Improving the Detection of Near-Earth Asteroids

Final Technical Report

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A large number of asteroids in the near vicinity of the Earth remain undiscovered. These asteroids represent both a potential resource for space activities because of their accessibility and a potential threat because of the possibility of a collision with Earth. At present, a small number of individuals and teams are engaged in the search for these objects.

The purpose of this report is to examine the existing and proposed techniques for locating Near-Earth Asteroids and assess the relative merits of these technologies with the goal of proposing a near term strategy.

The potential payoff of this activity is identifying a modest cost series of activities which can be implemented immediately in order to improve our knowledge of Near-Earth Asteroids in a reasonable timeframe. This is differentiated from existing proposals for the construction of fairly elaborate networks of new observing instruments which are likely to require 5 or more years to implement.

In addition, this research investigates the relative efficacy of Earth-based detection techniques and Spacecraft-based detectors in the specific test case of the potential for discovery of Earth-Sun Trojan asteroids.[1]

[1]This research is sponsored by SDIO/IST and managed by the Naval Research Laboratory.

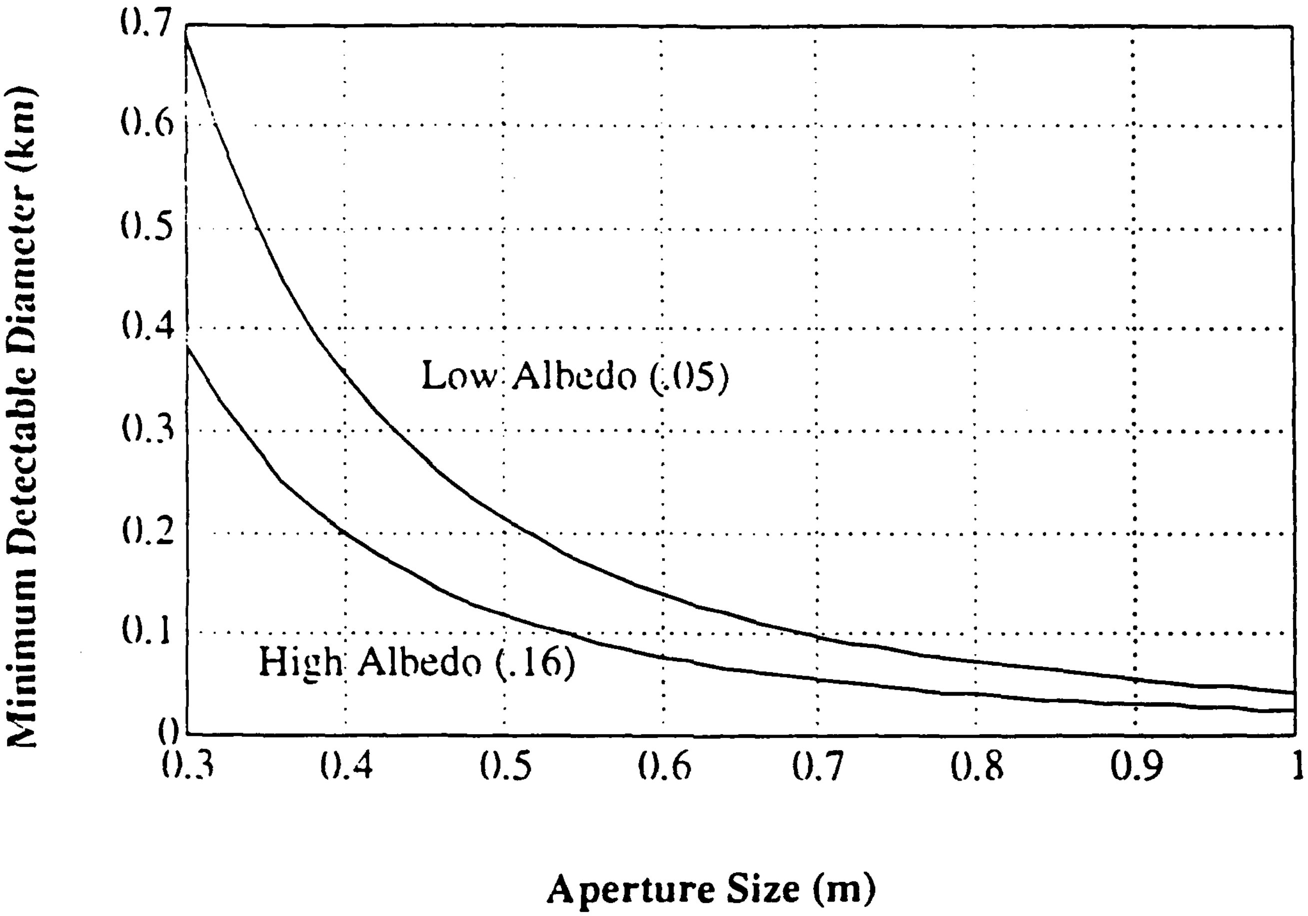


Diagram 1

Minimum Detectable Asteroid Size at 1.0 Astronomical Unit

This diagram shows the minimum detectable diameter of an asteroid which can be detected looking outwards (away from the Sun) at a target distance of 1 AU using telescopes of various aperture sizes. It assumes the use of a 70% quantum efficiency Charge-Coupled Device.

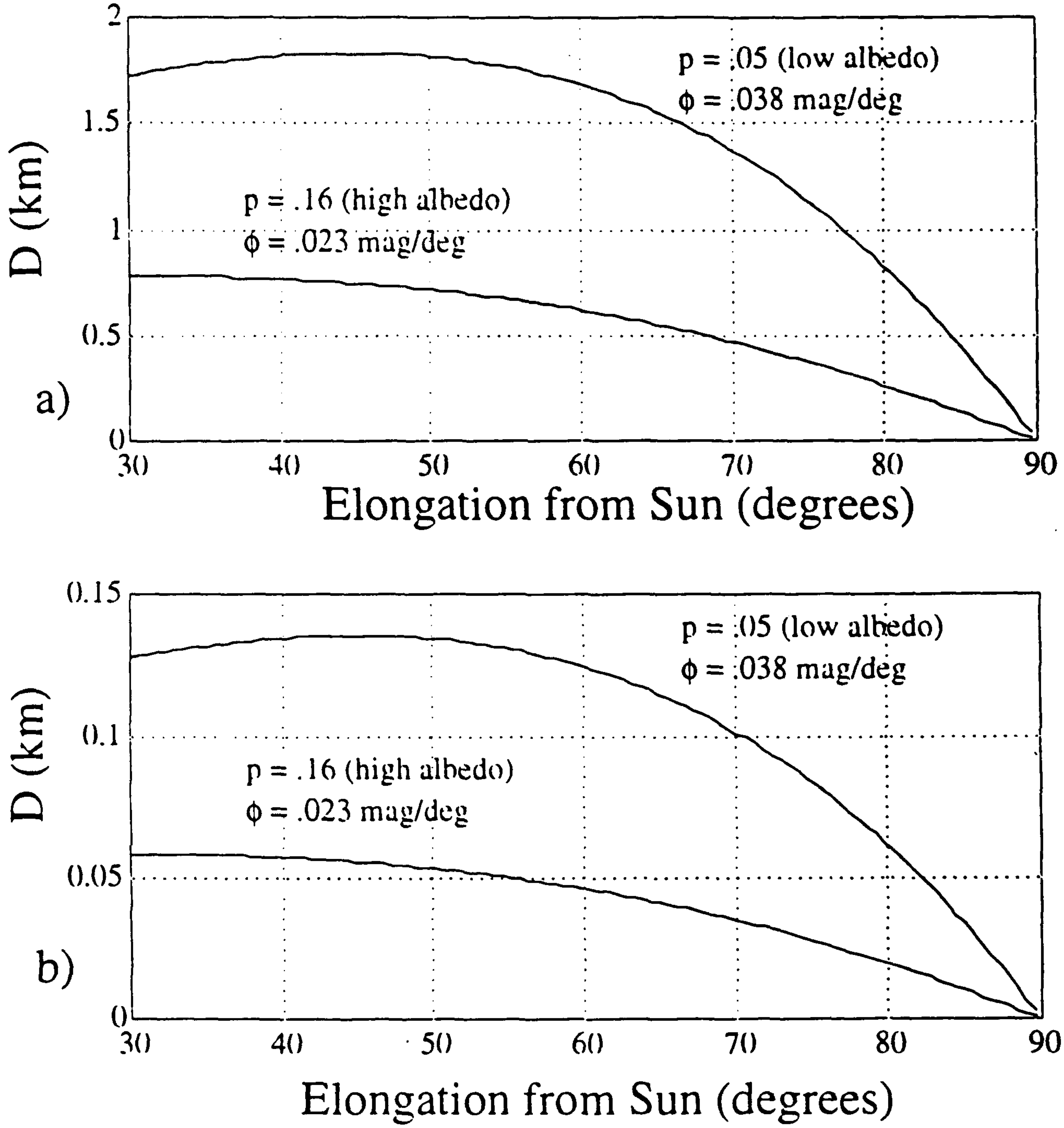
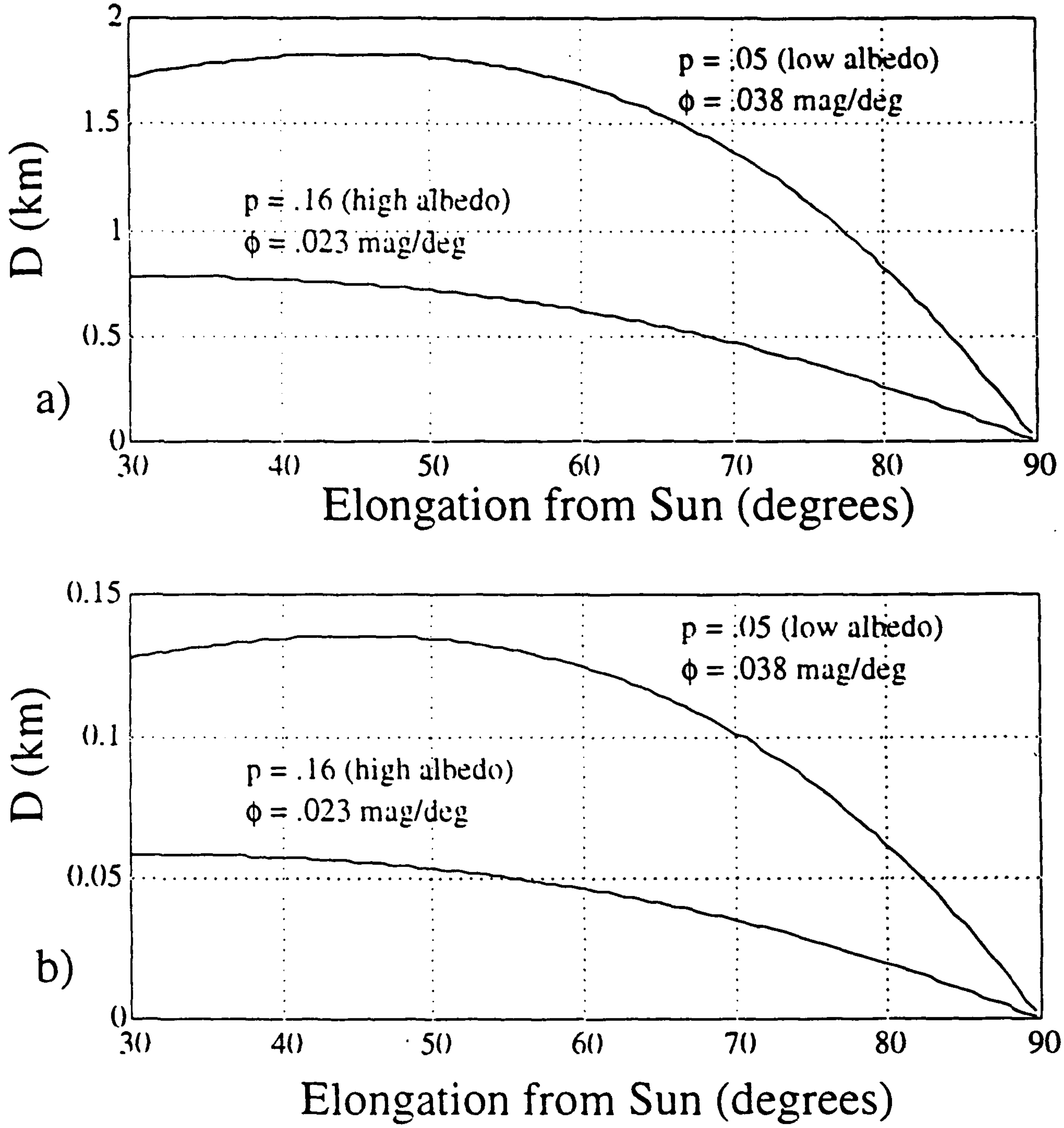


Diagram 2

Size range of Earth-Sun Trojan Asteroids visible from Earth

This diagram shows the minimum detectable diameter of an Earth-Sun Trojan Asteroid based on a) V=20 emulsion photographic techniqes with the 1.2 m Palomar Schmidt telescope and b) use of a 70% quantum efficiency Charge-Coupled Device. with a 2 m aperture scope.



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Recommendations Summary:

Allocate funds for small-scale projects such as 1.8m Project Spacewatch Scannerscope. (Approximate increase in near Earth asteroid detection is an increase from 15 new objects per year to 200 objects per year for a cost of $1.8 Million spent over a period of three years.)

Fund programs to increase the known NEA population as quickly as possible using *existing* intstruments and teams. These programs include AANEAS and LUKAS (see below)

AANEAS (Anglo-Australian Near-Earth Asteroid Search) (approximately 100 near asteroids detected with the UK Schmidt telescope per year for additional $250,000 per year.)

LUKAS (Lowell Observatory-UK Schmidt Asteroid Survey) uses computer scanning of archived photographic plates.

Add Charge-Coupled Devices (CCD's) to existing telescopes at prices ranging from $250,000 to $1 Million per telescope. (CCD's and related hardware and software offer the most significant technical improvement in asteroid detection, in our opinion. We therefore include some notes on their operation as Appendix A.)

Review the existing Infrared Astronomy Satellite (IRAS) data for imbedded asteroid information.

Experiment with improving the communications from academic and individual researchers on object detection to improve the chances of obtaining multiple observations and obtaining orbital elements.

Our analysis shows that ground based surveys are likely to be more cost effective than space missions for detection of Earth-Sun Trojans asteroids (which are examined as a test case.) However, we strongly urge experimentation with microspacecraft as means of carrying detectors and in particular, for conducting characterization missions to detected objects.

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List of Acronyms and Symbols

AANEAS	Anglo-Australian Near Earth Asteroid Search
AIAA	American Institute for Aeronautics and Astronautics
AU	Astronomic Unit (= distance from the Sun to Earth)
CCD	Charge-Coupled Device
ECCO	Earth Crossing Cosmic Object
GEODSS	Ground-Based Electro-Optical Deep Space Surveillance
HST	Hubble Space Telescope
IRAS	Infrared Astronomical Satellite
JPL	Jet Propulsion Laboratory
K-T	Cretaceous and Tertiary Periods
LEO	Low Earth Orbit
LUKAS	Lowell Observatory-UK Schmidt Asteroid Survey
MIT	Massachusetts Institute of Technology
MPC	Minor Planet Center
NASA	National Aeronautics and Space Administration
NEA	Near-Earth Asteroid
NSSDC	National Space Science Data Center
PACS	Palomar Asteroid and Comet Survey
PCAS	Planet Crossing Asteroid Survey
PSS II	Second Palomar Sky Survey
SIRTF	Space Infrared Telescope Facility
SOARD	Steward Observatory Asteroid Relational Database
TRIAD	Tucson Revised Index of Asteroid Data
ΔV	Delta-V, change in velocity
I_{sp}	Specific Impulse
p	Albedo
E	Solar Elongation
V	Relative Magnitude
α	Phase Angle
ϕ	Phase Function

Abstract

A large number of asteroids in the near vicinity of the Earth remain undiscovered. These asteroids represent both a potential resource for space industry because of their accessibility and a potential threat because of the possibility of a collision with Earth. Current search techniques for these objects include the old method of examination of photographic plates and the use of several new electronic devices such as CCD's. Preliminary research indicates that a comprehensive search should be undertaken. Such a search program would necessitate the construction of new telescopes as well the refitting of older ones, greater focus on communication within the search community, and possibly space-based missions to look for asteroids which may not be readily visible from Earth such as the hypothetical Earth-Sun Trojans. This report goes over the motivation of a near-Earth asteroid search program, examines past, current, and future search technologies, and assesses the utility of each. It then presents a variety of possible stategies ranging from low-cost upgrades to existing programs to large-scale space-based early warning systems. In the final analysis, relative non-interference is recommended for the next 5 to 10 years, with funding allocated to upgrade existing systems and continue research. At the end of this period, the knowledge base of the NEA population should have increased to the point where more rational planning can be undertaken for more large-scale projects.

1. Introduction

Over the last three decades, space has entered into the homes of America. First with Gemini and Apollo, then later with Skylab and the Space Shuttle, the manned space program has become rooted in the country's collective consciousness. But alongside the manned program, the unmanned probes have played a significant role. The hearts and minds of Americans young and old have gone out with the Voyagers and the Mariners, with the Vikings and most recently with Galileo and Magellan. The Planetary Exploration Program has been one of NASA's most successful, and with pictures of Venus and Mars, Jupiter and Saturn Americans and people all over the world have become more conscious of the solar system we live in.

Astronomy now holds an interest which would have been unpredictable before this century; as the mysteries here on Earth get fewer and fewer, people are beginning to turn their eyes outward to the new frontier. Science fiction has always been a good measure of where in that frontier America is looking. Thirty or forty years ago, stories in pulp magazines featured frontier life on dry, canal-networked Mars and swampy Venus. But in the last decade or so, as writers have become more attuned to science fact and readers have become more aware of the realities of the solar system, asteroids have appeared more frequently in stories of the future.

Asteroids have also been seeing a lot more interest in the scientific community, but not for the same reasons. Scientists see in asteroids a wealth of information about how the solar system formed, about compositions of planets and planetoids, comets and interplanetary debris. Two things capture the minds of Americans, however, and as one might guess from the history of this nation neither of them is interest in how the solar-system was formed or the flux of cosmic dust between Earth and Mars. The thing which grips Americans most about asteroids is their potential hazard — we in this country are amazingly concious of any kind of threat. The next thing Americans see is the potential for exploitation. With a typical frontier mentality, some Americans see asteroids not as useless hunks of rock or interplanetary debris, but as stepping stones to the stars.

For the near-term future, however, only a small subset of the asteroids drifting about the solar system hold significant interest. This is because the vast majority of asteroids are located between the orbits of Mars and Jupiter in the asteroid belt. The asteroids of immediate interest to us, however, are the ones which appear a bit closer to home. Near-Earth asteroids are noteworthy for several reasons. As current theory holds that about half of these NEA's are burnt-out cometary nuclei, study of these objects could provide great insight into the make-up and origin of both comets and main-belt asteroids. Their accessibility makes NEA's ideal candidates for scientific missions. Some NEA's are easier to reach than the surface of the moon, and hence could represent ideal sources of materials for fuelling an expanding human presence in space. If they exist, asteroids in the Earth-Sun libration points would prove invaluable in this area. By the same token, NEA's with orbits leading them on a collision course with Earth could represent a dire threat to all of civilization, if they exist.

And that is precisely the problem. *We don't know* if they exist or not. There may be an asteroid out there with "Planet Earth and Bust" written all over it, but then again there may not. There may be an asteroid full of valuable resources so easy to get to that you could reach it from LEO with a good sneeze. There may not be. Estimates for the number of NEA's between 100 and 1,000 meters in diameter suggest populations of around 100,000. Only about two hundred NEA's of any size have been discovered to date.

It's not that astronomers aren't looking for these asteroids; they are. In the last decade several programs which actively search for NEA's have been organized, and they have been remarkably successful. Over two thirds of the known near-Earth asteroids have been found in the last fifteen years. At the Mt. Palomar observatory astronomers have pored over photographic plates looking for asteroid trails for over a decade. In Arizona, Project Spacewatch has pioneered the use of Charge-Coupled Devices (CCD's) for semi-automatic searches using computers. International search networks have been formed, and databases of asteroid information have been created. Surveys of the sky have been conducted from the ground and from space. All of these programs are headed in the right direction, but even taken together they are not enough.

A concerted effort to find all the near-Earth asteroids is necessary, a sort of Geological Survey of the Solar System. This would provide a catalogue of resources and a guidebook to the solar system's more dangerous denizens. Like any survey, this effort would provide the information necessary to construct a rational long-term policy, and would therefore become the basis for mission planning and risk assessment for many years to come. As the human presence in space expands in the next century, such a catalog will find more and more use, but the work necessary to compile it should begin now.

This project will seek to describe past and present efforts in the search for near-Earth asteroids and suggest a future course. It will first of all present detailed arguments for the importance of the search, and then describe something of what the search is about. It will cover the history of past efforts and the status of current ones. It will describe the tools and methods used to conduct the search as well as those used to link the searchers together and present their results. Finally, it will provide a menu of future projects and possible missions, and suggest from it a selection which seems to be the best course for the years to come.

2. Motivation

In this world of tight budgets and scarce government resources, any new program of even moderate size must justify its claim to government funds. Each year project heads must be able to explain to Congress why taxpayers should continue to fund their research, and in recent years the cause of science alone has seldom proved enough. Magellan was sent out not just to investigate Venus and satisfy the curiosity of astronomers and geologists; it was justified partly as a way to study the greenhouse effect with a view toward controlling global warming on Earth. Galileo was sent out partly with the hope that study of Jupiter's clouds could give clues to the behavior of weather systems here. Similarly, the search for NEA's must have an application to life on Earth; pure science, though certainly *a* justification for the program, is not enough to win the funds to do it properly.

The motivation for the search for near-Earth asteroids comes from two main areas. NEA's represent both a potential threat to human life and civilization as a whole and a potential asset in mankind's expansion into the solar system. Both of these potentials should be carefully evaluated, but to do that a strong, coordinated effort to locate these objects is necessary. However, neither of these potentials should be believed or taken seriously without more detailed explanation. The following sections will seek to present that explanation.

2.1 The Threat of Asteroid Collision

The potential for a collision between earth and an asteroid is not something to worry about because it *might* happen. It *has* happened many times in the past and it *will* happen again and again for millions, if not billions, of years to come.

Perhaps the most dramatic example of the Earth's history with NEA's was put forth in a 1980 paper by Luis and Walter Alvarez and their team of researchers at the University of California at Berkeley. The theory they proposed, and which has since gained a wide measure of acceptance, was that the mass extinction at the boundary of the Cretaceous and Tertiary periods 65 million years ago was caused by the impact of a large asteroid or comet. This extinction is most well known for wiping out the dinosaurs, but it was also responsible for the extinction of three quarters of all species alive at that time and the destruction of 90% of the Earth's biomass. [51]

The asteroidal impact theory is supported by a layer of soil at the K-T boundary containing 160 times more iridium than normal. This is significant because iridium is rare on Earth but relatively common in meteorites. By examining the amount of iridium deposited around the world, scientists have judged that the impacting asteroid must have been around 10 kilometers in diameter. Geologists have been reluctant to accept such an impact as the sole culprit in the extinction of the dinosaurs, citing evidence of a more gradual extinction process occurring over a few thousand years. However, in the face of mounting evidence that such an impact did indeed occur, most will admit that it probably played a major role. Some of this evidence was found in the form of cracked crystals of quartz and tiny glass spherules called microtektites. [51] Just two years ago, microscopic diamonds were found in 65 million year old rocks in Canada which researchers guess were either brought to earth by the impacting meteorite or created by the immense pressures of the collision itself. Last year, leaf fossils from a sight in Wyoming date the impact to the month of June, when massive dust clouds blocked out the sun and caused the leaves on the trees to die and fall to the ground prematurely. A second, smaller impact occurring a few months later was also visible in this fossil record. Recent finds have indicated that the impact site was probably in the vicinity of the Caribbean Sea.

Further examination of geologic records has revealed evidence of large impacts corresponding to the time-periods of most of the major extinction episodes in the planet's history. A seeming periodicity in the cratering data along with an apparent increase in the rate of cratering near the times of many of the extinctions has lead to speculation that these impacts may be regularly occurring events triggered by some cosmic phenomenon. Theories have proposed that a dim companion star to the sun might periodically release showers of comets from the Oort Cloud, or that a similar effect is caused by the passage of the solar system through the galactic plane every 32 million years. Support for these theories is sketchy at best — one of the arguments against them is that eight of the sixteen craters used by Alvarez and Miller to show this periodicity were demonstrably caused by asteroids, not comets.[1] The fact of the extinctions remains, however, and the evidence linking them with impacts of extraterrestrial bodies is good. It is possible that humanity is widespread enough to survive such an impact, but then again perhaps not. As Ronald Prinn, author of a computer simulation modeling the aftermath of the K-T impact, pointed out at the conference on near-Earth asteroids held in San Juan Capestrano earlier this year, "The problem is no longer worrying about how to cause extinction, but to figure out how anything survived." [49] Certainly the technological civilization built up over the last thousand years would be wrecked by such an impact, or even a much smaller one.

As humanity has spread over the planet in the last few hundred years, records of the smaller collisions have also spread. While there are no records of anyone being killed by a meteor impact, estimates indicate that a person is hit somewhere in the world every nine years or so. [44] Property damage is higher; the same source gives the figure that sixteen buildings are damaged by meteorite impacts each year in North America. Records of larger impacts can be seen all around us, however. The Barringer Crater in Arizona was created by the impact of a nickel-iron asteroid about 30

[1] Note that according to Olsson-Steel, current statistics indicate that probably 80% of terrestrial impacts are with asteroids, not comets.

meters in diameter around 49,000 years ago. Its impact energy was more than 15 megatons of TNT.

In 1908 an object about 35 meters in diameter exploded in the air near the Tunguska River in Siberia. The explosion, which was recorded on instruments around the world, was estimated to be around 10 to 15 megatons. Trees were flattened for thousands of square miles. The area of total devastation has been compared to the size of Washington, D.C (everything inside the capital beltway) and New York City. [36] The explosion occurred in desolate Siberia, so one was hurt; the lone witness was a fur-trader at his post 110 km away, who was blown out of his seat by the shockwave. If such an explosion were to occur over a rural area in the United States today, casualty estimates would run to about 70,000 people. Over an urban area, the death-toll could reach over 300,000.

In 1965 a similar object exploded in the air over British Columbia with a force of 20 kilotons. In 1972 a 25 meter object streaked through the upper atmosphere over North America, but did not hit. In 1979 a burst similar to the 1965 British Columbia explosion occurred off the Southern tip of Africa. This was picked up by Vela early warning satellites and was thought at first to be a nuclear weapons test, perhaps conducted jointly by Israel and South Africa. Great concern was caused by this presumed test. Later evidence identified it as the explosion of an extraterrestrial object. In March of 1989, an asteroid "bigger than an aircraft carrier, traveling at 46,000 miles per hour" passed through the Earth's orbit at the point occupied by the Earth a mere six hours earlier. [54] Had this object, which was only discovered after it had passed by and is now designated 1989FC, hit the Earth, its impact energy would have been between 1000 and 2500 megatons of TNT, or over 200,000 times the energy of the bombs exploded over Hiroshima and Nagasaki. In January 1991, just a year ago, another asteroid, this one only about ten meters in diameter, passed within the orbit of the Moon.

Clearly there have been asteroids colliding with our planet in the past. Using several different methods, it is possible to predict the frequency with which these impacts will occur in the future. One may, for example use the lunar cratering rate as a yardstick. [32] The Earth's more active seismology as well as its dense atmosphere and running water conspire to hide much of the evidence of extraterrestrial impacts from the investigator, but the record on the Moon is plain to see. Most of the cratering visible on the Moon's surface comes from the period of the solar system's formation, when a considerably larger number of objects flew pell-mell through the inner orbits. The cratering rate on the Moon has been relatively even over the last few billion years, however. Looking at the number of large craters in the Lunar maria and accounting for the relative size of the Earth as compared to the Moon, Dave Morrison and Clark Chapman estimate that the Earth endures one collision of the magnitude which produced the crater Aristillus (55 km in diameter) every ten million years or so. Continuing with this logic, if the asteroids which produced these huge craters on the Moon's surface were about 10 kilometers in diameter, then the interval between impacts with objects on the scale of 1 kilometer should be some hundreds of thousands of years. As they put it, "In other words, *every year* the odds are one in some hundred thousand of having a civilization-threatening impact."

The numbers arrived at above can be confirmed with different methods. One such method, pursued by Olsson-Steel, is to calculate the collision probabilities of known Earth-crossers from their orbital parameters and the laws of physics. From this, a mean collision probability can be obtained, which Olsson-Steel gives for Earth as 6.93 per billion years. [33] That's a relatively small number, but when multiplied by the estimated 2100 Earth-crossers over one kilometer in diameter (See Table 2.1), that predicts one collision every 70,000 years. For asteroids over 100 meters in size, the prediction is for one impact every 500 years. That's a lot better odds each year than winning a high school raffle.

Note that there is considerable debate about the demographic breakdown of the NEA population. Estimates vary widely between sources, and are constantly in flux. As current search programs increase the base from which estimates are made, they will improve in accuracy, but all that can be done for now is to take the most current guesses. Table 2.1 takes its numbers from the report of the NASA International Near-Earth-Object Detection Workshop, known as the Spaceguard Survey. The frequency of collisions derived from the Spaceguard population estimates using Steel's estimate of NEA collision frequency is presented alongside the numbers from the workshop report to emphasize the rough nature of these estimates. There is a real difference in feel between a frequency of one collision per five hundred years and a frequency of one per two thousand; a factor of three or four takes on a lot more significance when one is considering civilization-threatening disasters. All this only emphasizes the need for a better NEA search program so that we can rationally evaluate the risks involved.

NEA Population		Frequency of Collision (years)	
Diameter (m)	Number	Spaceguard	Steel
10	150 million	10	1
100	320,000	2,000	500
1,000	2,100	200,000	70,000
10,000	1.00	100,000,000	100,000,000

Table 2.1: Current assessments of the NEA population with estimates of impact frequency for a range of asteroid sizes.

Earlier the chances of a 100 meter asteroid impacting the Earth each year were compared to those of winning a small raffle. When it comes to raffles and lotteries, however, the chances of winning aren't the only important thing. Those chances have to be balanced with the size of the prize. In the case of an asteroid collision, the prize may be bigger than anyone wants.

To get an idea of the size of this prize, lets take a look at what would happen if an asteroid 100 m in diameter hit the Earth. Taking an average density of about 3.5 g/cm^3, such an asteroid would have a mass of about 1.83 x 10^9 kg.[2] Then, assuming an impact velocity of 20 km/sec (about the velocity of 1989FC with respect to the Earth), the kinetic energy of the object would be about 3.66 x 10^{17} Joules. Converted into an equivalent weight of TNT, this would be a 95 Megaton explosion, or over 7000 Hiroshima sized A-bombs. Over 2,800 square kilometers would be totally devastated. As shown above, using Olsson-Steel's data set the chances of an asteroid this size hitting the Earth each year could be as high as 1 in 500. Table 2.2 shows the results of applying this calculation to other sized impactors.

Asteroid Impact Energies				
Asteroid Diameter (m)	Mass (kg)	Ergs	Hiroshimas	Megatons TNT
10	$2 \cdot 10^6$	$4 \cdot 10^{21}$	7	.10
100	$2 \cdot 10^9$	$4 \cdot 10^{24}$	7000	100
1000	$2 \cdot 10^{12}$	$4 \cdot 10^{27}$	7,000,000	100,000
10000	$2 \cdot 10^{15}$	$4 \cdot 10^{30}$	$7 \cdot 10^9$	100,000,000

Table 2.2: Asteroid impact energies in a variety of measures.

For asteroids greater than 400 m or so in diameter, the impact becomes global. For these collisions the dust and other ejecta thrown

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[2] 3.5 is a typical value for an ordinary chondritic meteorite, thought to be similar in composition to some S type asteroids; see Ostro for densities of asteroid types and Luu and Jewitt for relative frequencies of S and C type asteroids.

into the atmosphere by the impact would probably bring about a nuclear winter threatening plant and animal life all around the world. Impaction experts at Caltech analyzed the effects of a collision with of 400 m diameter object traveling at 11 km/sec:

> The medium-mass class ECCO [Earth Crossing Cosmic Object] would pass through the atmosphere in less than a second. Upon impact, a very strong shock wave would be driven into the ground and into the object, releasing an explosive fireball with 2.5 million metric megatons of explosive TNT energy, which would cause the object to change from solid to liquid to gas in several fractions of a second as well as vaporize the ground at the point of impact. Temperatures in the range of 20,000 degrees Kelvin (K) (35,500 F) would be generated. (The surface of the sun reaches temperatures of only 6,000 K.) In less than half a second, the object would bury its pulverized self in the Earth. At the same time a spherical shock would be driven into the atmosphere producing local temperatures of 10,000 K (17,500 F) dropping to several hundred degrees perhaps 500 km (300 mi) away. This blast wave would travel roughly 22,000 mph and basically level everything within a radius of 150 miles. There would be a great amount of excavated material, mostly on the edges of the crater, and ejecta of large particles such as molten droplets of rock — a rain of red-hot glass — would fall over a radius of 200 km (125 mi) away. A plume of hot gas from the vaporizing ECCO and ground would shoot back up into the atmosphere carrying with it large amounts of fine ejecta which would be distributed worldwide darkening the sky and possibly leading to climatic changes exemplary of the "nuclear winter" concept. In the end, a crater of perhaps 5- to 10-km (3- to 6-mi) would be excavated to a depth of probably the diameter of the object, about 400 m (0.25 mi). [44]

Each year the chance of winning this prize is about 1 in 40,000. We probably won't have to deal with this sort of disaster this year or the next, but someday, somewhere, someone will.

With a good idea of how often these asteroids hit the Earth, and the amount of damage they cause, one can estimate the risk they represent. As there have been no recorded deaths from this "cosmic threat", one might expect that the risk to the average American would be fairly low. The very low chance of an impact times the very high number of people who would die if one should occur leaves a very respectable risk. Table 2.3 below, is taken from a New York Times article which used statistics from Dave Morrison and Clark Chapman. [4]

So one might ask: just how worried should we be? In 1980, the Advisory Council to NASA put it this way: "In the 130 million years the dinosaurs roamed the Earth, they failed to develop the technology to avoid their extinction. Homo Sapiens has developed an adequate technology. He can avert any further extinction by asteroid

Threats: A Comparison

Estimated Risk for an American over a 50-year period

Risk of death from botulism	1 in 2,000,000
Risk of death from fireworks	1 in 1,000,000
Risk of death from tornadoes	1 in 50,000
Risk of death from airplane crash	1 in 20,000
Risk of death from asteroid impact	**1 in 6,000**
Risk of death from electrocution	1 in 5,000
Risk of death from firearms accident	1 in 2,000
Risk of death from homicide	1 in 300
Risk of death from automobile accident	1 in 100

Table 2.3: A comparison of threats

impacts. We think he should." [44] A year later the Jet Propulsion Laboratory held a workshop in Colorado to investigate the threat. It invited asteroid and comet experts, engineers, and military planners who computed the statistics and the probabilities involved and prepared a 100 page draft report. The report was never released. The reason, according to some, was that the NASA and JPL managers were afraid of excessive public alarm should they go public with it. In April of 1990 the American Institute of Aeronautics and Astronautics (AIAA), released a position paper indicating that they, at least were worried. "Earth-orbit-crossing asteroids clearly present a danger to the Earth and its inhabitants. . . . we would be derelict if we did nothing," the report said. [54] Conferences on the subject have been held around the world, and press coverage abounds. The close flyby of 1989FC prompted Congress, too, to take a closer look at the subject, funding a series of workshops to determine the proper course of action. Few people seem to doubt that some sort of action should be taken.

In order to take any sort of action, however, the asteroids which may prove to be threatening must first be found. With accurate knowledge of their orbits, potentially dangerous asteroids can be tracked and future collisions predicted. This knowledge has been accumulating over the past few decades, each year at an accelerating rate. That rate is still exceedingly slow, however, and unless a concerted effort is made to find them now, it may take another hundred years to find all the NEA's which could pose significant danger.

2.2 Asteroid Resources

The second main motivation for looking for NEA's lies in their potential as resources for the industrialization of space. In the various asteroids close to Earth can be found a variety of metals, water (which can be used for rocket fuel as well as life support), silicates, and even organic compounds. Certainly these are all materials which can be found elsewhere, but it is the particular virtue of many NEA's that they are easier to reach than any other extraterrestrial bodies, and contain these resources in much more accessible forms than their competitors. Some of them are also of a size such that we can begin to think about moving them around, possibly giving them a little nudge to bring them into Earth orbit where they could be systematically disassembled. Even the slag from such an asteroid could be used as shielding at great savings.

To get an idea of the potential savings, take for example the smallest known asteroid, 1991 VG. At about 10 m in diameter, this object would have a mass of about 500,000 kilograms if a typical asteroidal density was assumed. With absolute best launch costs today of about $2,500/kg to LEO, this small hunk of rock would have a value of $1.3 billion.

2.2.1 Classification and Composition

The known near-Earth asteroids can be divided into three different families: the Amors, Apollos, and Atens. The Amors are also known as Earth-approaching asteroids; they have perihelia between 1 and 1.3 AU, often crossing the orbit of Mars but not that of the Earth. The Apollos are the Earth-crossers, with perihelia under 1 AU but apohelia greater than 1 AU. The third group, with the fewest known members, is the Atens. Atens make their passage around the Sun entirely within the Earth's orbit. A total of 184 NEA's have been discovered as of September 1991. Of these, 85 are Amors, 88 are Apollos, and 11 are Atens. A fourth family of NEA's, the Earth-Sun Trojans, is thought to exist, though no members of this class have yet been found. These asteroids would be in orbits librating around the triangular Lagrange points of the Earth-Sun system — roughly 60° ahead or behind the Earth in its orbital path about the Sun (See Figure 2.1). The recent discovery of 1991 VG has prompted a proposal by Gehrels for the creation of a new, fifth family, perhaps called the Arjuna asteroids, for objects with similar orbits.

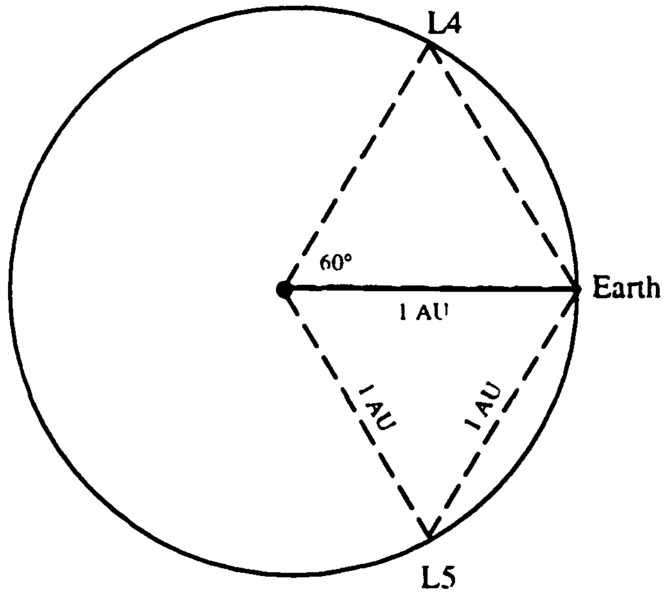


Figure 2.1: The stable Lagrange Points in the Earth-Sun system

Individual asteroids, when they are first discovered, are designated by a four digit number and two letters. The number is the year in which it was first discovered — not necessarily the year in which it was first observed, as often a newly discovered asteroid can be spotted later in old photographic plates. The first letter indicates the date of discovery down to the half-month: asteroids discovered in the first half of January get an A, in the second half of January a B, in the first half of February a C, etc. The second letter goes from A to Z sequentially for each asteroid discovered in the half-month. Thus the asteroid 1989DB, which caused so much consternation with its near-miss, was the second asteroid discovered in the second half of February of 1989. When the asteroid's orbital parameters are fixed with sufficient accuracy to ensure observational recovery when the asteroid next passes close by the Earth, it is given a name and a unique number.

A designation with a bit more meaning for purposes of mineral exploitation is the asteroid's spectral classification. The spectral classification system gives each asteroid a single letter which describes certain aspects of its observable features in much the same way as the stellar classification system denotes a yellow star as type G. Unfortunately, the spectral classification of asteroids has undergone a very confusing evolution over the past 15 years, during which time several different schemes have evolved. In 1974 asteroids were split into two major classifications, C for Chondritic and S for Silicaceous, with asteroids which didn't fit nicely into either category designated by the letter U (for Unclassified). As more and more data was gathered on the spectra of asteroids, various new letter classifications were branched off and changed around, until today we are left with 14 different designations.

This spectral code can be employed with some utility to guess at the mineral composition of an asteroid. As there have to this date been no missions to take samples from actual asteroids, these compositions are somewhat hypothetical. They are based on comparisons between the spectra of meteorites of known composition and those of the asteroids in question. The validity of this comparison is bolstered by the current belief that most meteorites come from Apollo-Amor group asteroids. The recent analysis of the asteroid 1986DA, which indicates that it is probably a large chunk of nickel-iron alloy thrown off from the differentiated core of a larger asteroid in a collision also supports this technique.

Table 2.4 presents a summary of the current beliefs as to the mineralogy of the various spectral classes. [15] Note that these are merely guidelines; individual asteroids may have substantially different makeups than those suggested by their spectral class, especially if they are covered with a thick regolith concealing the material of the main body from view.

Type	Inferred Surface Morphology
A	olivine or olivine-metal
B C F G	hydrated silicates + carbon/ organics/opaques
D P	carbon/organic-rich silicates?
E	enstatite or possibly other iron-free silicates
M	metal (poss. trace silicates) metal + enstatite?
Q	olivine + pyroxene + metal
R	pyroxene + olivine
S	metal + olivine + pyroxene
V	pyroxene + feldspar
T	possibly similar to types P/D

Table 2.4: Asteroid Composition

The list of useful minerals in these asteroids is considerable. It includes olivine (iron-magnesium silicate), pyroxene (iron-magnesium silicate), and feldspar (calcium-sodium-potassium alumino-silicate) as well as metals in the form of nickel-iron alloys. Carbonaceous chondrites, meteorites thought to represent the composition of many C-type asteroids, contain small spherical inclusions (chondrules) of olivine or other minerals in a clay matrix which can hold as much as 20% water. Some of these also contain as much as 5% carbon in the form of either graphite or tar-like organic compounds. Some C-type asteroids, possibly extinct cometary cores, may also contain significant amounts of volatiles such as nitrogen and the noble gases.

These minerals translate into several valuable products for use in space. Water, as well as playing a vital role in life-support, can be separated into oxygen and hydrogen and thus serve as rocket fuel. Oxygen can also be extracted from silicaceous materials, and volatiles extracted through heating. Nitrogen in particular would be useful for fertilizers, explosives, and life-support systems, and would otherwise have to be brought up from Earth. Silicon, present in some M type asteroids, can be used for construction of solar cells and semiconductors. The organic compounds present in some carbonaceous asteroids could be used to produce assorted useful polymers. The nickel and iron available in these asteroids in particular would require much less processing than would be necessary to extract them from lunar materials.

2.2.2 Accessibility

In evaluating the accessibility, and hence the usefulness of a given source of materials, several factors must be considered. As on Earth, the straight line distance between two points often has little relevance. What is important instead is the difficulty of traveling that distance. Just as uphill journeys require more energy than travel on level surfaces, the difficulty of travel in space is largely determined by gravity gradients. Travel times, too, may be compared to the Earthbound case, for the faster routes will usually be more expensive. Going to Europe one can either take eight hours to get there by regular plane or take the Concorde and get there in a couple of hours but pay more than twice as much. The final factor is one of convenience. Close-by places are in general convenient to reach, as one can leave at any point and still take the same amount of time to arrive. For destinations further away, plane schedules come into play, and things get more complex. To reach some places, an elaborate chain of flight transfers becomes necessary, and missing even one can cause large delays. In a similar manner, opportunities for fast, efficient travel between two objects in the solar system only come about at certain intervals. The more complex the planned trajectory becomes, with multiple-swingby gravity assists and other complicated maneuvers, the less frequent possible launch opportunities become. All of these factors of energy required, flight time, and frequency of opportunities must be balanced against each other to evaluate the overall accessibility of an object.

In the solar system, where everything is orbiting around at least one, if not two or more different things, distances are measured not in meters or kilometers but in velocity increments. Since everything is moving with respect to almost everything else, to reach a given object it is necessary to match velocities with it. This velocity increment, known as the ΔV, is a measure of the energy, and more importantly the fuel required to reach a given object.

In judging the accessibility of a possible source of materials, one must first decide on the place where the materials are to be utilized, and then calculate the ΔV from the source to that location. Thus, the ΔV from the source object to LEO may provide an excellent measure of this factor. Note that this is different than the ΔV from LEO to the source. On the outward journey relatively little mass is being carried; what is important is the return trip, which carries a greater mass but in most cases can use aerobraking, resulting in a smaller ΔV. Table 2.5 is taken from a section of a JPL document on space resources written by R.L. Staehle. [4] As it shows, it requires less ΔV to bring material from any of the NEA's than it does from the lunar surface, the other main possibility for space-based resources. The ΔV to LEO from 1982 DB, until last year the most accessible of the NEA's, is as much as 30 times less than from the lunar surface.

In flight times the known near-Earth asteroids compare favorably to everything except the surfaces of the Earth and Moon, which both require substantially higher ΔV to reach. Actual flight times for resource deliveries may exceed those presented in the table, however, as lower-thrust but more efficient electric propulsion may be used. Relatively infrequent mission opportunities would also tend to make NEA's less attractive than the lunar surface as sources of material, were it not that they contain resources such as water and volatiles which would otherwise have to be brought up from Earth at great expense. The Earth-Sun Trojans, if they exist, would be particularly good in this department, as their position in nearly the same orbit as Earth would give continuous transport opportunities at extremely low ΔV's.

Location	Minimum ΔV to LEO (km/sec)	Flight Time (ballistic)	Frequency of Opportunity (ballistic)
1982 DB	0.1-0.5	2-8 mo	2-10 yr
Near-Earth Asteroids	0.5-2	2-20 mo	2-5 yr
Earth-Sun Trojans	≤1.4-2	0.8-2 yr	continuous
Phobos Deimos	~1.5-2	0.5-2 yr	1-2 yr
Lunar Surface	3.2	3-5 d	continuous
Mars Surface	5.6	0.5-2 yr	1-2 yr
Earth Surface	9.1	10-15 min	continuous

Table 2.5: Accessibility of Solar System Objects

This is why the search for NEA's is so important. We know of only a tiny fraction of the objects circling the Sun in the close vicinity of our planet; it is quite possible that there are asteroids out there which could be reached from Earth orbit with a good-sized sneeze. In just the last year two new small asteroids were found which were more accessible than the previous winner, 1982 DB. More asteroids, larger and with smaller ΔV's are probably out there. The presence of Earth-Sun Trojan asteroids could have a tremendous impact on mankind's expansion into space, but we still don't know if they exist. A strong program to seek out these asteroids and evaluate their potential usefulness is needed to chart the course of the next century in space. The sooner these asteroids are found, the firmer the basis of that course will be.

3. The Search

The search for near-Earth asteroids is a rather broad and indistinct topic. It has a fairly extensive history, though much of that story belongs more to the more general search for asteroids and the field of astronomy than it does to the search for NEA's in particular. Only in relatively recent times have programs been launched to look for these objects. This section will present a brief history of the search and describe the programs past and present which have been responsible for NEA discoveries. It will also describe the tools used to conduct the search and the ways in which results are communicated. A separate subsection on space-based searches will be included.

3.1 History of the Search for NEA's

In 1898, almost one hundred years after the discovery of the first known asteroid by Giuseppe Piazzi, the first of the near-Earth asteroids was found. Named Eros, this asteroid crossed the orbit of Mars and approached that of Earth, and under today's classification system belongs to the Amor group. That classification system was not developed until the discoveries of 1862 Apollo and 1221 Amor in 1932. Many of the first discoveries of these asteroids were made at Heidelburg, where the use of photographic plates was being pioneered. It was the development of these techniques which made the dated designation scheme necessary for asteroids which had not been observed long enough to merit names and numbers.

The later 1930's and early 40's saw little progress in asteroid research, due mainly to the distruption of World War II. The first of the systematic surveys of the celestial sphere were started in 1949, signalling the beginning of a more comprehensive and ordered approach to astronomy. These two surveys, both of which ran for seven years, discovered several NEA's, though their discovery was incidental to the main purpose of the programs. The National Geographic Society-Palomar Sky Survey discovered four NEA's using the (then) new 1.2 m Schmidt photographic telescope, while the Lick Proper Motion Survey discovered three.

The incidental nature of these discoveries is worth note. Asteroids appear as long streaks on photographic plates, and they are not particularly choosy as to which plates they appear on. This has frustrated a good number of astronomers through the years, who see only that the observation they were trying to make has been ruined by an ugly streak. These irritated astronomers have long tended to throw these plates, which they deem to be useless, into the waste basket without reporting them. One German astronomer even referred to asteroids as the "vermin of the skies." [52] This attitude has resulted in a great loss of data; indeed, the recovery and followup of the asteroids first discovered in the surveys described above have been attributed to "the diligence of certain individuals, who were. . . intrigued by the long trails." [16] Scott Dunbar, one of the main searchers for the Earth-Sun Trojans, tells of numerous occasions when another astronomer would describe trails characteristic of NEA's ruining his plates. On one occasion, Dunbar overheard an astronomer talking about such a trail in an area of the sky where Earth-Sun Trojan asteroids would be likely to appear; followup was impossible, however, as the astronomer had thrown the plate away. [12]

Throughout the 1950's and 60's, incidental discoveries of NEA's continued, while more specifically oriented programs were being formed. The Yerkes-McDonald "Survey of Asteroids" and the Palomar-Leiden Survey were two such programs directed at asteroids. The Indiana Asteroid Program (1947-67) was another such, and the Crimean Astrophysical Observatory has been making systematic observations of asteroids since the mid-1960's. [21]

In recent times, the larger surveys have been better about following up incidental asteroid discoveries, while smaller surveys have been conducted in a more focused vein. An example of the former is the second Palomar Sky Survey (PSS II), which had discovered 10 near-Earth asteroids as of early 1988. Another is Kowal's deep solar system survey from 1976 to 1985, also using the 1.2 m Palomar Schmidt. An example of the latter is the three month survey conducted using the 1.2 m UK Schmidt telescope in Australia during 1981, which came to be known as the United Kingdom-Caltech Asteroid Survey (UCAS).

The first search program dedicated exclusively to the discovery of near-Earth asteroids was not started until 1973. Initiated by Elinor Helin and Eugene Shoemaker, the Planet Crossing Asteroid Survey (PCAS) has been the most successful program at finding NEA's to date. Using Mount Palomar Observatory's .46 m Schmidt, the PCAS searchers cover wide areas of sky during five-night runs in the dark lunation of each month. Together with the Palomar Asteroid and Comet Survey (PACS) started by Shoemaker and his wife in 1982, PCAS has found over 70 near-Earth asteroids.

In 1983, Project Spacewatch joined the ranks of asteroid searchers. Headed by Tom Gehrels, this program has pioneered the use of Charge-Coupled Devices (CCD's) in astronomy with its .91 m CCD equipped telescope. This new CCD technology permits the use of computers to analyze telescope images in a fast, efficient manner. Its discovery rate for NEA's has risen to about 15 each year and is expected to rise as technology continues to improve.

3.2 Tools and Techniques

The principles guiding search efforts for near-Earth asteroids are to a large extent dictated by the characteristics of the objects being sought. NEA's are first of all relatively rare. They are in addition fast-moving, faint, and only visible for a short period of time. These factors have determined the techniques used for the search.

3.1.1 Traditional Search Methods

The first of these characteristics requires that any search cover a large area of sky to have any chance of finding the asteroids at a decent rate. For this reason, the instruments which have been most successful in finding NEA's have been the wide-angle Schmidt telescopes. The 1.2 m Schmidt telescope at Mt. Palomar can cover 41 square degrees at once out to a visual magnitude of 20. The .46 m Palomar Schmidt covers an even larger field, 64 square degrees, but can not spot as faint objects.

Instrumentation is not the only factor involved, however. The methods of image processing used determine the necessary length of the exposures, which in turn dictates the rate of sky coverage. For example, the PCAS coverage averaged 13,000 square degrees per year in the period from 1973 to 1981, but with the introduction of new processing methods (stereo microscopy) and the resulting reduction in exposure times, coverage has risen to between 40,000 and 50,000 square degrees each year.

It is the relatively fast motion of asteroids which allows them to be detected. Since the turn of the century, most asteroids have been found by examination of photographic plates; almost all the currently known NEA's were discovered using this method. Two major techniques are commonly employed.

In the first, two consecutive photographs of a section of sky are taken. The exposures are usually 10-20 minutes in length, during which time the telescope moves at the same rate as the stars. In the resulting plates, asteroids and other fast-moving objects will appear as long streaks. The length and direction of the streaks on the two exposures will help in determination of the object's orbital parameters. Closer objects will tend to have longer streaks, so NEA's will tend to stand out from the crowd. The limiting magnitude for this technique is determined by the apparent motion of the object, not the exposure time, as the light is distributed over the length of the streak instead of being concentrated in a point.

Using the second technique, two photographs are taken of a star field about 45 minutes apart. The resulting plates are examined under a stereo microscope; objects which have moved relative to the field will stand out due to a stereopsis effect. This method allows shorter exposure times to be used; it is the employment of this technique which has produced the marked jump in sky coverage in the last few years noted above. It is limited, however, in that it cannot be used with the 1.2 m telescope as the 14 by 14 inch plates from the larger telescope are too large to be viewed through a stereo microscope.

Because NEA's are relatively faint, observations are usually made on the nights surrounding the new moon of each month. Directing the telescope at a high opposition angle during this dark lunation period gives the best results; the higher the angle the greater the quantity of reflected sunlight which reaches the Earth from the object, and the easier the object is to see.[1] One of the reasons the Earth-Sun Trojans are so hard to look for is that if they exist, they would never reach full opposition. Thus, less of the light they reflect from the Sun would reach Earth, and they would appear to be much fainter.

The more powerful telescopes to not contribute as much to the search as they might, however. In addition to having, for the most part, smaller fields of view than those typically used for asteroid searches they are limited by the abilities of the other telescopes being used. If one telescope spots an asteroid with visual magnitude of 18.5 and the only telescopes available for followup have a limiting magnitude of 15, the new discovery is unlikely to be recovered at a later date except by accident.

This is one of the reasons why cooperation is so important to the search for NEA's. Each dark lunation lasts for only five or six days, and by the next one a newly discovered asteroid will have probably passed on in its orbit to a position in which it is no longer visible from Earth. Followup observations must be made over a period of several weeks to secure accurate enough orbital parameters to recover the asteroid at a later date. This would not seem difficult to accomplish, but time on large telescopes is in high demand and is usually alloted well in advance. Discoveries are by

[1]The opposition angle is the angle between the Sun, Earth, and object being observed.

nature unpredictable, so it is hard to schedule followup observations ahead of time. Thus maximal use must be made of the short period during the dark of the moon when the asteroids are bright enough to be seen by the relatively low-power telescopes used for the surveys.

It is in this area that the photographic searches have long suffered. The physical labor involved in setting the telescope position, loading and unloading film canisters, and timing exposures is considerably time-consuming. Thus the actual photographs often do not get examined until several days after they were taken, which in the short period of the dark lunation may be too late for comprehensive followup. The more coordinated searches develop the plates right away and examine the plates for asteroids during the afternoons of the dark period so that as little time as possible is wasted.

Over the last few years, however, more efficient electronic search techniques have gained more and more popularity. The Lowell Observatory-UK Schmidt Telescope Asteroid Survey (LUKAS) has been experimenting with several new techniques. To catch the faintest possible asteroids, the plates are tracked at the mean asteroidal rate, thus enhancing exposure time. Also, the LUKAS program has begun digitizing plate images and analyzing them for asteroids automatically by using computers. Currently only the LUKAS plates are digitized and archived, but the ultimate intent is to use this method on all plates taken with the UK Schmidt, thus catching incidental asteroid observations automatically. It is also hoped that with the accumulation of a large database of such images it will be possible to correlate isolated observations with known asteroids and eventually run statistical population analyses.

3.2.2 Charge-Coupled Devices

A Charge-Coupled Device (CCD) is a solid state chip containing an array of photoelectrically sensitive pixels in a gridlike pattern. Placed on the focal plane of a telescope, this device traps incoming photons, converting them into electrons. Each pixel is also a tiny capacitor which can hold a charge until it is given the command to move it, at which point the pixels are shifted row by row to the edge of the chip, where they are read in by a computer.

It is a relatively simple sounding device in principle, yet its application over the last decade has revolutionized astronomy. CCD's are more sensitive than photographic emulsions, and they have a 2-3 times greater bandwidth. The computer linkage allows automation of many steps of the search procedure and real-time processing of data.

For the search for NEA's, this has several important implications. When CCD's are used, painstaking examination of images becomes unnecessary; known stars can simply be subtracted out of the pictures, leaving only the objects of interest. Real-time processing means that no time is lost between the actual observation and the discovery so that followup observations can proceed immediately. The presence of the computer also allows more exact measurements as well as automatic calculation of orbital parameters and future positions.

In normal usage, CCD pictures are taken with fixed length exposures so that light can accumulate and fainter objects can be observed. This makes sense for observation of fixed objects such as stars, but for moving objects provides little extra benefit, as the light does not accumulate in one spot. In looking for these objects CCD technology provides a new facility for continuous scanning over large areas. Instead of taking exposures one at a time, reading out the CCD pixels at the end of each and then shifting to a new location, large areas may be scanned at one time by simply turning off the telescope's motor and letting the Earth's rotation take effect. By shifting the pixels over the chip at a constant speed equal to the rate the telescope moves across the sky a sort of moving picture is obtained. This technique, known as scannerscopy, greatly increases sky coverage in such a search, and cannot be done with old-style photographic techniques.

The benefits of CCD scannerscopy are enhanced by the greater quantum efficiency of CCD chips when compared to photographic emulsions. The CCD currently in use by Gehrels at the Steward Observatory has a quantum efficiency of 30% over the wavelength range 500-800 nm, and a new, thinner chip with quantum efficiency of about 70% is on order. Photographic emulsions, in comparison, have quantum efficiencies of only a few percent and roughly half the bandwidth of most CCD's.

CCD technology does have its limitations, however. Current chip sizes are quite small; the RCA chip used by Gehrels in the Spacewatch Telescope is a 512 x 320 pixel array, and covers in a single frame only 0.044 square degrees. In sidereal scan mode this results in a coverage of about 1.8 square degrees per hour, a factor of 150 less than is achieved with the .46 m Schmidt employed by Helin and Shoemaker in the PCAS. Larger chips (2048 x 2048 pixels) are under development, and work is being done on the construction of a multiple-CCD array at Princeton. A wide-angle Schmidt equipped with such an array would be the ideal instrument for conducting NEA searches. It would, however, present a significant challenge in data-processing. Current trends in computer development — specifically, the advent of mini-supercomputers — would tend to indicate that this is a challenge which can be met practically and economically.

Another serious problem is present in the physical equipment necessary for CCD usage. This equipment is at present quite fragile, and must be cooled with liquid nitrogen. It also requires significant servicing, and currently the body of people qualified to carry this out is extremely limited. Also, most efficient use of CCD's can be made if they are actively moved across the sky at a rate faster than is achieved with the drive turned off. Current equipment on the Spacewatch telescope is inadequate to the task, however, and it is likely that similar difficulties would somewhat limit the benefit to be gained by refitting existing telescopes with CCD equipment.

Nonetheless, the 0.9 m CCD equipped telescope used by Gehrels in Project Spacewatch has accumulated a quite impressive record. In the period from September 1990 through June of 1991, it discovered no less than 15 NEA's. This rate is expected to increase to 36/year with the purchase of a new CCD of twice the current one's quantum efficiency; Gehrels expects to purchase this CCD and have it in operation by 1994. If funds are obtained for the planned 1.8 m Scannerscope, a discovery rate as high as 200 NEA's per year is thought to be possible. Note that according to Gehrels, about half of these are likely to be small asteroids under 100 m in diameter. The smallest to be found so far is the recently discovered 1991 VG, which is only 8 m in diameter and now holds the title for the most accessible near-Earth asteroid.[2]

There is every reason to believe that as technology advances in the years to come, current difficulties with CCD's will be solved. Over the next decade, they will certainly come to dominate the field of astronomy.

3.2.3 GEODSS

[2]There is still some doubt as to the nature of 1991 VG. A recent Chilean observation may indicate that it is a man-made object such as a discarded booster from an old Apollo mission. See New York Times Article.

The Ground-based Electro-Optical Deep Space Surveillance program was developed in the early 1980's by the Air Force for artificial satellite tracking. A planned network of observatories equipped with 1 m telescopes using television cameras of the intensified silicon-diode array (ebsicon) type, GEODSS would also be ideally suited for NEA search work. In the period from 1980-1984, L. Taff of the MIT Lincoln Laboratory adapted the first of these telescopes for asteroid observation and used it to conduct a systematic search. A discovery rate of 25 NEA's per year was predicted for the system, but in fact none were found, though several main-belt asteroids were reported. GEODDS is apparently expected to be upgraded with a series of telescopes placed in 100,000 km orbits sometime soon.

3.3 Communications

As has been mentioned above, the short viewing opportunities for NEA's make good communications systems essential to the search for near-Earth Asteroids. There are a fairly large number of telescopes in various parts of the world; there is also a consistent need for followup observations of NEA's. Time on those telescopes is tightly scheduled, however, so to take the most advantage of what time there is, a large amount of coordination is necessary. To organize such a search on an international level standard methods of communication and data collection and distribution are necessary. Communications are particularly of concern with regard to observatories in the second and third worlds, which have not fully entered into the electronic network enfolding the West.

The need for followup observations of NEA's does not stop after the period around the initial discovery. The vast majority of known asteroids do not have orbital parameters fixed well enough to merit naming and numbering. Even now, 1% of the numbered asteroids have been lost. Of the known NEA's, only 80 have been numbered, and 719 Albert and two others have been lost. In the period from August-November of 1986, in which 713 asteroid dicoveries were reported, around 60% of the discoveries were observed on only a single night. Admittedly, the record is somewhat better for NEA's than for main-belt asteroids, but it is still clear that more attention needs to be given to fixing of asteroid orbital parameters.

Currently, the Minor Planet Center in Cambridge, Massachusetts does most of the work of coordinating asteroid observations. In countries with access to the Internet, asteroid observations are reported to the MPC via electronic mail. The MPC then checks observation data against the known asteroid population to see if a new discovery has been made. Particular attention is paid to possible NEA's, in which cases the MPC frequently requests observations by small-field, long focus reflectors if the object has passed beyond opposition or for some other reason can no longer be followed by the discoverer. Japanese amateurs in particular have been active observers in recent years.

Many observatories in the second and third worlds do not have access to electronic mail, however, and must communicate their observations by telex or by sending tapes or floppy disks containing observation archives. This makes communication difficult both ways, so that observation time in those areas may be underutilized. There is a particular need for observations in the southern hemisphere. Even in the West, however, there are still a number of observers who submit their data either typed or on computer printout.

In 1990 the Planetary Science Intitute initiated an Observer Alert Network for near-Earth asteroids. Letters were sent to 111 observatories suggesting a program wherein alerts would be sent out upon discovery of a new NEA as a method of soliciting further observations. Only 20 observers responded and are on the program's active list. The program seems to be largely phone and e-mail based, but as yet still lacks wide recognition. It also does not seem to be coordinated with the MPC, and for that reason is probably missing a large number of regular and amateur astronomers.

Network News, a kind of electronic bulletin board which goes out to universities, businesses, and government institutions all over the world is another facility which could be of use. This service has separate news groups for astronomy, space science, and now space news. It has a wide readership among university faculty and graduate students, some of the prime possible observers. Other electronic news journals are available upon request by e-mail.

Data storage is another key aspect of the NEA communications system. The Minor Planet Center in Cambridge maintains a large database of asteroid information including astrometric observations and osculating orbital elements. This information is regularly published in the *Minor Planet Circulars*, which sees distribution over a large portion of the astronomical community, and is available in electronic form. The Institute for Theoretical Astronomy in Leningrad seems to serve a similar function for the Russian community, though its data net is not as wide. The Tucson Revised Index of Asteroid Data (TRIAD), created in the late seventies, is available as part of the Infrared Astronomical Satellite (IRAS) Asteroid and Comet Survey final data product number 13, otherwise known as the Asteroid IRAS Database, or AID. AID, along with the Asteroids II Database, may be accessed through the National Space Science Data Center (NSSDC) of the Goddard Space Flight Center in Greenbelt, Maryland, and is available on 9-track tape. Some of this information is also available in the affiliated European Data Center in Strasbourg, France. A large bibliographic file containing most asteroid related references has long been maintained by Clifford Cunningham of the Dance Hill observatory in Ontario, Canada.

Much of the above data is redundant, however, with the same data being incorporated in several different products of varying accessibility. In an effort to bring all asteroid data together into one database, the last few years have seen the development of the Steward Observatory Asteroid Relational Database (SOARD) under the auspices of the Unversity of Arizona and the NASA Space Engineering

Research Center. SOARD has evolved to include all the data from Asteroids II and IRAS, as well as assorted observations in spectroscopy, photometry, and radiometry and version of Cunningham's Minor Planet Bibliographic Index updated to include over 12,000 references. It is updated regularly through literature searches, reports from individual observers, and data from the *Minor Planet Circulars*. The database is at present only available in dbase IV format, however, and is not available on-line. Executable versions of the database have been distributed to several sites around the United States, but access is still rather limited. Plans are underway for a government funded database at the NSSDC which would incorporate SOARD with other sources of astronomical data.

3.4 Space-based Activities

Observation from space is an expensive, but highly valuable source of information in the search for near-Earth asteroids. Without the light-distorting presence of the atmosphere fainter objects become more clearly visible and new spectra are opened up for observation. Using modern technology immense amounts of data can be acquired from space-based resources in an amazingly short time.

3.4.1 Current Space Resources

The best example to date of this utility is the Infrared Astronomical Satellite. Launched in 1983, IRAS was in orbit for less than a year and yet accumulated such a vast quantity of data that it still has not been thoroughly processed. The asteroid observations conducted as part of the IRAS mission constitute "the largest, most complete and least biased survey of asteroids and comets yet conducted." [30] This is all the more impressive considering that the detectors best for asteroid observations were those which suffered the most degraded performance. IRAS is still an enormous resource which has proven to be of immense use; we can only guess what it would have been like had those instruments functioned properly.

As the IRAS survey covered the entire sky, many observations were made of point sources which could not be correlated with known asteroids at the time and for which followups were not made. These observations were not extracted from the IRAS data in the initial processing runs, but still represent an excellent resource. Re-running the data processing program with a list of known objects updated to include recent discoveries would probably be of considerable benefit.

The recently launched Hubble Space Telescope also has considerable potential as an asteroid observing instrument. The onboard High-Speed Photometer, Faint Object Spectrograph, and Planetary Camera are the instruments most likely to be of use in asteroid observations. Observation time for the HST is extremely hard to come by, however, so its usefulness in the NEA search is likely to be somewhat limited.

The European Space Agency's astronomical satellite Hipparcos, launched in 1989 is proving to be of substantial use despite the failure of its apogee motor. It is providing observations of substantially higher accuracy than have ever been achieved before, but is somewhat limited in that it can only view relatively bright objects (limiting magnitude 12.5-13). As a result, only 50 asteroids have been selected for observation. A second Hipparcos satellite is being considered, however, and would likely have a higher limiting magnitude.

The planned Space Infrared Telescope Facility (SIRTF) is yet another space based instrument of great potential. It provides two major benefits to NEA research. First of all, as it conducts its observations in the infrared band, it is not dependent on reflected sunlight for observations. Thus objects not at opposition may be observed, and the potential for spotting such objects as Earth-Sun Trojans exists. Its onboard infrared spectrograph also has great potential in characterization of asteroid surface minerology. SIRTF, like the HST, suffers from time oversubscription, however, and has not yet even been launched.

3.4.2 Future Prospects in Space

Several political factors have contributed to a recent expansion in the potential for future space-based asteroid observation missions. One piece of fallout from President Bush's Space Exploration Initiative has been increased attention to NEA's as potential sources of material. Consideration was given in the recent Synthesis Report to manned asteroid missions before taking the step to Mars. Also, with the end of the Cold War, there has been some thought on the subject of converting SDI into an asteroid defense system. [44]

With these political changes NASA has as also been restructuring its priorities. Increased emphasis is being put on small missions, particularly with regard to recent advances in miniaturization. These advances have made possible tiny space vehicles with significant range capablilities which have come to be known as "microspacecraft". The reorientation within NASA toward smaller missions with shorter development times has made it possible that consideration will once again be given to an asteroid observation mission capable of surveying a large portion of the inner solar system and establishing once and for all the existence or non-existence of the Earth-Sun Trojan asteroids. Such a mission, along with an examination of current space survey technology, will be considered in more detail in the next section.

4. Solutions

In the preceding sections the reasons for conducting a near-Earth asteroid search and the methods for carrying it out have been discussed. What remains is to examine our priorities and the options for action in the next few decades. Once these have been clearly set forth and thoroughly discussed, a judicious plan of action can be developed and acted upon.

It is important to keep in mind, however, that there is no final solution, no truly optimal search strategy. Any number of search plans could provide an excellent sampling of the NEA population for purposes of scientific research or mineral exploitation. For those purposes, it doesn't really matter if a survey misses an asteroid here and there. However, no practical search plan will find all the asteroids which pose a threat to Earth. At some point a balance must be found between assessments of costs and danger levels. What is important to do is to formulate a strategy that can accomplish its goals efficiently and to set those goals so that it can do so without excessive expense.

4.1 Priorities

As described in section 2 above, there are three basic reasons for conducting an extensive NEA search. Those reasons are: (1) pure science; (2) exploration for easily accessible resources; and (3) assessment of threat potential. These motivations do not carry equal political weight, however. Neither of the first two carries the same urgency as the third reason, nor do they hold the public's interest to the same extent. Probably 80% or more of the recent material written on the subject of NEA's is concerned with the collision threat; their potential as sources of materials and their purely scientific interest are usually mentioned only as sidelights. This slant of necessity will exert a strong influence over an assessment of search priorities.

From a purely scientific standpoint, there is no pressing need to find all, or even most of the asteroids in our vicinity. This does not mean that an extensive survey would be unprofitable from a scientific standpoint, only that such a survey need not be very complete to provide useful information. The current population of known NEA's is pathetically small, forcing astronomers to guess at the constitution of the population as a whole. The larger the known sample becomes, the better idea we will have of the overall NEA distribution, and hence of the structure and origin of the solar system. To give an example of how little we know at this time, it has just been over the last year or so that astronomers have begun to notice a bend in the size-frequency relations around the smaller, 10-

100 m diameter asteroids. The higher frequency of the smaller asteroids has led to speculation that many of them are the products of cometary breakups and advanced the understanding of the solar system environment by that much.

Besides a characterization of the NEA population, the priority from the pure science standpoint would be the determination of the structure and composition of these objects. Probes sent to look at asteroids close-up would go a long way toward answering the questions of their origin and their relationship to the meteorites found on Earth. An accurate survey of asteroids close by Earth could provide invaluable insights into the creation of the asteroid belt and thus into the science of solar system formation as a whole.

From all this it seems that there would be two main scientific priorities. The first would be a relatively cheap enhancement to existing search programs. This would increase the discovery rate of NEA's by three or four times over the next few years, and provide the basis for better population studies. The second would be the launch of several planetary probes to investigate NEA's from close quarters.

When the problem is addressed from a resource oriented perspective, the priorities are somewhat different. Unmanned probe missions would still be important to gain an accurate picture of asteroid compositions, but the search for uncataloged objects would take a different cast. Figure 4.1 shows the ΔV distribution among a population of 73 NEA's with well known orbital parameters. [58] From the graph it can be seen that about 10% of known NEA's can be reached with ΔV's under 5.5 km/sec. If such a relationship holds as more NEA's are discovered, a tenfold increase in the known population would mean the discovery of another 70 asteroids with interesting ΔV's, giving a lot more freedom to pick and choose among asteroids for accessibility and useful composition. It's likely that with such a large number of new discoveries, objects even more accessible than the best ones known today would be found. Pushing an asteroid into Earth orbit for exploitation would be a sufficiently ambitious undertaking to justify significant expenditures now save even a little ΔV.

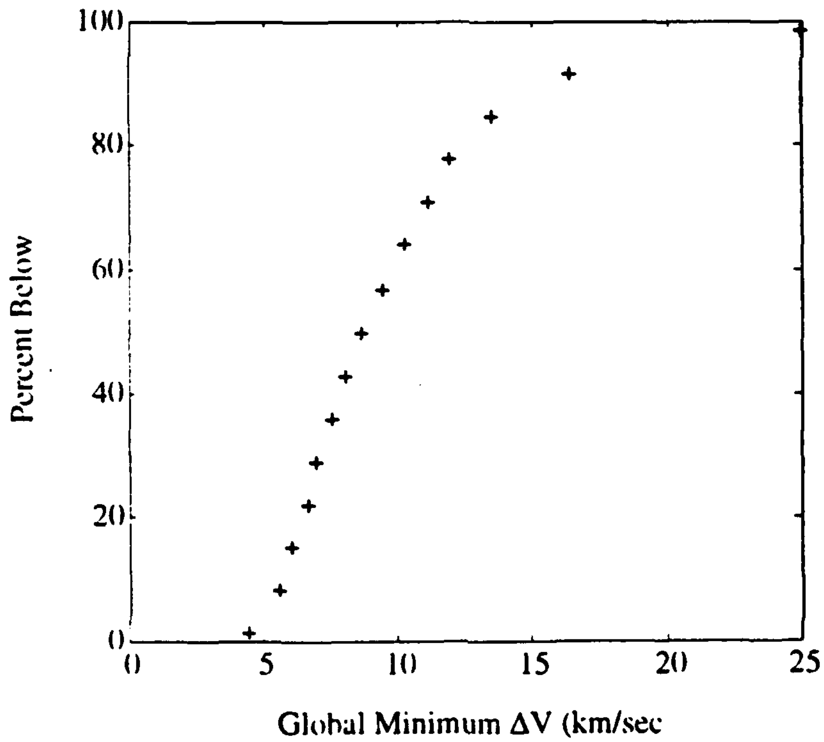


Figure 4.1: ΔV distribution in a population of NEA's.

Another special priority of any effort to find asteroids suited for exploitation would be the search for asteroids in the Earth-Sun Trojan points. These asteroids would be unlikely to be discovered in a normal search, and yet could prove to be the most valuable sources of materials in the neighborhood of Earth, not to mention the knowledge which could be derived about our solar system just from knowing whether or not they exist. A special effort would have to be made to spot these asteroids, and as will be shown below a ground based search may not be adequate to the task. A space-based probe of some sort may be necessary to once and for all prove or disprove their existence.

The priorities for a search motivated by fear of asteroid and comet impacts would be quite different from those described above. For this purpose, a much more extensive survey of the NEA population would have to be undertaken. The ultimate objective would be to find and track all the asteroids in the vicinity of the Earth down to the smallest objects capable of penetrating the Earth's atmosphere to impact with significant force. Of course, there are several problems with a statement like that. First of all, one must decide what sort of impact is 'significant'. As is shown above, even a 10 m diameter asteroid could impact with the energy of several Hiroshima-sized bombs; this would seem 'significant' to many people. Yet there are an estimated 150 *million* NEA's in that size range; to even think about trying to find and track them all seems ridiculous.

The problem doesn't get much more tractable even if one takes a more stringent definition of which class of impacts is most significant. The point at which the effects of an asteroid impact become global is the subject of hot debate. Some people claim global effects could result from collisions with asteroids as small as 300 m in diameter. Others place the threshold a bit higher. According to the Spaceguard Survey Report of the recent NASA workshop, "The threshold for an impact that causes widespread global mortality and threatens civilization almost certainly lies between about 0.5 km and 5 km diameter, and it probably lies near 2 km." Given that much uncertainty with such high stakes, it would seem best to play it safe and call anything 300 m in diameter or larger significant. Even at this large size, however, current population models predict that there are some 30,000 asteroids to find, more than 150 times the number of NEA's of any size which have been found to date.

Clearly, any attempt at an asteroid search of the type described above will necessitate some hard decisions and some compromises. In establishing priorities for such a search other factors will inevitably creep in. As Duncan Steel, one of the Spaceguard Workshop members puts it, "One could argue that any effort available should rather go into looking for hazardous long-period comets (or, indeed, asteroids like 1991 DA) rather than the NEA's of 0.5-1.0 km, since they are more of a danger than the NEA's, quite likely. It may shake down that lpc's pose 30-50% of the hazard, and unlike NEA's (for which we might expect a 10-50 year lead-time) lpc's may be found to be on a collision course only 6-12 months ahead of time." [60] A cataloging and tracking strategy would probably prove to be hopelessly inadequate for dealing with the cometary problem, as the numbers are greater, the area to search is larger, and the flux of new objects into the system is higher.

It may be that the difficulty of conducting a thorough general survey of threatening objects would suggest a different strategy entirely for countering the impact threat. Perhaps a more passive early warning system would be desirable. Such a system might scan only the Earth's immediate vicinity, giving less warning time before and actual collision but able to spot even the smaller objects with a high level of completeness. While offering a greater level of security, this option would undoubtedly be much more expensive than even comprehensive survey programs, and might have to be based in orbit to achieve the desired effect.

As with the other cases examined above, planetary probes would be useful in dealing with the asteroid impact threat. Such probes would provide valuable information about the composition of possible impactors, which would lead to increased understanding of how they would behave in the event of a collision. Such knowledge would help immensely in making realistic damage and danger-level assessments and thus in determining the best course for a survey attempt.

On the other hand, an investigation of the possibility of the existence of Earth-Sun Trojan asteroids would have little merit if the main priority was to deal with the threat of NEA impacts. It is conceivable that resonances with Venus or Mars could disturb an asteroid in a relatively stable libration orbit onto a new path that could threaten Earth, but such an eventuality seems extremely unlikely.

Each of the motivations for looking for near-Earth asteroids entails a separate set of priorities for the search. Some of these priorities, such as the need to send probes to these objects to get more information on their composition, are common to all of the concerns. Others are not. In determining a course of action for the next few decades, an 'optimal search strategy', these priorities must be balanced with each other, with financial resources, and with scientific and political realities.

4.2 Options

Even when given a clear set of priorities, it is no easy task to determine what action to take. To a large extent, the available options depend on the commitment level the government is willing to make. That, in turn, is closely related to monetary issues. For that reason, I will present the elements of possible NEA search programs in terms of the financial commitment necessary to carry them out.

4.2.1 Low-Budget, Short Term Programs

For a relatively small investment, on the order of a few million dollars, currently existing NEA search programs could be greatly enhanced. Many of these efforts are working on shoestring budgets and are missing asteroids just because they cannot afford the staff to process the data they collect. Other programs could be greatly improved by the addition of a relatively cheap hardware upgrade. With a little more cash flow, programs could be started to take advantage of dead time on currently existing telescopes. I will note here a few specific cases where a small influx of money could achieve excellent results. These are not the only places where small amounts of funding could go a long way, however, and that should be kept in mind.

The Anglo-Australian Near-Earth Asteroid Search (AANEAS) is one such promising program hobbled by a lack of funding. Currently, the program is limited to examining plates taken by the 1.2 m UK Schmidt telescope for suspicious trails. As the program's director, Duncan Steel, is quick to point out, "The plates are *not* optimized for this search; in fact quite the opposite, they are taken as part of the Second Epoch Southern Sky Survey. Thus most fields are well away from the ecliptic, which is the best place to look; also well away from opposition, again the best place for NEA's." [60] Given the funds to support 3 new observers and buy the film supplies needed, Steel believes that AANEAS could discover 100 new NEA's each year. At the moment, with only two investigators, the program finds only about one new NEA each month. The improvement would come from taking advantage of the 8 nights each month when the telescope is not used, as well as times of poor seeing. Viewing conditions would not be optimal, but the exposures and search area could be tailored to the search instead of working from plates taken for other purposes. The greater aperture size of the UK Schmidt when compared to the 0.46 m telescope being used for the PACS and PCAS at Palomar would also help compensate for poor, bright-moon viewing. For funding, all that would be needed to support the above improvements to AANEAS would be $250,000 per year. This is truly a paltry sum of money compared to the benefits which could be gained from the program.

Another program which makes use of the UK Schmidt telescope is being handicapped by lack of funds. LUKAS is making use of a new technique to scan in photographic plates from the 1.2 m UK Schmidt and analyze them automatically for NEA trails using a computer. This program has the potential to not only check all of the new exposures taken for NEA's, but also to go back using old, archived plates and find asteroids which were missed the first time around. Apparently there are over 15,000 plates waiting to be scanned in from the Lowell observatory alone. But according to Steel, "problems with funding from the US end has slowed things down." [60] Programs like this could be greatly improved by a small addition of funds, and would doubtless prove to be of great benefit to regular astronomical research as well as helping in the search for NEA's.

One program which would benefit more from a hardware upgrade than from increased manpower is Project Spacewatch. Tom Gehrels, the project's leader, has hoped to supplement the existing 0.91 m Spacewatch Telescope with a new 1.8 m CCD equipped scannerscope for over a decade. He has acquired a mirror, and has secured a site to locate it and the staff to man it, as well as detailed plans for its construction and installation. [61] Such a telescope would be a marked improvement over the old 0.91 m telescope, not only because of its greater aperture size, but also because it could be used in a powered scanning mode allowing greater coverage than with the old telescope. Gehrels estimates that the scannerscope could in a few years be discovering as many as 200 NEA's per annum, up from the current rate of about 15. A large scannerscope of this type would also prove to be an excellent testbed for the new technologies which would be necessary for a large scale dedicated search program. NEA search software and techniques of CCD astronomy developed over the next few years in conjunction with the installation of the new telescope would prove invaluable in any such program. Gehrels has prepared a detailed budget for the construction of his desired 1.8 m scannerscope. He calls for, over a period of three years, $1.8 million. This is not a great deal of money on the scale of other projects being proposed for the NEA search.

Another possibility for hardware upgrades would be to sponsor the refitting of existing telescopes with CCD equipment. The advantage of this option is that it would be cheap; Gehrels estimates that most suitable telescopes could be rigged with CCD's for between $250,000 and $500,000, with a few such as the 100 in telescope on Mt. Wilson running as high as $1,000,000. These refits would benefit not only the NEA search, but most other investigations undertaken with the telescopes as well. Astronomers at many of these telescopes would probably be more than willing to devote a portion of each month's dark lunation to an NEA search in exchange for the improved performance in other tasks that the upgrades would imply. Refits of this sort could be applied on a case-by-case basis or as part of a larger search program. The only real disadvantage in refitting old telescopes is that they could not be used in the fast-scanning mode of a telescope designed specifically for that purpose.

Other, more indirect methods exist for supporting the search for near-Earth asteroids. One possibility in this vein is to fund a re-analysis of the data from the IRAS program. Observational data is available from this source on many asteroids which had not been discovered when the original data-analysis software was run. Current estimates suggest that there may be observations of 10,000 or more asteroids with unknown orbital parameters contained in the IRAS data. [30] This data could be searched to help fix the orbital parameters and determine the albedos and diameters of newly discovered asteroids with only roughly determined ephemerides. Observations of specific areas of the sky conducted as part of the IRAS Serendipitous Survey cover an additional area of 1108 deg^2 and have not been examined closely for asteroid observations. It is thought that the number of asteroid observations which could be recovered from this data would amount to about 10% of the number found in the survey data, and extend to a limiting magnitude which is a factor of 4 better than for those observations.

New techniques have been developed for analysis of the IRAS data since the original processing was done in the first half of the 1980's. Re-evaluation of the criteria indicating an observation of a near-Earth asteroid could result in new discoveries above and beyond the uncataloged observations described above.

Also of note is the possibility that observations of Earth-Sun Trojan asteroids could be hidden in the reams of IRAS data. Since observations were made at solar elongations of between 60 and 120 degrees, the potential for such observations to exist is definitely there. At least one researcher examining the IRAS data has spotted what he thinks may be evidence of an ES-Trojan asteroid. [62] Further analysis is definitely needed, however, and would be very inexpensive to finance.

One more method of encouraging the search for NEA's that has been suggested is to offer a small reward for information leading to the discovery of an NEA. This sort of effort would be aimed at graduate students, third world facilities, and amateur astronomers, and would be more public-relations oriented than hard core. Even if it did not gain significant numbers of new discoveries, it might raise interest in the subject around the world and encourage the formation of new, productive search groups. Such awareness would have a beneficial effect in reducing the number of asteroid observations which are tossed away as mere disfigurements of other photographs taken for other purposes. It would also be likely to increase the willingness of participating institutions to pursue follow-up observations of newly discovered asteroids, a crucial step in the permanent capture of asteroids which have only been viewed once or twice.

4.2.2 Extensive, Earth-based Search Programs

With a larger governmental commitment, on the scale of tens of millions of dollars a year, new possibilities take shape in the search for NEA's. At this level of effort, it begins to become realistic to attempt a large-scale survey with the intent of locating and tracking most of the larger NEA's. Such an effort would invariably be motivated mainly by fear of the asteroidal impact threat, as the needs of space science and space industrialization would probably not be seen as immediate enough to merit such intensive action. Much thought has been expended by a variety of sources as to what the size and scope of such a net should be. Of major note in this area is the report of the NASA International Near-Earth-Object Detection Workshop, known as the Spaceguard Survey. This section will analyze the Spaceguard proposal along with other thoughts on comprehensive NEA search networks.

On September 26, 1990, the House Committee on Science, Space, and Technology submitted the following statement on the NEA impact threat.

> The Committee believes that it is imperative that the detection rate of Earth-orbit-crossing asteroids must be increased substantially, and that the means to destroy or alter the orbits of asteroids when they threaten collision should be defined and agreed upon internationally. . . .
>
> The Committee therefore directs that NASA undertake two workshop studies. The first would define a program for dramatically increasing the detection rate of Earth-orbit-crossing asteroids; this study would assess the costs, schedule, technology and equipment required for precise definition of the orbits of such bodies. The second study would *define systems and techniques* to alter the orbits of such asteroids or to destroy them if they should pose a danger to life on Earth. The Committee recommends international participation in these studies and suggests that they be conducted within a year of the passage of this legislation. [64]

The results of the first of these workshops, held in San Juan Capestrano in the summer of 1991, are now available in the report known as the Spaceguard Survey. This report represents the work of the top members of the international astronomical community concerned with asteroids. Though it may claim to, it probably does not, however, represent the consensus of these astronomers. From all reports the San Juan Capestrano workshop was the scene of heated debate on a number of the report's key points, and the "consensus" was reached more from necessity than from true agreement. For this reason, the results presented in the report should not be taken as gospel; many of the figures it gives are extremely rough estimates. More accurate numbers wait on an increase in the pool of known NEA's.

Ironically, the data needed to plan the survey well can only come from the survey's results. One solution to this sort of vicious circle would be to fund smaller scale search programs for another five years or so. With current trends toward increased discovery rates in these smaller surveys, the known population of NEA's could be increased five or even tenfold, certainly enough to provide a firmer basis for program-shaping decisions.

The search program set out by the Spaceguard Workshop would consist of six CCD equipped telescopes with 2-3 m diameter apertures. These would be placed around the world in both hemispheres so as to cover as large a portion of the celestial sphere as possible, and would scan the skies to a magnitude of V = 22. They would be supported by a network of follow-up telescopes, possibly including a dedicated radar station. According to the workshop's simulations, over a search period of 25 years such a configuration would spot about 90% of NEA's larger than 1 km in diameter, two-thirds of NEA's larger than 500 m in diameter, and about a tenth of the asteroids over 100 m in diameter. Costs of the program are estimated at an initial $50 million in capital investment with annual operating expenses of $10 to $15 million.

The solution offered by the Spaceguard Workshop is an excellent response to the task given to it by Congress. There are, however, some fundamental problems with the assumptions on which it is based. In one subsection of the report, entitled "Smaller Asteroids, Comets, and Meteoroids," the position taken by the workshop on asteroids in the 100 m to 1 km diameter range is summarized:

> Impacts by these bodies are below the energy threshold for global environmental damage, and they therefore constitute a smaller hazard in spite of their more frequent occurrence. Unlike the large objects, they do not pose a danger to civilization. [59]

This seems a very shaky premise on which to base a program of such potential importance. The estimates upon which this premise are based consider only the nuclear-winter-like effects of large quantities of dust thrown up into the Earth's atmosphere. These models generally assume that "global environmental damage" will only occur if the dust layer thrown up by an asteroid impact covers the entire Earth for an extended period of time. They do not take into account the extremely fragile nature of the present day terrestrial ecosystem. With human pollution and tampering with the environment still largely unchecked, a somewhat smaller impact, say on the scale of a mere thousand megatons, might cause irreparable damage to the Earth's habitat. This is without addressing at all the danger that a smaller impact occurring in a nuclear armed third-world country could be mistaken for an attack and cause a limited or even global nuclear exchange.

And yet the position taken by the workshop members is very understandable. Detection of almost all of the NEA's in the 0.1-1 km diameter range would be a truly daunting task. The Spacewatch Survey in its recommended form would discover only about 10% of the NEA's in this size class over the projected 25 year period. Extension of the search period to 100 years yields little better results. To truly cope with these smaller asteroids the search would probably have to be conducted up to a limiting magnitude of V = 26 or higher, requiring telescopes with apertures over 10 m in diameter and much higher expenses. In defense of its position, the Spaceguard report notes that if the recommended search strategy was followed it would provide after a period of about 100 years a slightly better than even chance of spotting the next Tunguska-sized impactor. Taking into account the technological progress over that period, they claim, such an asteroid would almost certainly be spotted.

In one other area the Spaceguard Survey report leaves something to be desired. In its discussion of the need for follow-up observations to fix the orbital parameters of newly discovered asteroids, the report suggests that a network of semi-dedicated telescopes in the 1-2 m aperture range would be desirable, and mentions the possibility of a dedicated radar facility on the scale of the instruments in Arecibo, Puerto Rico and Goldstone, California.

But when it comes to describing the budgetary outlays for these functions, the follow-up functions are dismissed with the following statement:

> As noted previously in this Report, it would be desirable to have one or more dedicated planetary radars and large-aperture optical telescopes (4-m class). However, we anticipate that a great deal of useful work could be done initially using existing planetary radars and optical facilities. Therefore, for the purposes of this Report, we simply allocate a sum of $2 million per year for the support of radar and optical observing on these instruments. [59]

Compared with the care which seems to have been put into other sections of the report, this kind of statement seems quite irresponsible. The report quite clearly states that it plans for operations of at least 25 years in length and possible up to 100 years or more. To dismiss the network of follow-up telescopes by allocation of a small amount of funds during the initial period seems extremely short-sighted, and may conceal considerable later expenses not mentioned in the report. Radar installations on the scale of the Arecibo installation do not come cheap, nor do 4 m aperture telescopes. Moreover, with an expected monthly discovery rate of over two times today's entire known NEA population, demand on these follow-up facilities would be quite high. It is doubtful that current resources could come even close to handling the necessary traffic when existing programs even now have to struggle to get follow-up observations for their discoveries.

Alternatives to the Spaceguard approach exist. In its section on NEA detection, the International Asteroid Mission report of the students at ISU suggested a search program that would use existing telescopes. [55] Their plan was to refit many older telescopes with CCD equipment as described in the section above, and then to dedicate all the Schmidt telescopes with apertures over 60 cm to the search for NEA's during several periods in the year, probably the dark lunations of each month. Both the Arecibo and Goldstone radars would also be commandeered for some portions of the year. The plan is interesting, and it would certainly be cheaper than the Spaceguard plan, but it would probably generate enormous hostility in the astronomical field. Few astronomers would be pleased to see their research pushed aside and their telescopes commandeered for whatever reason.

In any case, it seems that with a relatively modest expenditure of funds it is possible to conduct a fairly comprehensive survey of the near-Earth asteroids. Costs, if not as low as predicted by the Spaceguard report, would be small compared to such mammoth programs as the space shuttle or space station, even if the a considerable scaling up was introduced. Such a program would provide warning of possible dangers while at the same time adding to our knowledge of the solar system and helping to pave the way for the industrialization of space. It is certainly worth considering.

4.2.3 Large-scale/Space-based Endeavors

Though we might wish it, not all of the tasks of a near-Earth asteroid search can be accomplished from the Earth's surface. Some of these problems may be better addressed from a space-based platform, others simply cannot be achieved using surface instruments.

One example of a problem which may be best solved from space is that of early warning of hazardous NEA's and long period comets. No ground based system of the Spaceguard variety will ever provide a complete safety net from these errant planetoids. It may be that to ensure adequate warning before a possible collision a space-based system would be necessary. Such a system could be placed so as to be able to spot the hard-to-detect Aten asteroids as easily as Apollos or Amors, and could be designed so as to detect only the asteroids presenting an immediate threat. This would sidestep the near-impossible task of spotting and tracking *all* of the near-Earth asteroids, and would protect against lpc's as well. It would probably be extremely expensive, however, and would provide shorter warning periods than a more aggressive search strategy.

4.2.3.1 Earth-Sun Trojan Asteroid Search

One area in which the need for a space-based mission has long been considered is in the quest for proof or disproof of the existence of asteroids in stable libration orbits around ES L4 and L5. The existence of stable orbits where these asteroids might be found was proven by Dunbar in 1980. [65] Subsequent attempts to spot these unusual objects were not limited in scope and only managed to put an upper bound on the number of ES Trojans of greater than 1 km diameter.

As can be seen from Figure 4.2 below, the geometry of the libration points makes it quite difficult to search the areas around ES L4 and L5. Attempts to locate these asteroids must look at an angle facing *toward* the sun, not away from it as in most opposition oriented searches. This not only means that the asteroid is reflecting a smaller percentage of the Sun's incident light toward Earth, but also means that the region of sky to be searched is only visible low on the horizon during the hours around dusk, when there is still substantial light-pollution from the Sun.

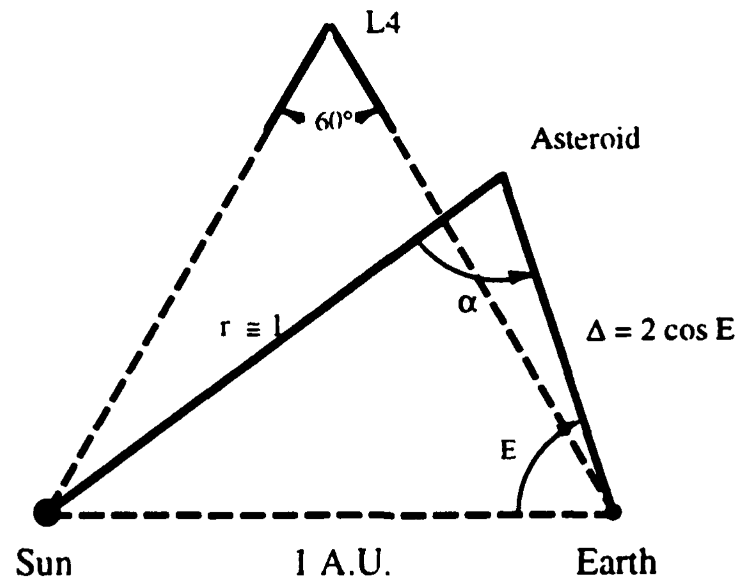


Figure 4.2: Earth-Sun Trojan asteroid viewing geometry

The difficulties involved in an Earth-based search for these asteroids have led to speculation that a space based search might be more effective. One possibility would be to send an explorer inside the Earth's orbit to look out toward opposition for Trojan asteroids. Such a probe might simultaneously serve to look for the shadowy Aten asteroids, which are the most difficult of known NEA's to spot from Earth. Some quick calculations of relative magnitudes and aperture sizes can tell us if this sort of mission is practical. Dunbar gives the equations relating the apparent magnitude of an asteroid to its phase angle and distance

$$\log D = 3.12 - 0.5 \log p - 0.2\, V(1,0) \qquad [4.1]$$

$$V = V(1,0) + 5 \log r\Delta + \phi\alpha. \qquad [4.2]$$

or

$$D = r\Delta\sqrt{10^{(6.24-0.4V+\phi\alpha)} / p} \qquad [4.3]$$

where Δ is the distance from the asteroid to the observing point and r is the distance from the Sun to the asteroid, both in A.U., p is the asteroid's albedo, α is the phase angle, and ϕ is the phase function in magnitudes/degree. The astronomical relative magnitude system, based on the relation

$$2.5 \log(L_1/L_2) = V_2 - V_1 \qquad [4.4]$$

allows us to relate the magnitude calculated using the equations above to the necessary aperture size. All one need know is the limiting magnitude of one telescope and the ratio of the quantum efficiencies. Figure 4.3 shows the results of this calculation for one possible orbit. Noting that earlier Earth-based searches have ruled out ES Trojans much larger than a kilometer in diameter and that Dunbar has shown that asteroids smaller than 100 m in diameter would be cleaned out by solar radiation pressure, the asteroids spotted by the hypothetical probe seem to be in roughly the desired size range. However, to get down to the lower end of the size range for low-albedo asteroids (which are the type most likely to be found in Trojan orbits and also the most potentially useful) it would take an aperture size of 0.7 m, which is clearly much too large for the relatively inexpensive mission which is hoped for. One might hope that this could be overcome by moving the probe's orbit in toward Earth, but at that point the issue of inclinations must be considered. According to Dunbar, Earth-Sun Trojan asteroids could inhabit stable orbits with inclinations of as much as ±12°. As the orbit of a probe gets closer to that of the Earth the increased phase angle will more than cancel any benefits gained by reduction of distance (see Figure 4.4).

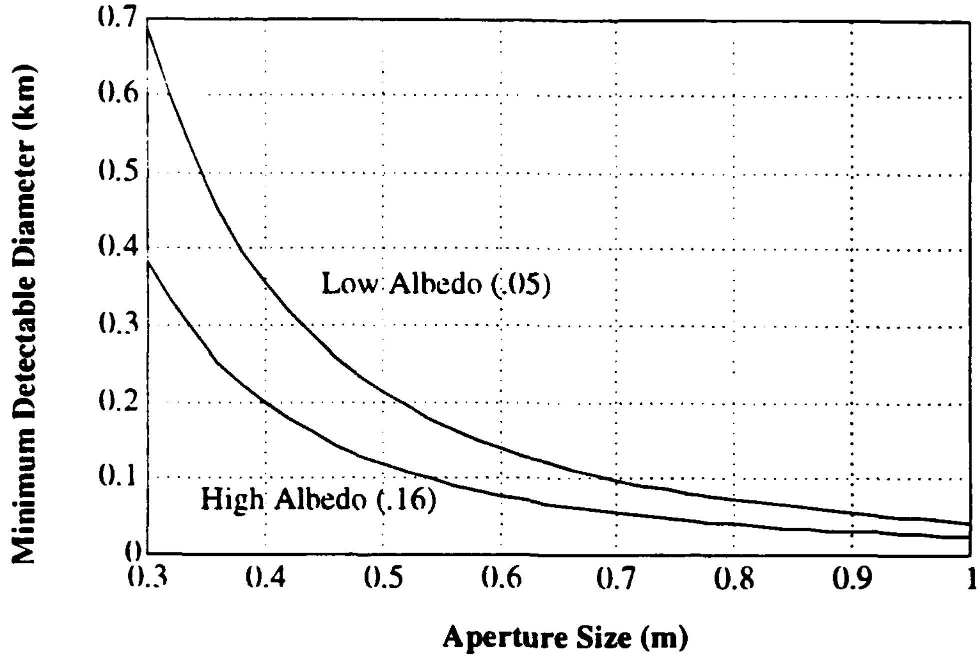


Figure 4.3: Graph of asteroid diameter vs. telescope aperture size. Calculations are for viewer at 0.8 AU looking directly outward at object at 1 AU. Quantum efficiency of 70% (upgraded Spacewatch CCD chip) is assumed.

Thus it seems that the concept of sending a probe inside the Earth's orbit to look outward is not the answer we are looking for. Other possibilities for space-based missions to search for these elusive asteroids. An infrared observer might be more effective at finding these objects, but the cooling cost of maintaining such an instrument over a mission of any sort of extended duration could be prohibitive. Another possibility now being examined is the use of radar to search for the ES Trojans. Alan Willoughby at NASA Lewis is just now beginning to look at the possibility of an electrically propelled mission which would use a prototype of the planned SP-100 space reactor to power a radar beam while the energy is not being used to propel the spacecraft. However, this too is likely to run into difficulties balancing range and field of view requirements.

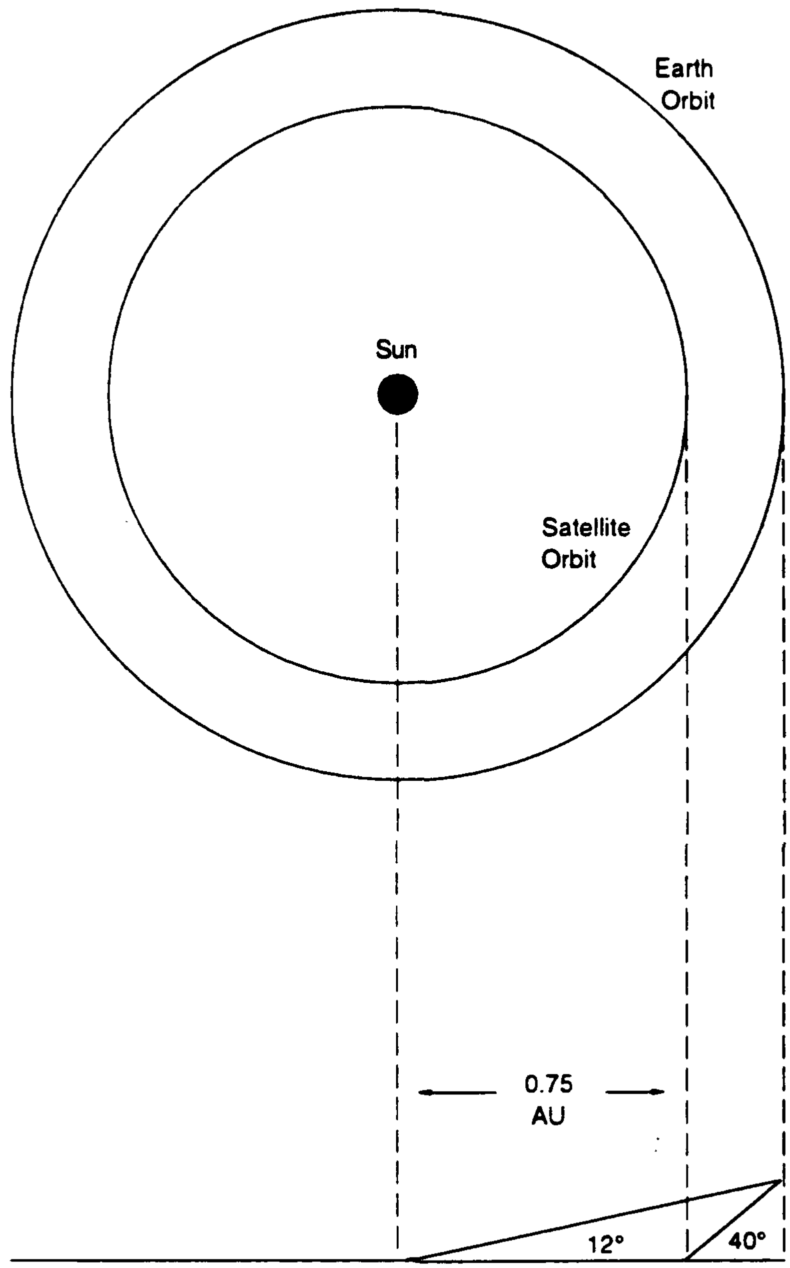


Figure 4.4: Even at 1/4 the distance to the Sun, a 12° inclination translates into a 28° phase angle.

Having rejected the most commonly suggested possibilities as impractical, perhaps it is best to take a more careful look at the most commonly rejected possibility: observation from Earth. Figure 4.5

shows plots of the asteroid diameters visible from Earth at various elongations. Figure 4.5 (a) shows the capabilities of the 1.2 m Palomar Schmidt used by Dunbar and Helin to conduct the last ES Trojan search from 1978-1982. In (b) we see the potential of a 2 m aperture telescope equipped with top of the line (70% quantum efficiency) CCD technology, the sort suggested for use in the Spaceguard Survey. Note that the amplitudes of stable libration orbits around ES L4 and L5 calculated by Dunbar correspond to elongation angles of between 35 and 70 degrees. Also note that the improved performance at small elongations visible in the low-albedo curves is largely illusory; objects in that region would only be visible near dusk and low on the horizon, so that the benefits derived from the improved phase angle would doubtless be counteracted by the relatively bright sky. Nonetheless, such a telescope seems to be capable of spotting all but the smallest possible objects in librating orbits about L4 or L5. It appears that a systematic search from Earth conducted by modern, fairly large aperture telescopes could answer the question of the existence of Earth-Sun Trojan asteroids once and for all, at relatively little cost when compared with a space mission.

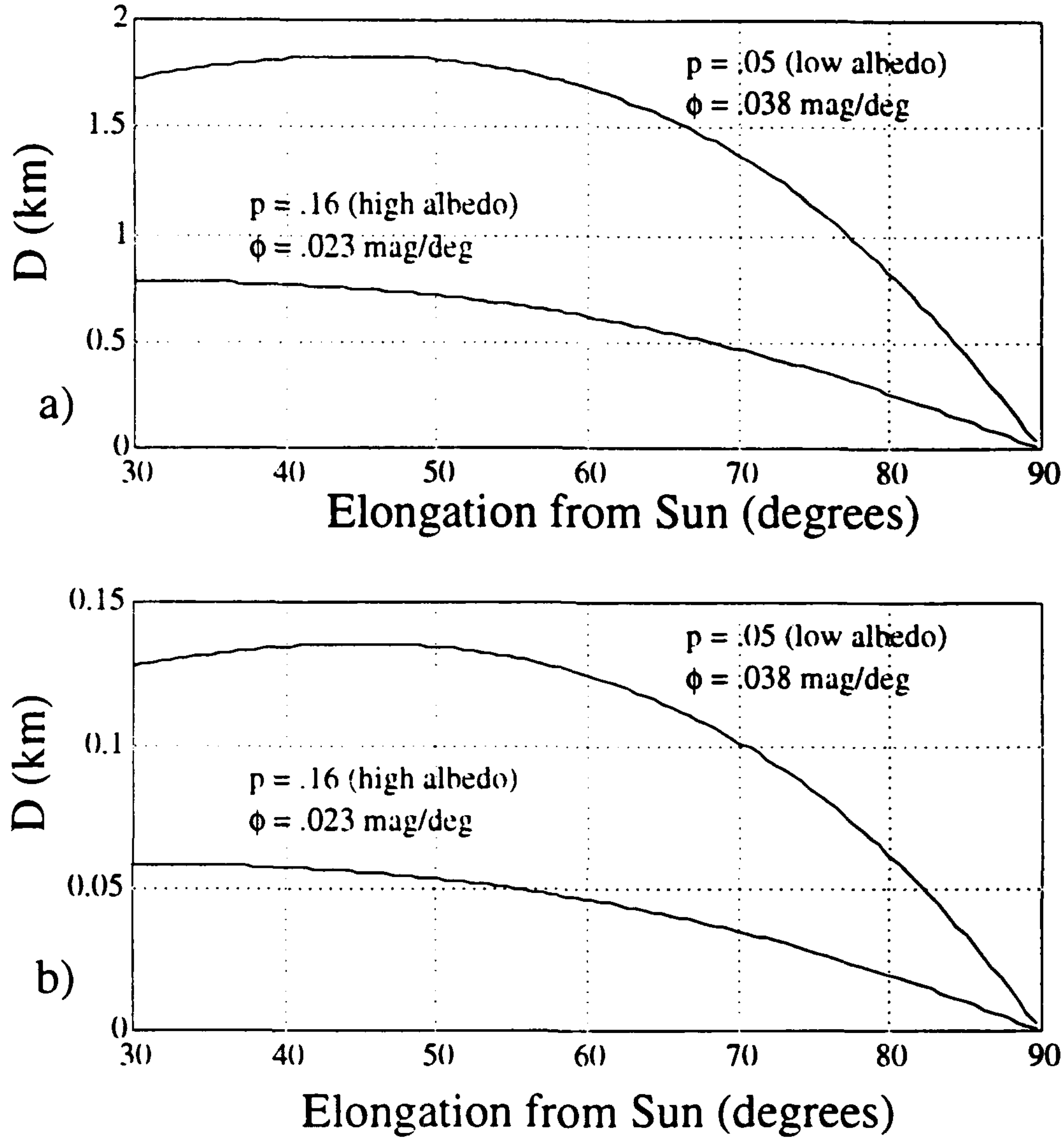


Figure 4.5: Size range of Earth-Sun Trojan asteroids visible from Earth. a) Calculations based on the 1.2 m Palomar Schmidt with V = 20 limiting magnitude emulsions. b) Calculations based on a 2 m aperture telescope equipped with 70% quantum efficient CCD's.

4.2.3.2 NEA exploratory probes

Though some tasks of the NEA search may be done from the ground, others can only be done from space. As has been noted above, one such task is the further characterization of NEA compositions by sending probes to study them up close. Knowledge of the asteroids' compositions will serve several purposes. It will help scientists understand their origins, and thus make clearer estimates of their relative populations possible. It will provide insights into their usefulness a sources of materials for space manufacturing. It will also enable a more detailed analysis of both the how much of a threat they represent and how to deal with them when the danger materializes.

A number of interesting concepts for NEA rendezvous missions are already present in the literature. One such design, made to fly as a secondary payload on one of the large Ariane launch vehicles, employs electrical propulsion to send a 400 kg payload with a number of measuring instruments to do a flyby of a single asteroid. [28] Another more ambitious concept uses an Atlas-Centaur configuration to deliver a 1200 kg payload equipped with a large instrument package and a robotic daughter probe which would actually soft-land on the target asteroid. [5] This plan also considers use of a more complex trajectory to perform a flyby of a second asteroid as well. A third proposal endorses a series of missions using a Pegasus launcher to send small (70 kg) single-instrument probes on flybys of a number of different NEA's. [66]

The instruments proposed for use on these missions share many similarities. All include CCD equipped cameras for visible light examinations. Magnetometers to check for residual magnetic fields are also common to the proposals. Other instruments include IR and

UV spectrometers for compositional analysis, and photopolarimeters. Each of the mission concepts also includes plans for a particle sensor which would smell the glove of dust surrounding the asteroid to get an analysis of possible volatiles.

Standard missions to the most accessible of the known NEA's have clearly been carefully examined. Further analysis of this sort of mission would be redundant and beyond the scope of this report. One thing which hasn't been adequately considered is the possibility of running this type of mission to a hypothetical Earth-Sun Trojan asteroid.

A mission aimed at close analysis of an asteroid librating about ES L4 or L5 would have several advantages over missions to Apollo or Aten asteroids. One of these advantages is in flexibility. Table 6 gives the dates of the next dozen opportunities for missions to 1982 DB, which was until last year the most accessible of the known near-Earth asteroids. Of these, less than half are within 500 m/sec of the asteroid's vaunted 4.45 km/sec ΔV. Missions to Earth-Sun Trojans could launch at any time and would thus not be subject to the problems of missed flight windows and rapid redesign to fit new trajectories.

Date	Flight Time	Total ΔV
01-24-93	607	4.66
12-18-94	403	8.13
01-24-96	899	6.16
01-31-97	475	5.70
01-07-98	737	5.69
01-10-00	646	5.03
01-22-02	640	4.48
01-26-04	573	4.87
01-29-06	507	5.39
01-26-07	873	5.88
02-03-08	440	6.11
01-08-09	693	5.36

Table 6: Launch Windows for Missions to 1982 DB in the next twenty years.

The orbital mechanics of transfer to the triangular libration points or any other point along the Earth's orbital path are quite simple. As is shown in Figure 4.6, one simply lowers the perigee or raises the apogee according to the desired change in the orbital frequency. This allows transfers taking an integral number of orbits for completion; the more orbits, the slower the necessary adjustment in angular speed and the lower the required ΔV. Figure 4.7 shows the ΔV's necessary to complete transfers to orbits in the complete range of stable libration amplitudes predicted by Dunbar, roughly from 35-110°. Note that the number of orbits is roughly but not exactly equal to the number of years for the transfer, and that if a few years can be spared for the transfer, ΔV's as low as 1/4 that of 1982 DB can easily be achieved.

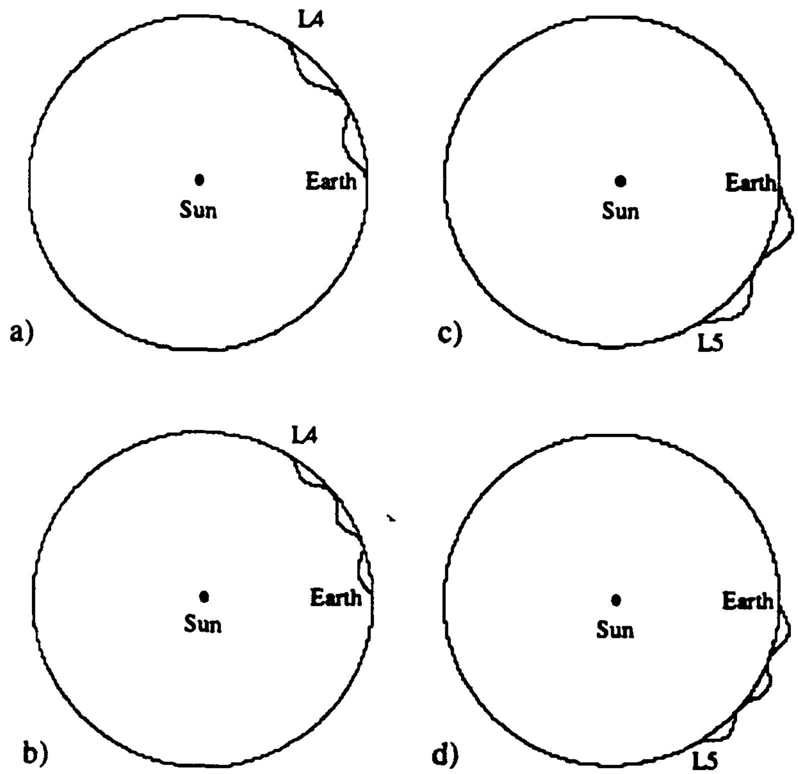


Figure 4.6: Trajectories for transfer to triangular libration points: a) 2-orbit transfer to L4; b) 3-orbit transfer to L4; c) 2-orbit transfer to L5; d) 3-orbit transfer to L5

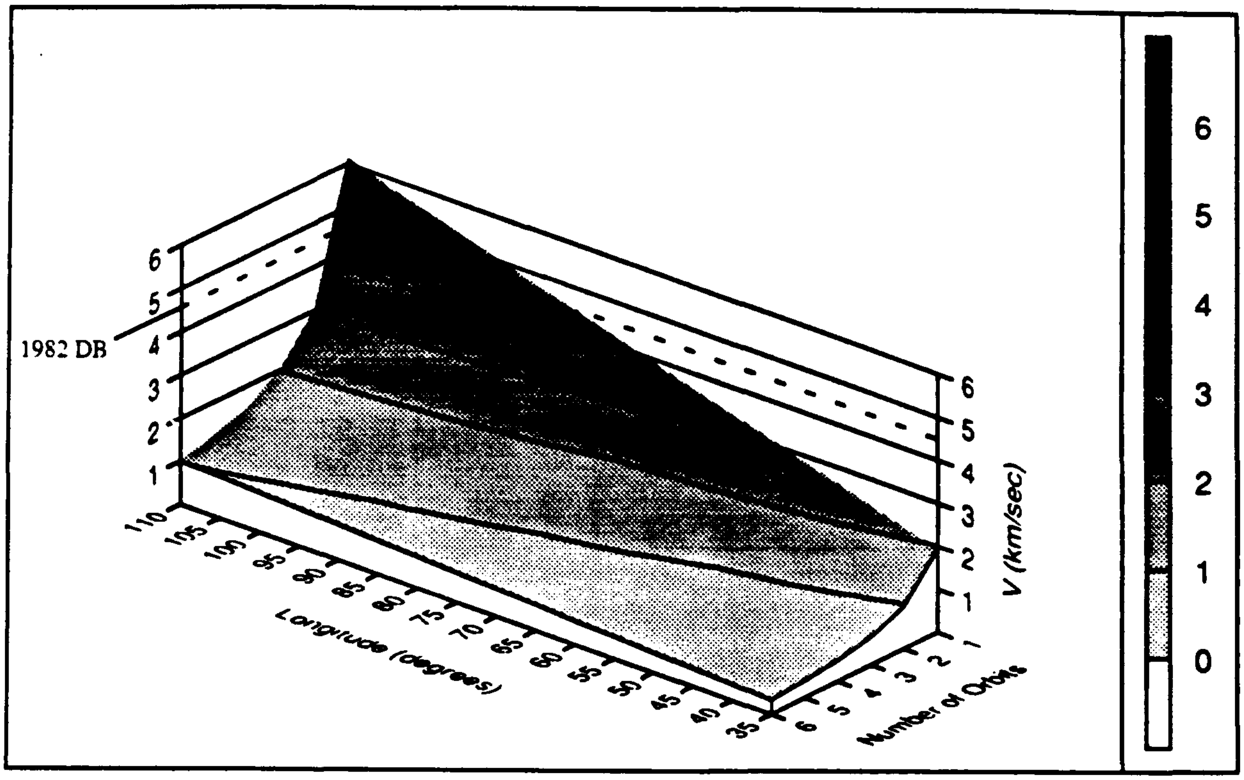


Figure 4.7: ΔV's for transfer to various longitude libration orbits as a function of time taken for the maneuver. Inclination changes were not included in the calculations.

The implications of this savings in ΔV are enormous. As is shown by Figure 4.8, the benefits in terms of payload ratios are quite large. For instance, taking six years for transfer, an Atlas II rocket which could only send a little over 300 kg to rendezvous with 1982 (assuming an optimal launch window was used) could send a 1200 kg payload to L4. By the same measure a Pegasus could send a 73 kg payload to rendezvous with an asteroid at L4 but only 19 kg to meet 1982 DB. Alternatively, the savings in ΔV gained by traveling to an Earth-Sun Trojan asteroid could be used to fly the same payloads on smaller launchers, saving millions of dollars with each flight. The calculations used to generate Figure 4.8 assumed a solid fuel kick motor with I_{sp} of 290 sec, but as is shown in Figure 4.9, payload ratios in the regime of NEA probe missions are much less sensitive to changes in I_{sp} than changes in ΔV.

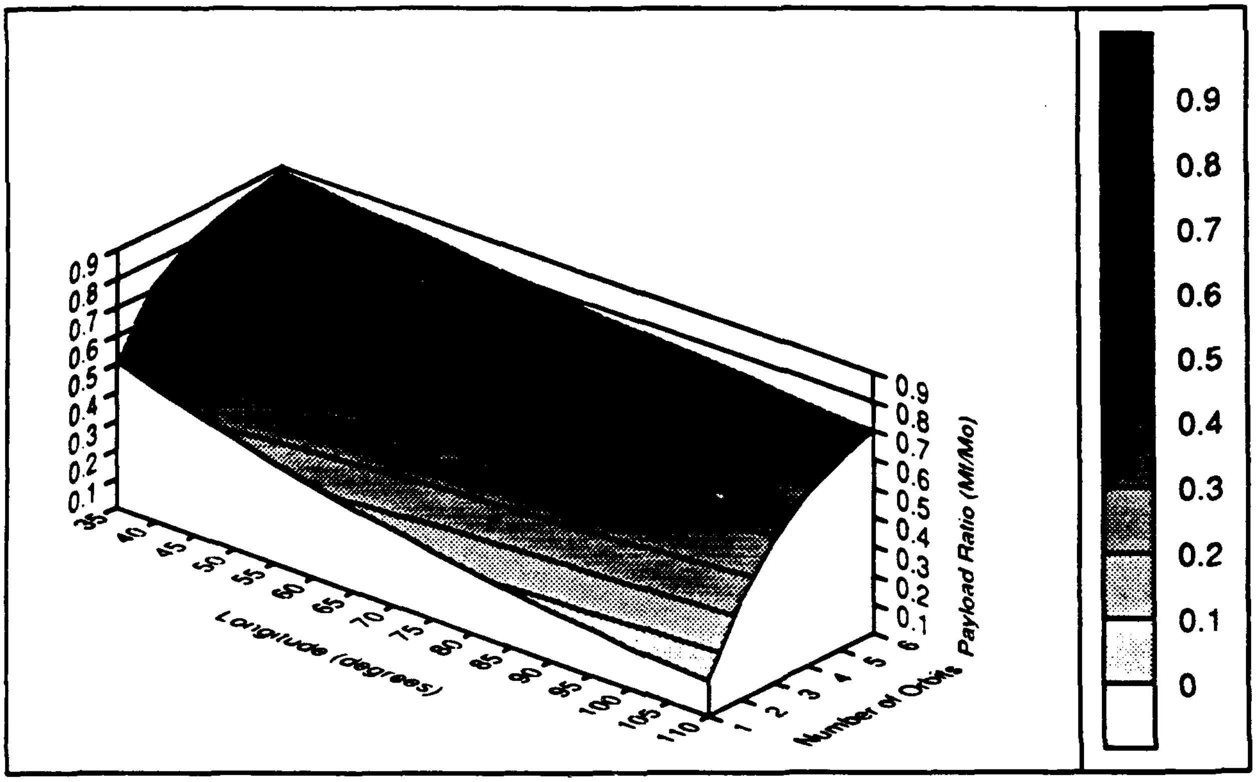


Figure 4.8: Payload ratios for transfer to various longitude libration orbits as a function of time taken for the maneuver. Inclination changes were not included in the calculations.

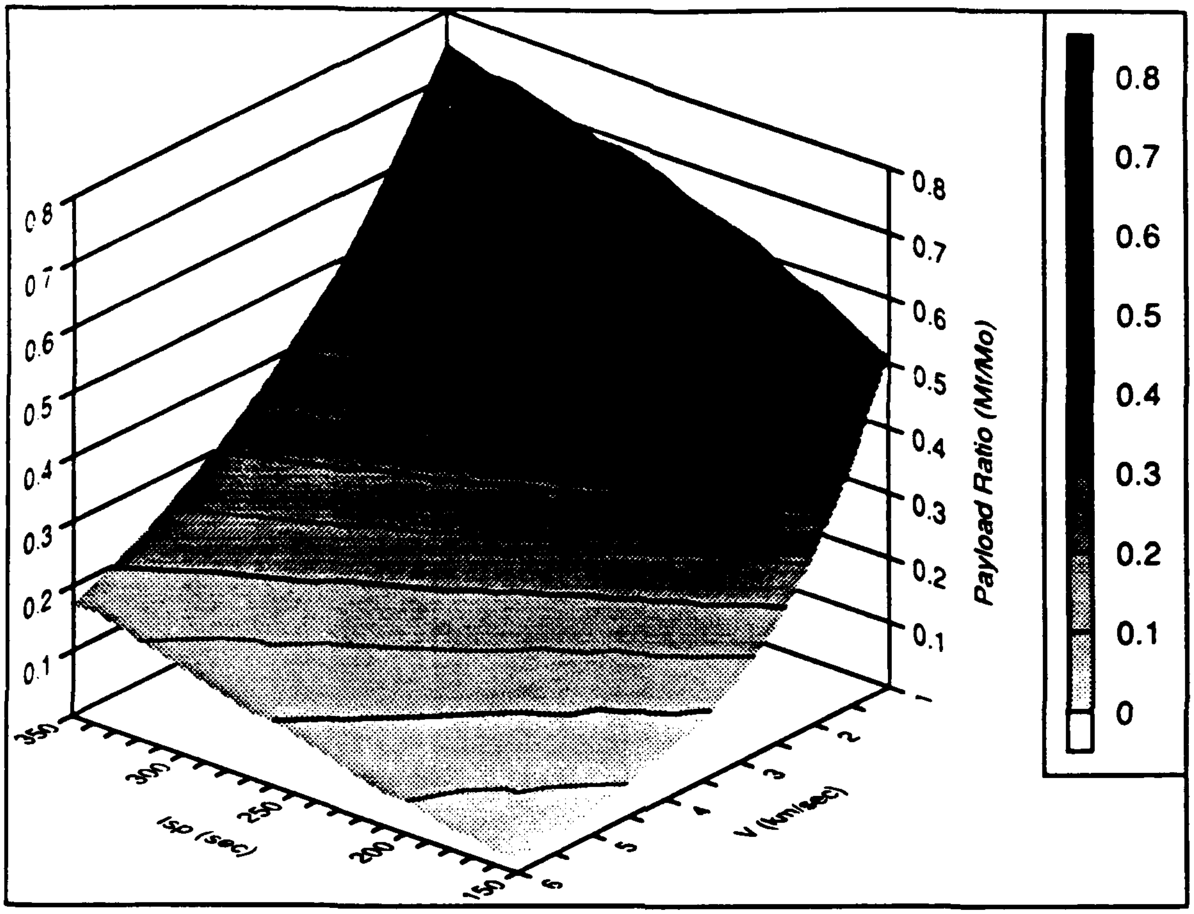


Figure 4.9: Influence of ΔV and I_{sp} on payload ratios for NEA probe missions.

It is clear that space-based missions have an important role to play in the search for near-Earth asteroids. The key is to minimize the cost of that role while continuing to conduct the necessary research. The solution to this problem may well lie in the nascent technology of microspacecraft. Miniaturization has made possible the development of sensors, power supplies, and transmitters weighing on the order of a single kilogram apiece. Flying these components on small launchers such as the Pegasus could drastically reduce the costs of an NEA exploration program while keeping most of the functionality of larger, less efficient missions.

5. Recommendations

The purpose of this report is to formulate an *optimal* strategy for the conduct of the near-Earth asteroid search. The motivations for such a search as well as the priorities and options for carrying it out have been discussed at length. The opinions and suggestions which follow are based on that discussion, but are of necessity derived from a rather subjective evaluation of the relative importance of the factors involved.

Tthe driving factor in charting a policy or future course for the search for NEA's is not what should or could be done in the immediate future, but what *has* been done in the immediate past and what is being done right now. There are holes in our present knowledge base with regard to NEA's, holes which make it unwise to embark on a grand course of action in the immediate future. The debate at the recent San Juan Capestrano conference emphasized how much uncertainty there is even among the field's leading members about the extent of the threat from asteroid and comet impacts.

At the same time the known population of NEA's has grown enormously over the last few years. With a very small injection of funds into presently existing programs that population could grow by another factor of ten over the next five or six years. The field is in an incredible state of flux, with new instruments and techniques under development and still largely untested. The two graphs presented in section 4.2 showing what can be achieved with telescopes now compared to ten years ago is an excellent illustration of the strides which are being taken in the astronomical field. To base a policy for the next hundred years or even quarter-century on the present knowledge base would be, in our opinion, foolhardy.

Developments should be allowed to proceed without significant interference for the next five or ten years. Funding should be allocated for small-scale projects like the new 1.8 m scannerscope for Project Spacewatch and increased budgets for programs like LUKAS which are developing and putting into use new search technologies. Programs like AANEAS, PACS, and PCAS should be funded strongly to help increase the known NEA population as quickly as possible. The IRAS data should be re-evaluated, and time secured on a large telescope to determine the existence or non-existence of Earth-Sun Trojan asteroids once and for all. The new field of microspacecraft should be closely monitored and perhaps supported by missions undertaken in conjunction with the Planetary Exploration Program. Research into nuclear winter effects should be continued in an effort to better establish a clear size threshold for asteroids which present a danger to the global environment and civilization as a whole.

The threat posed by asteroid impacts is real and finite. It is not, however, particularly pressing. A few years either way are extremely unlikely to make any difference from the asteroid's standpoint, but could make a lot of difference from ours. At the present time our knowledge is inadequate to the formation of a rational, efficient search policy. A long-term strategy formed now would probably be extremely wasteful of resources; it would certainly not be optimal. We can and should, however, implement now the clearly defined near-term steps which will enable rationale decision-making in this area.

Bibliography

[1] Andreev, G.V., "Was the Tunguska 1908 Event Caused by an Apollo Asteroid?", *Asteroids, Comets, Meteors III*, Proceedings of meeting held at Uppsala University, June 12-16, 1989, pp. 489-492.

[2] Binzel, Richard P., "Asteroids and Comets", *The Planetary Report*, Vol. XI, No. 6, November/December 1991, pp. 5-11.

[3] Bowell, E., and N.S. Chernykh and B. G. Marsden, "Discovery and Follow Up of Asteroids", *Asteroids II*, eds. Gehrels, T., R. Binzel, and M. Matthews, University of Arizona Press, 1989, pp. 21-38.

[4] Broad, William J., "There's a 'Doomsday Rock,' But When Will It Strike?", *New York Times*, June 18, 1991, p. C1.

[5] Canough, G.E., and L.P. Lehman, "Unmanned Scientific Mission to the Asteroids", *Space Manufacturing 6*, AIAA, 1987, pp. 367-371.

[6] Chernykh, N.S., and L.I. Chernykh, "Astrometric Works on Asteroids and Comets at the Crimean Astrophysical Observatory", *Asteroids, Comets, Meteors III*, Proceedings of meeting held at Uppsala University, June 12-16, 1989, pp. 33-36.

[7] Cunningham, C., "The Minor Planet Index to Scientific Papers", *Asteroids, Comets, Meteors III*, Proceedings of meeting held at Uppsala University, June 12-16, 1989, pp. 37-38.

[8] Cutler, Andrew Hall, "Accessibility of Near Earth Asteroids for Resource Exploitation", *Space Manufacturing 6*, AIAA, 1987, pp. 372-375.

[9] Davis, Donald R., and Alan Friedlander, "It's a Small, Small World; Missions to Near-Earth Asteroids", *The Planetary Report*, Vol. XI, No. 6, November/December 1991, pp. 12-15.

[10] Davis, Donald R., and Clark R. Chapman, "Near Earth Asteroids: Observer Alert Network and Physical Observations", *NASA Space Engineering Research Center for Utilization of Local Planetary Resources, Annual Progress Report*, 1991, pp. V6-9.

[11] Dunbar, R. S., and E. F. Helin, 1983. "Estimation of an Upper Limit on the Earth-Trojan Asteroid Population from Schmidt Survey Plates. *Bull. Amer. Astron. Soc.*, vol 15, no. 3, p. 830.

[12] Dunbar, R. S., personal communication, 1991.

[13] Farquhar, Robert W., "Halo-Orbit and Lunar-Swingby Missions of the 1990's", IAF-90-308, International Astronautical Federation, 1990.

[14] French, L.M., and R.P. Binzel, "CCD Photometry of Asteroids", *Asteroids II*, eds. Gehrels, T., R. Binzel, and M. Matthews, University of Arizona Press, 1989, pp. 54-65.

[15] Gaffey, Michael J., and Jeffrey F. Bell and Dale P. Cruikshank, "Reflectance Spectroscopy and Asteroid Surface Minerology", *Asteroids II*, eds. Gehrels, T., R. Binzel, and M. Matthews, University of Arizona Press, 1989, pp. 98-127.

[16] Gaffey, Michael J., Eleanor F. Helin, and Brian O'Leary, "An Assessment of Near-Earth Asteroid Resources", *Space Resources and Space Settlements*, NASA, 1979.

[17] Gehrels, T. and R. S. McMillan, 1982. "CCD Scanning for Asteroids and Comets." *Sun and Planetary System*, eds. W. Fricke and G. Teleki, pp. 279-284.

[18] Gehrels, Tom, "Spacewatch Discovery of Near-Earth Asteroids", *NASA Space Engineering Research Center for Utilization of Local Planetary Resources, Annual Progress Report*, 1991, pp. III30-34.

[19] Gehrels, Tom, and R.S. McMillan, "Sky Surveillance with CCD Scanning", Draft of a proposal to the USAF, 1991.

[20] Gehrels, Tom, personal communication, 1991.

[21] Helin, E. F., and R.S. Dunbar, "Search Techniques for Near-Earth Asteroids", *Vistas in Astronomy*, Vol. 33, pp. 21-37, 1990.

[22] Helin, Eleanor, "Near-Eearth Asteroid (NEA) Workshop Review", *Asteroids, Comets, Meteors III*, Proceedings of meeting held at Uppsala University, June 12-16, 1989, pp. 613-614.

[23] Henderson, Breck W., "Scientists Support Building Telescopes to Protect Earth from Asteroids", *Aviation Week & Space Technology.*

[24] Jones, Ross M., "Think Small—in Large Numbers", *Aerospace America*, October 1989, pp. 14-17.

[25] Jones, Ross M., "Microspacecraft Missions and Systems", pp. 448-454.

[26] Kresak, L., "The Flux of Earth-Crossing and Moon-Cratering Interplanetary Bodies", *Progress in Planetary Exploration*, Vol. 1, No. 8, 1981, pp. 85-90.

[27] Lebofsky, Larry A., and Macia L. Nelson, "Compositions of Near Earth Asteroids", *NASA Space Engineering Research Center for Utilization of Local Planetary Resources, Annual Progress Report*, 1991, pp. III26-29.

[28] Lorenz, Ralph D., "Design of an Electrically-Propelled Asteroid Rendezvous Probe Launched as a Secondary Payload", 4th Annual AIAA/USU Conference on Small Satellites, 1990.

[29] Luu, Jane, and David Jewitt, "On the Relative Numbers of C Types and S Types among the Near-Earth Asteroids", *The Astronomical Journal*, Vol. 98, pp. 1905-1911, 1989.

[30] Matson, Dennis L., and Glenn J. Veeder and Edward F. Tedesco, "The IRAS Asteroid and Comet Survey", *Asteroids II*, eds. Gehrels, T., R. Binzel, and M. Matthews, University of Arizona Press, 1989, pp. 269-281.

[31] McFadden, L. A., and D.J. Tholen and G.J. Veeder, "Physical Properties of Aten, Apollo, and Amor Asteroids", *Asteroids II*, eds. Gehrels, T., R. Binzel, and M. Matthews, University of Arizona Press, 1989, pp. 442-467.

[32] Morrison, David, and Clark Chapman "Target Earth: It *Will* Happen", *Sky and Telescope*, Vol. 79, No. 3, 1990, pp. 261-265.

[33] Olsson-Steel, Duncan, "The Asteroidal Impact Rate upon Terrestrial Planets: An Update", *Astronomical Society of Australia*, Vol. 8, No. 3, pp. 303-307, 1990.

[34] Ostro. S.J., et. al., "Asteroid 1986 DA: Evidence for a Metallic Composition", *Science*, Vol 252, pp. 1399-1404.

[35] Pierce, David A., "A 'Hollow' Asteroid", *Sky and Telescope*, Vol. 79, No. 3, 1990, pp. 272-273.

[36] Pike, John, "The Sky *Is* Falling; The Hazard of Near-Earth Asteroids", *The Planetary Report*, Vol. XI, No. 6, November/December 1991, pp. 16-19.

[37] Ravine, M. A., and T. A. Soulanille, "Cameras for Microspacecraft", pp. 460-467.

[38] Russel, K.S., and E. Bowell, "Automated Analysis of UK Schmidt Plates to Identify Solar System Objects", *Asteroids, Comets, Meteors III*, Proceedings of meeting held at Uppsala University, June 12-16, 1989, pp. 167-169.

[39] Sargent, Mark G., "Chemical Launch System Options for Microspacecraft", pp. 455-459.

[40] Staehle, R.L., "Resource Exploration Missions", *Research on the Use of Space Resources*, William F. Carrol, ed., NASA, 1983.

[41] Sykes, Mark. V., and Elizabeth M. Alvarez del Castillo, "The Steward Observatory Asteroid Relational Database", *NASA Space Engineering Research Center for Utilization of Local Planetary Resources, Annual Progress Report*, 1991, pp. V1-5.

[42] Taff, L. G., 1980. "The Lincoln Laboratory Earth-Crossing Asteroid Search", *Bull. Amer. Astron. Soc.*, vol 12, p. 666.

[43] Taff, L. G., 1981. "A New Asteroid Observation and Search Technique", *Publications of the Astronomical Society of the Pacific*, Vol. 93, 1981, pp. 658-660.

[44] Tamir, David A., "Dealing with the Collision Threat From Earth-Crossing Cosmic Objects (ECCO's)", Prepared for AIAA Public Policy, 1990, *Draft*.

[45] Tedesco, E.F., and B.A. Lindblad, "Asteroid, Comet, Meteor Data Bases Workshop", *Asteroids, Comets, Meteors III*, Proceedings of meeting held at Uppsala University, June 12-16, 1989, pp. 605-608.

[46] Tedesco, E.F., and D.L. Matson and G.J. Veeder, "Classification of IRAS Asteroids", *Asteroids II*, eds. Gehrels, T., R. Binzel, and M. Matthews, University of Arizona Press, 1989, pp. 290-297.

[47] Tholen, David. J., "Asteroid Taxonomy", *Asteroids II*, eds. Gehrels, T., R. Binzel, and M. Matthews, University of Arizona Press, 1989, pp. 298-315.

[48] Veeder, Glenn J., and Edward F. Tedesco and Dennis L. Matson, "Asteroid Results from the IRAS Survey", *Asteroids II*, eds. Gehrels, T., R. Binzel, and M. Matthews, University of Arizona Press, 1989, pp. 282-289.

[49] Verschuur, Gerrit L., "This Target Earth", *Air & Space Smithsonian*, November 1991, pp. 88-94.

[50] Weissman and Wetherill "Periodic Trojan-Type Orbits in the Earth-Sun System", *Astronomical Journal*, Vol 79, No. 3, p. 404, 1974.

[51] Weissman, Paul R., "Are Periodic Bombardments Real?", *Sky and Telescope*, Vol. 79, No. 3, 1990, pp. 266-270.

[52] Yeomans, Donald K., "Killer Rocks and the Celestial Police; The Search for Near-Earth Asteroids", *The Planetary Report*, Vol. XI, No. 6, November/December 1991, pp. 4-7.

[53] Zelner, B., and E.N. Wells and C.R. Chapman and D.P. Cruikshank, "Asteroid Observations with the Hubble Space Telescope and the Space Infrared Telescope Facility", *Asteroids II*, eds. Gehrels, T., R. Binzel, and M. Matthews, University of Arizona Press, 1989, pp. 949-969.

[54] AIAA Position Paper, "Dealing with the Threat of an Asteroid Striking the Earth", April 1990.

[55] International Space University, *International Asteroid Mission*, Chapters 1-3, University of Toronto Session, 1990.

[56] *Science News*, "Diamonds not a dinosaur's best friend", Vol. 140, No. 10, p. 156.

[57] *Science News*, "Paleobiology" column, vol. 140, No. 25-26, p. 421.

[58] Lau, C.O., and N.D. Hulkower, "Accessibility of Near-Earth Asteroids", *J. Guidance*, Vol. 10, No. 3, May-June 1987, pp. 225-232.

[59] *The Spaceguard Survey*, Report of the NASA International Near-Earth-Object Detection Workshop, David Morrison, Chair, 1992.

[60] Steel, Duncan, personal communication.

[61] Gehrels, Tom, and Robert S. McMillan, "Sky Surveillance with CCD Scanning", USAF Draft Proposal, 1991.

[62] Sykes, Mark, personal communication.

[63] Steel, Duncan, and Robert H. McNaught, "The Anglo-Australian near-Earth asteroid survey", *Aust. J. Astr.*, Vol. 4, No. 2, pp. 42-48, October 1991.

[64] NASA Multiyear Authorization Act of 1990, House Committee on Science, Space, and Technology Report, p. 30.

[65] Dunbar, R. S., *Dynamics and Stability of Trojan Librations in the Earth-Sun System — Implications for the Existence of an Earth Trojan Asteroid Group*, Princeton University PhD Dissertation, Department of Physics, 1980.

[66] Belton, Michael J.S., "Low Cost Missions to Explore the Diversity of NEO's and to Provide a Scientific and Technical Basis for Intercept Activities", NASA Workshop on Near Earth Object Interception, Los Alamos National Laboratory, 1992.

[67] Rustan, Lt. Col. Pete, "Orbital Launch Vehicle Capabilities", SDIO/TNI Report, 1992.

[68] Davies, John K., *Satellite Astronomy*, Ellis Horwood Limited, England, 1988.

[69] Birney, D. Scott, *Observational Astronomy*, Cambridge University Press, 1991.

Appendix A.

Notes on Charge-Coupled Devices

Charge-Coupled Devices as discussed in the body of this report, have demonstrated their utility as detectors for asteroids. This brief note summarizes the characteristics of these devices. The author is indebted to Astromed Limited of Cambridge, England and, in particular to Dr. Craig Mackay for providing the supporting information for these notes.

CCD's are typically constructed as arrays of silicon substrate covered by a two dimensional array of electrodes separated from the substrate by an oxide insulation layer. When a photon is absorbed by the silicon, a single electron is freed to move within the silicon lattice.

The array of electrodes is used to trap these freed electrons and manipulates the pattern of charge which represents the incoming information to analog amplifiers (usually co-located on the same chip) which provide the signal readout.

Limitations

Two general areas of limitation exist with respect to these devices. These are the sensitivity of the detector and the fact of sources of noise which merge with the signal information.

Sensitivity

Sensitivity to light is defined as the effectiveness of a CCD in generating electrons from the incident light falling on the device as a function of wavelength. This is referred to as **Quantum Efficiency.** The attached CCD Datasheet and Selection Guide (From Astromed Ltd.) shows typical quantum efficiency curves for real CCD devices. See, for example the second page of the Datasheet. The polysilicon covering electrodes act like a yellow filter, blocking bluer light from entering the substrate. Blue sensitivity can be increased by etching the silicon wafer to allow light to enter from the side opposite the electrodes. This is called **Thinning** and the resulting CCD's are said to be Thinned. **Coating** the front of the CCD with a thin phosphor layer is another method of improving the "blue" sensitivity of the device. The phosphor layer absorbs light efficiently from 90 nm to 480 nm and then emits green light at around 560 nm. This extends the sensitivity of the CCD at approximately 15% quantum efficiency over the coated region. The Datasheet shows Quantum Efficiency characteristics for both coated and thinned CCD's with the coated CCD's using the coating trade name of ASTROCHROME.

Noise

Two major sources of noise are present in CCD systems. These major sources are thermal noise and readout noise. The thermal energy of the electrons in the silicon crystal lattice allow some electrons to break free and move, just as electrons generated by incident photons. These constitute noise and are present even when no light is falling on the CCD array. These thermally produced electrons are known as **dark current**. Dark current can be reduced by two means. The electrode pattern can be altered to improve the dark current situation in an architecture called **Multi-Phase Pinned** CCD's. These devices are capable of reducing the dark current by a factor of 100 to 1000.

The most important method of reducing dark current noise is **cooling of the CCD**. This reduces the dark current by a factor of approximate 10 for every 20 degrees Celsius temperature reduction.

The following table shows the effects of cooling on CCD's in terms of the resulting dark rate which is the number of thermal electrons per unit time injected into the system.

Temperature in Degrees C.	**Electrons per pixel per sec.**
+20	10,000
-40	10
-60	1

Temperatures of -40C and -60 C can be achieved using solid state cooling systems (Peltier Effect) with air as the heat sink (for -40C) and water for the -60C system.

Using liquid nitrogen as a coolant at -130C, a dark rate of about 1 electron per pixel ***per hour*** can be achieved, although the plumbing complexity and need for expendable coolant provides challenges for remote telescopes and automatic operation.

Readout Noise

The charge read out of the CCD is passed via an integral buffer amplifier transistor co-located on the CCD array chip. This transistor has an internal noise level which is added to the signal. The slower the signal is read out of the CCD, the lower the noise level injected by the internal buffer amplifier. The following table shows the readout noise at various rates with an actual Astromed 3200 CCD system:

Pixel period microseconds	**Full read time (in seconds)**	**Read noise (electrons rms)**
50	14	6
23.3	6.5	8
18	4.4	11
12.5	3.0	20

Other Noise Sources

Although dark current and readout noise are the predominant factors affecting the signal to noise ratio of CCD operations, two other sources should be considered. **Light leakage** refers to light other than that from the desired source which may fall on the CCD due to defects in the optical train of the instrument. In addition to this source of noise, **Cosmic ray events** occur when cosmic rays striking the upper atmosphere generate muons as secondary particles. These muons are detected at the rate of about 2 events per square centimeter of CCD per minute. Due to the time characteristic of these cosmic ray events they can be filtered out via software processing of the signal.

Micro Photonics Inc.
4949 Liberty Lane, Suite 170, PO Box 3129
Allentown PA 18106 - 0129
Tel. (215) 366-7103 Fax . (215) 366-7105

CCD Datasheet and Selection Guide

Introduction

Astromed have been manufacturing cooled CCD cameras for over eight years, and is now able to offer offer a broad range of CCDs from different manufacturers for use with its camera systems.

The physical characteristics of all the CCDs offered are basically very similar. However, the CCDs have different performance characteristics (such as spatial resolution, pixel size etc.) designed for specific imaging applications.

Physical Characteristics

A charge-coupled device (CCD) consists of a set of polysilicon electrodes deposited on a silicon substrate and separated by an oxide insulation layer. The electrode size determines the pixel size and hence the spatial resolution of the device.

Operation

The electrodes are held at different potentials and incident photons of light cause the excitation of electrons in a doped depletion layer on the silicon substrate. These are held in position by the applied voltages on the electrodes.

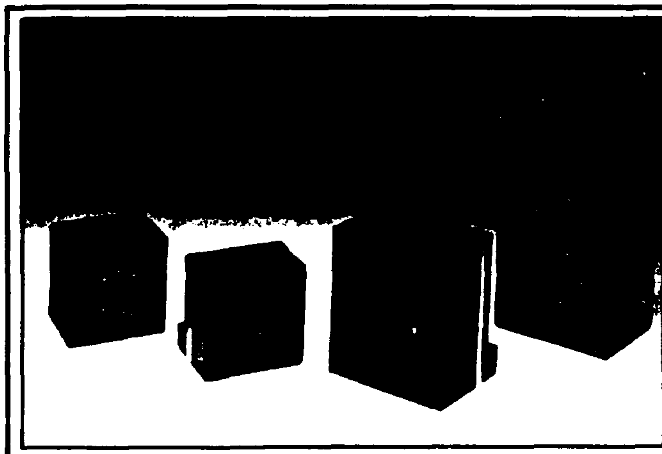
This charge may then be transferred (or coupled) to adjacent electrodes by altering their relative potentials. In this way the charge pattern, corresponding to the intensity of incident photons, may be moved along a line of pixels and into an output register for digitization

The **Dynamic Range** of a CCD is defined as the ratio of the largest signal which the CCD can handle to the read-out noise in a single exposure. Typical values for **EEV P86000** CCDs (CCD02-06-1-203) are 500,000 and 5 electrons respectively, giving a dynamic range of 100,000:1. This wide dynamic range is achieved because CCDs are designed for use at much higher light levels and normally with higher dark currents.

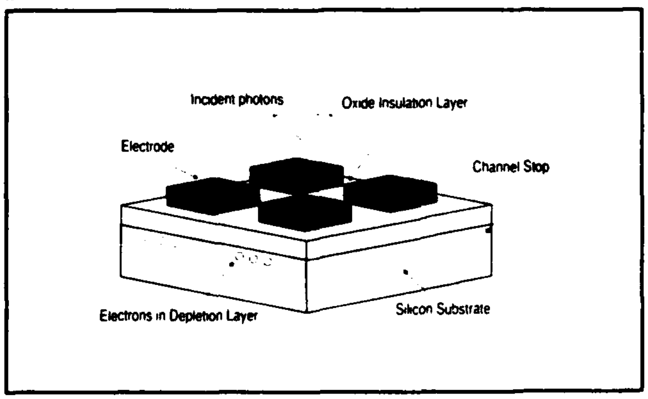
Cooling the CCD and reading it out slowly dramatically reduces the noise level, but has no effect on the maximum signal that the CCD can store.

Features

- Upto **2000 x 2000** pixel area
- **Super-MPP**™ operation mode for ultra-low dark current
- **ASTROCHROME 90**™ coating for enhanced ultra-violet response
- **Thinned** CCDs for ultra-high quantum efficiency
- **Anti-blooming drains** to protect the CCD from high light overload



Cooled CCD camera heads housing the CCDs



CCD Construction

Quality

All the CCDs offered by Astromed are manufactured to the highest standards and selected for optimum performance.

Top grade (Grade 1) CCDs are supplied as standard. The grading of a CCD relates to the number of defects present in its structure. These defects occur during the manufacturing process and manifest themselves as small blemishes in images recorded by the system.

Specially selected 'super' grade CCDs which are as near cosmetically perfect as possible can also be offered as an option. Contact Astromed for more details about these CCDs.

The table at the back of this datasheet gives information regarding the quality of the CCDs offered by Astromed. In the Table, the defects are categorised as follows:

- Pixel defects are pixels in the CCD which deviate by a significant percentage from neighboring pixels when illuminated.
- Clusters are a grouping of pixel defects.
- Columns are a grouping of pixel defects along a single column.

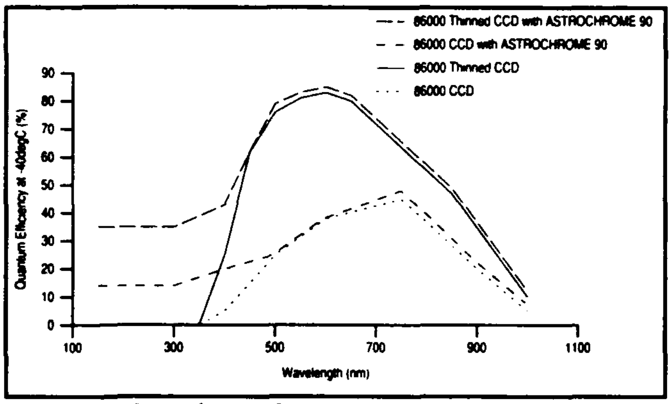
It is important to appreciate that each CCD manufacturer uses a different scheme for specifying and counting defects in a CCD so the figures given in the table are not quite as directly comparable as they might appear.

Spectral Characteristics

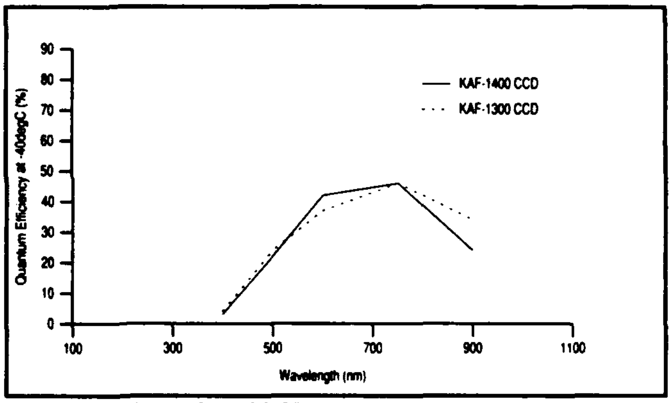
The graphs alongside show the Response Spectra curves produced by a few of the CCDs offered by Astromed.

Quantum Efficiency is defined as the effectiveness of a CCD in generating electrons from the incident light falling on the CCD, as a function of wavelength.

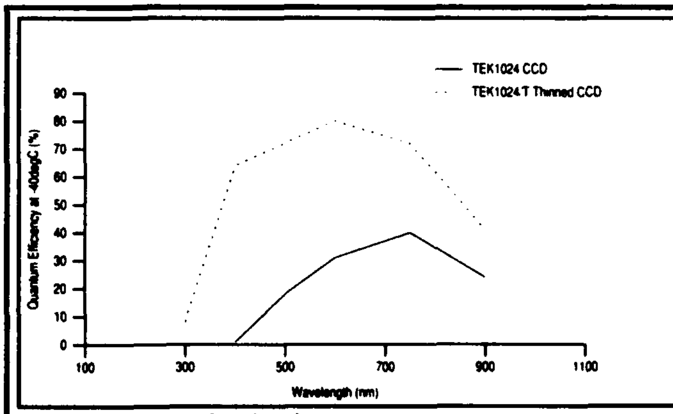
The CCDs all show similar spectral sensitivities between 400 and 1000nm. However, special techniques can be used to increase the spectral sensitivity of the CCDs. These are discussed in the next section.



CCD Response Spectra for EEV CCDs



CCD Response Spectra for Kodak CCDs



CCD Response Spectra for Tektronix CCDs

ASTROCHROME 90™

The spectral sensitivity of a CCD can be extended into the ultra-violet region by the addition of Astromed's **ASTROCHROME 90**™ coating.

Deposited as a uniform layer, less than one micron thick on the front window of the CCD, **ASTROCHROME 90**™ extends the spectral sensitivity to around 180nm. If the camera is operated without a front window this sensitivity is further extended to 90nm. The spectral response above 500nm is virtually unaffected, exhibiting the same characteristics as an uncoated CCD.

ASTROCHROME 90™ has been shown to be extremely stable over a wide temperature range (120-350 °K) and is unaffected by temperature cycling. It is available for all types of EEV and Kodak CCDs.

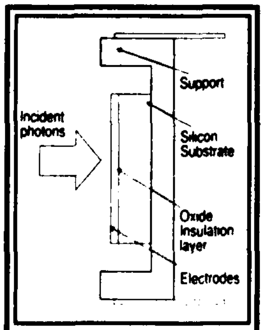
Thin CCDs

A further option available is the use of 'thinned' CCDs. The CCD is treated so that the side of the CCD away from the electrodes is mechanically and chemically etched to an overall thickness of only 10-15 microns.

The CCD is then mounted so that incident radiation falls on the **rear** surface of the CCD. This means that the radiation does not need to pass through the covering electrodes before entering the silicon substrate and producing electrons.

Consequently, sensitivity to wavelengths at the blue end of the spectrum is enhanced as no light is absorbed before interacting with the silicon. The sensitivity of the CCD to light at other wavelengths is also improved, as illustrated in the Response Spectra graphs.

Thinned CCDs may also be coated with ASTROCHROME 90™ to further enhance their sensitivity in the ultra-violet region. The spectral response above 500nm is virtually unaffected, exhibiting the same characteristics as an uncoated thinned CCD. In some cases the response in the 350-450 nm region can be reduced by coating a thinned CCD.



Standard CCD

MPP CCDs

The thermal energy of the electrons in the silicon substrate layer means that some of the electrons are able to break away from the electron lattice and become free to move through the silicon in just the same way as electrons excited by external photons.

These electrons constitute the **dark current** and are seen as a signal which is present even when there is no light falling on the CCD. This signal is generated at all times: during an exposure and during read out.

MPP CCDs have an architecture which is capable of reducing the dark current. This architecture, called multi-phase pinning (MPP), can be programmed to give a typical reduction in the dark current by a factor of up to 1000.

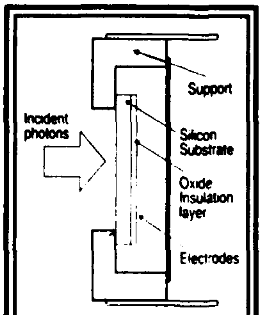
As the dark current is reduced, so the full well capacity of the CCD is reduced. At the lowest dark current levels, full well capacity is typically 40-50,000 electrons. However, in all Astromed systems the operating mode of the CCD is software selectable, so the user is able to make a trade-off between the dark current level and the full well capacity to suit their particular application.

Using Imager 2, EEV MPP CCDs can be operated in three different modes:

- Super-MPP™ mode (EEV CCDs only)
- MPP mode
- Standard mode (EEV CCDs only)

In **Super-MPP™ mode** the CCD gives dark current figures approximately 1000 times lower than standard CCDs. This is very important for many ultra-low light level applications requiring maximum sensitivity, with very long exposures and slow readout. This mode only applies to EEV CCDs.

In **MPP mode** the CCD gives dark current figures approximately 25-100 times lower than the dark current produced by normal CCDs, for many ultra low light level applications, with long exposures.



Thin CCD

In **Standard mode**, the CCD functions as a normal CCD, to enable the standard full well capacity of the CCD to be achieved.

The typical full well and dark current figures for an Astromed TE3/A CCD camera system are given in the table below for an EEV P86000 CCD (CCD02-06-1-203) operating in these three different, software selectable, modes.

Table 1: MPP Specifications (EEV CCDs)

Mode	Dark current (e^-/pixel/sec)	Full well (e^-)
Super-MPP	0.01	40-50,000
MPP	0.1	90-120,000
Standard	10	250-500,000

The benefits provided by MPP CCDs are substantial, especially for imaging applications where the exposure times are much longer than the read-out times. In such applications, TE cooled camera heads fitted with MPP CCDs can now be used where the low dark current performance of an LN cooled camera head is required along with the versatility of the smaller TE cooled camera heads.

Additional CCDs

Other makes and types of CCDs can also be used with Astromed's cooled CCD camera system for specialist imaging applications. Contact Astromed for further details.

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Table 2: CCD Selection Table

EEV CCD Features	P86000 (CCD02-06-1-203)	P86000 Thinned (CCD02-06-1-206)	P88131 (CCD05-10-1-202)	P88231 (CCD05-20-1-202)	P88331 (CCD05-30-1-202)	P88531 (CCD05-50-1-202)	CCD15-15-1-202
Pixel array format (Horizontal x Vertical)	385 x 578	320 x 512	298 x 1152	770 x 1152	1242 x 1152	2186 x 1152	256 x 1024
Sensitive Area (mm)	8.5 x 12.7	7.0 x 11.0	6.7 x 25.9	17.3 x 25.9	27.9 x 25.9	49.2 x 25.9	6.9 x 27.6
Pixel size (microns)	22.0 x 22.0	22.0 x 22.0	22.5 x 22.5	22.5 x 22.5	22.5 x 22.5	22.5 x 22.5	27.0 x 27.0
Typical full well capacity (electrons (e⁻))	350,000	350,000	350,000	350,000	350,000	350,000	1,000,000
– for MPP version	40,000 - 120,000	40,000 - 120,000	40,000 - 120,000	40,000 - 120,000	40,000 - 120,000	40,000 - 120,000	70,000 - 360,000
Typical read noise (e⁻) at 40kHz	6	6	5	4	4	4	4
Typical dark signal (e-/pixel/sec) at -40 °C	10	10	10	10	10	10	10
– for MPP version	0.01 - 0.1	0.01 - 0.1	0.01 - 0.1	0.01 - 0.1	0.01 - 0.1	0.01 - 0.1	0.01 - 0.1
Defects for GRADE 1 CCDs							
Pixels	7	7	3	6	9	18	-
Clusters	0	0	2	4	6	14	-
Columns	1 (usually 0)	1	2	5	8	13	-

KODAK CCD Features	KAF-0400	KAF-1300†	KAF-1400	KAF-1600	KAF-4200
Pixel array format (Horizontal x Vertical)	768 x 512	1280 x 1024	1317 x 1035	1536 x 1024	2048 x 2048
Sensitive Area (mm)	6.91 x 4.6	20.5 x 16.4	8.98 x 7.04	13.8 x 9.2	18.43 x 18.43
Pixel size (microns)	9 x 9	16 x 16	6.8 x 6.8	9 x 9	9 x 9
Typical full well capacity (electrons (e⁻))	85,000	150,000	45,000	85,000	85,000
Typical read noise (e⁻) at 40kHz	8	8	8	8	8
Typical dark signal (e-/pixel/sec) at -40 °C	0.05	0.05	0.02	0.05	0.05
Defects for CLASS 1 CCDs (bracketed figures are for defects at the centre of the CCD):					
Pixels	2	5 (2)	5 (2)	5 (2)	15 (6)
Clusters	0	0	0	0	0
Columns	0	0	0	0	0

† The Kodak KAF-1300 has anti-blooming drains that allow 1000-fold light overload without affecting the rest of the CCD. These drains give a CCD response ~ 2/3 of that of other Kodak CCDs

Tektronix CCD Features	TEK-512	TEK-512/T	TEK-1024	TEK-1024/T	TEK-2048	TEK-2048/T
Pixel array format (Horizontal x Vertical)	512 x 512	512 x 512	1024 x 1024	1024 x 1024	2048 x 2048	2048 x 2048
Sensitive Area (mm)	13.8 x 13.8	13.8 x 13.8	24.6 x 24.6	24.6 x 24.6	49.2 x 49.2	49.2 x 49.2
Pixel size (microns)	27.0 x 27.0	27.0 x 27.0	24.0 x 24.0	24.0 x 24.0	24.0 x 24.0	24.0 x 24.0
Typical full well capacity (electrons (e⁻))	400,000	400,000	350,000	350,000	350,000	350,000
– for MPP version	100,000	100,000	150,000	150,000	150,000	150,000
Typical read noise (e⁻) at 40kHz	8	8	8	8	8	8
Typical dark signal (e-/pixel/sec) at -40 °C	6	30	6	30	6	30
– for MPP version	0.6	3	0.8	3.5	0.8	3.5
Defects for GRADE 1 CCDs (bracketed figures are for defects at the centre of the CCD):						
Pixels	10	10	40 (10)	40 (10)	160	160
Clusters	-	-	4 (2)	4 (2)	16	16
Columns	0	0	2 (0)	2 (0)	8	8