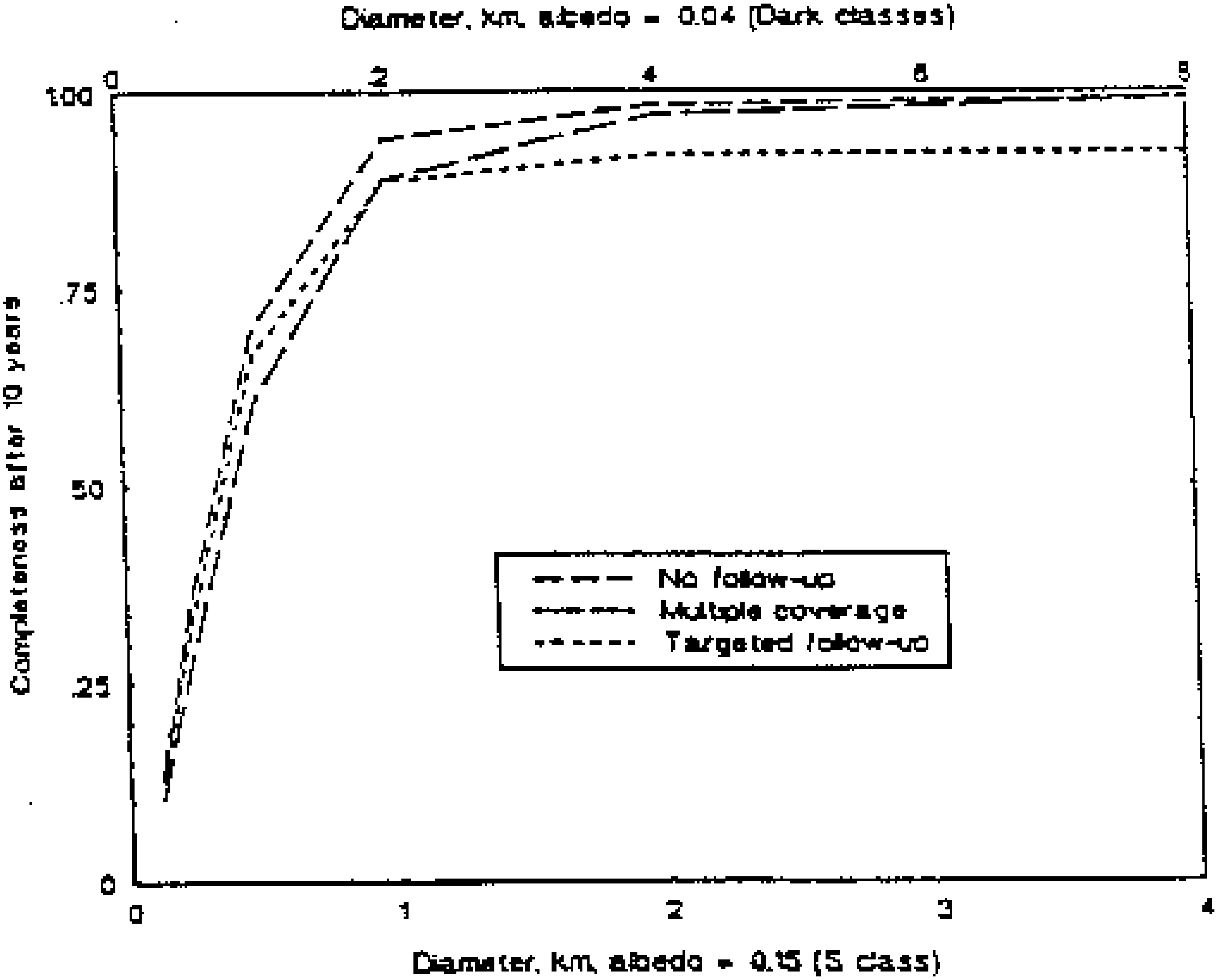


Figure 9. Completeness of survey vs. size of object (light and dark classes as in Fig. 6), for different follow-up strategies (see text), using GEODSS as an example.