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PLANETARY ASTEROID DEFENSE STUDY: ASSESSING AND RESPONDING TO THE NATURAL SPACE DEBRIS THREAT

A Research Paper

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by

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Preface

Interest in developing an asteroid defense system, intensified by the impact of comet Shoemaker-Levy 9 with Jupiter in 1994, continues to grow by leaps and bounds. Many major US publications such as Newsweek, Time, Ad Astra, Technology Review, Nature and even The Economist have run extensive articles on the subject. However, the interest goes well beyond the United States and the press. Russia, Italy, and Australia have recently hosted conferences on the asteroid threat and the United Nations will host one of its own in April of this year.

Because of public interest, and at the urging of scientists and astronomers, the US Congress commissioned the Spaceguard survey to examine the asteroid threat. Though no major decisions were made as a result of the survey (briefed in 1992), all agreed that the subject warranted continued discussion. In January of 1996, a NASA sponsored follow-on committee, headed by Dr. Eugene Shoemaker, will present recommendations for asteroid defense to Congress. Most expect the Shoemaker Committee to recommend an asteroid search program much like the one proposed in the original Spaceguard report.

While all of this is going on, it appears that the US military, specifically the Air Force, has declined to participate in these surveys and the subsequent Congressional briefs. The reluctance is somewhat understandable since scientists are just beginning to understand and quantify the threat. Planetary Defense, if undertaken, would be a new challenge, but one that clearly falls in the realm of military responsibility. The US Military has organizations, equipment and talent that could be invaluable to an asteroid defense program. We hope that this study will convince our leadership that the Air Force has both the capability and responsibility to participate in the defense of Earth (and our space assets) from natural space debris.

We would like to express our sincere gratitude to the following people for their assistance. We literally couldn't have done it without them.

Of the multitude of people and agencies who have assisted us in the preparation of this study, we owe special thanks to the **Institute for National Security Studies, Colorado Springs** for seeing the potential in our proposal and funding our research.

Dr. Peter Brown of the University of Western Ontario, Canada for sharing his expertise and sound advice in the study of the meteor stream threat. Peter went out of his way many times to help us find information and make the contacts that made the paper possible.

Ellen Carey and Jean Gilbert of William Beaumont Hospital Medical Library, Royal Oak, Michigan for their assistance in obtaining documents pertaining to risk assessment.

David Morton, Hazard Center Library, University of Colorado-Boulder for their hospitality and assistance in locating sources relating to disaster planning. We are also indebted to the Hazard House for the long-term use of many excellent references during our studies.

John Darrah, Chief Scientist, Sandy Sutherland, and Lt Col Shirley Hamilton from Headquarters, Air Force Space Command for providing materials, insight, and contacts to the numerous agencies involved in asteroid research.

Lt Col Neil McCasland for providing a sanity check, playing devil's advocate and generally making us think. Our lengthy discussions helped solidify many of the ideas expressed in the paper.

Bob and Patsy Hancock of Colorado Springs for making our trip enjoyable and memorable (thanks for dinner, too).

Dr. Jack Hills of Los Alamos National Labs for his technical advice and many tremendously useful papers on the subject.

Dr. Gregory Canavan of the Los Alamos National Labs for his advice and technical expertise, as well as his insight into the asteroid "community" and the preparation of the Spaceguard reports.

Dr. William Wiesel, Dept of Astronautical Engineering, Air Force Institute of Technology for taking time out of a busy schedule (even canceling class) to discuss and advise on the project.

Maj Karl Johnson, our faculty research advisor for his incredible support throughout the year. He kept our research flowing smoothly and relieved us of many administrative burdens.

Most of all, we would like to thank our friends and families for motivating us when we were beleaguered, and for bearing with us when we were gung-ho.

This research project would have been very difficult without the assistance and encouragement of these individuals. However, the conclusions and recommendations, as well as any errors, are entirely our own.

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Abstract

The threat posed to Earth and Earth-orbiting spacecraft by natural space debris (asteroids, comets and meteor streams) is examined in an effort to quantify the threat and identify available, low cost mitigation measures. Our study found that the Earth resides in a *swarm* of natural debris that consists of at least three families of asteroids (the Apollo, Aten and Amor asteroids), several short-period comets and at least 11 active meteor streams.

The results of recent studies regarding the risk of a significant asteroid or comet impact on Earth are presented. Best estimates indicate the probability of a large impact within the next century is about 1 chance in 10,000. Further, there is a much higher probability of a smaller (Tunguska sized) impact sometime in the next century. The myriad of potential impact effects are discussed in detail for various impactor sizes. The threat that meteor storms pose to space-borne assets is also discussed. There has not been a major meteor storm since 1965, hence our modern space systems have never been subjected to a severe storm. There is a very high probability that we will see an extremely active storm from the Leonid stream around 17 November 1999. We discuss the meteor stream threat to our space systems (as an integrated network), and what we should do to lessen the possibility of losing satellites in future meteor storms.

The natural space debris threat is real and mitigation measures should be implemented. Before this can happen, the threat must be communicated. Problems communicating the natural space debris threat are discussed using historical examples. With these problems in mind, we offer suggestions to more clearly quantify and

communicate the threat to decision-makers in the future. The need for a better threat model is discussed and the framework for an improved model is provided.

The need for an asteroid and comet search program is discussed, and basic search system requirements are derived. Using these requirements, we evaluate the utility of several existing and proposed systems. Then, the general architecture and approximate cost of a suitable search program is presented. We estimate the program cost to be $56.5M to $57M non-recurring, and $12.6M to $15.4M/yr for operations. A limited search capability could be had for $19.5M to $20M non-recurring, and $10.6M/yr to $13.4M/yr for operations. The need for meteor stream characterization and the development of a storm warning capability is introduced, and a cost estimate presented. To characterize all 11 active streams and develop a basic meteor storm warning capability for our satellite programs will cost approximately $3.2M over eight years.

Given that the threat is real, we examine the roles and responsibilities of the US military regarding the defense of Earth and our space assets from asteroids, comets and meteor storms. Within the last 15 years, the military has responded to natural disasters such as floods, hurricanes, earthquakes and volcanic eruptions. Based on existing policies, and the historical role of the military in disaster response, we believe that the military has a responsibility to address the natural space debris threat. Finally, several threat mitigation measures are presented. Active measures such as the deflection or destruction of potential impactors are briefly discussed. However, we recommend the search and planning measures be given first priority. A summary of key recommendations is provided in the final chapter.

PLANETARY ASTEROID DEFENSE STUDY: ASSESSING AND RESPONDING TO THE NATURAL SPACE DEBRIS THREAT

CHAPTER 1

Introduction

On 1 February 1994 at 22:38 Universal Time, a piece of natural space debris entered the Earth's atmosphere just north of Kosrae island, off the coast of New Guinea. Traveling at ~15 km/sec (33,555 mph), it streaked across the sky toward the northwest and exploded about 20 km above the sea, near the island of Tokelau, with a force of ~11 kilotons of TNT.[1] At its peak, the brightness exceeded magnitude -25 (similar to the Sun).[2] The explosion triggered sensors on several US early warning satellites.[3] Fortunately, the blast occurred at high altitude and over a sparsely populated area; thus, no damage was done.

On 23 March 1989, an asteroid about 800 meters (1/2 mile) in diameter missed Earth by about 6 hours.[4] If it had hit, the impact would have released energy equivalent to about 40,000 Megatons of TNT or 2,000 hydrogen bombs.

On 8 December 1992, another asteroid, named Toutatis missed hitting the Earth by about 2 lunar distances.[5] Toutatis is nearly 4 km in diameter (2.5 miles), more than twice the size required to create a global catastrophe.[6] Its impact would release more energy than all the nuclear weapons in existence, about 9 million megatons.

These are just a few examples of the risks we face each day from Natural Space Debris (NSD). While the probability of a large asteroid like Toutatis hitting us is relatively low, it may not be as low as we have traditionally believed.

The Threat

In 1989 the US Congress commissioned NASA to study the threat posed by Earth-orbit crossing debris and investigate means of mitigating that threat. Christened the "Spaceguard" study, a team of over one hundred of the top US and international scientists participated. Their conclusion was that natural space debris does present a real (though not eminent) threat to Earth and that some reasonable effort should be made to find, catalog and track Earth-orbit crossing objects.[7] Further, they found that, if a large asteroid were on a collision course with Earth, we now have the technology to deflect or destroy it and prevent catastrophe.

Since the publication of the Spaceguard Survey report in 1992, much work has been done by scientists around the world to further define the risks presented by NSD. In the following pages we will present our assessment of the risk based on the most current data available and what should be done about it. We intend to assess the results of the Spaceguard Survey and to use additional new information to better understand the threat posed by NSD and investigate tools that the military, particularly the Air Force, may have available to counter the threat.

Roles and Responsibilities of the United States Military Regarding NSD Defense

The US military's role in providing domestic disaster relief is not a new one, but it is indeed an ever-changing one. In the past, military assistance was simply welcomed;

today it is expected. Further, there is growing pressure at all levels of government to ensure designated agencies provide the necessary assistance and relief in a timely manner. Our paper will discuss how evolving policy, doctrine and detailed preparedness planning have all contributed to improving the military's response to domestic emergencies. We will also discuss several challenges and concerns that the military must address in order to plan for, and respond to, a disaster resulting from an asteroid impact.

Our premise is that the hazard posed by natural space debris is much like that of any other natural hazard. The military, particularly the Air Force, can't afford to ignore natural space debris and its potential for causing serious damage. In the last decade, military units participated in relief operations stemming from volcanic eruptions, earthquakes, hurricanes and floods. It seems only logical that national leaders and the public will continue to look to the military for help in times of disaster. Thus, it follows that the military must assume some degree of responsibility for NSD defense.

The necessity of planning for a domestic disaster resulting from natural space debris has apparently never been seriously considered within the Air Force. The defense of Earth from asteroid impact has, in the past, been considered both expensive and unnecessary. Recent events, such as those presented above, combined with new data and theories regarding the nature of the NSD threat, give reason to re-examine these issues.

Notes

[1] "Satellites Detect Record Meteor," *Sky & Telescope*: 11 (June 1994).

[2] Ibid.

[3] Ibid.

[4] George E. Brown Jr., Chairman, House of Representatives, Committee on Science, Space and Technology. "The Threat of Large Earth-Orbit Crossing Asteroids," Hearings before the House Sub-committee on Space on Results of Spaceguard Study. 24 March 1993.

[5] Corey S. Powell, "Asteroid Hunters," *Scientific American*: 34-40 (April 1993).

[6] Clark Chapman and David Morrison, "Impacts on the Earth by Asteroids and Comets: Assessing the Hazard," *Nature* 367: 35 (6 January 1994).

[7] David Morrison, Chairman of Asteroid Detection Workshop (Spaceguard Study), NASA Ames Research Center. "Statement Given House of Representatives, Committee on Science, Space and Technology, before the House Sub-committee on Space. 24 March 1993.

CHAPTER 2

Natural Space Debris

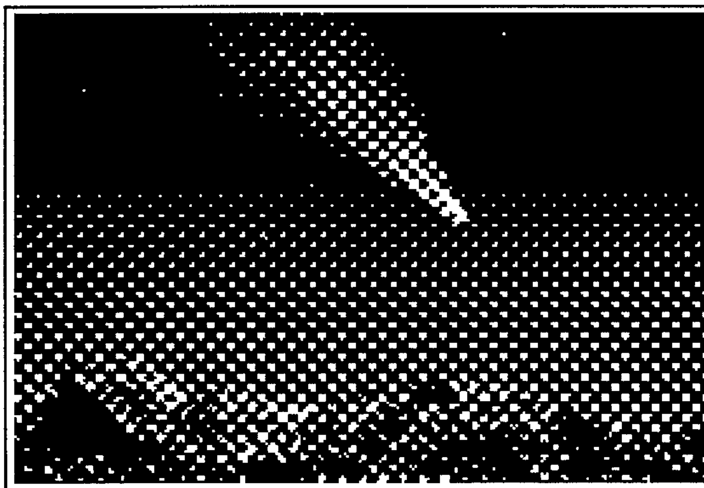
Definition of Natural Space Debris (NSD)

Natural space debris, for the purposes of our discussion, consists of all naturally occurring solid matter orbiting the Sun whose orbits intersect or share that of the Earth from time to time, or might do so in the future. Thus, we are specifically excluding man-made debris (i.e.: objects orbiting the Earth or Sun placed in orbit by man). We are also excluding natural debris in permanent orbit around the Earth since most of it is relatively small and the quantity is fairly constant. While the Spaceguard study focused on objects greater than 1 km in diameter, our discussions will include objects of all sizes; from the smallest grain of sand to the 10 km diameter *planet-busters*.[1]

Sources of Natural Space Debris

There are two major sources of natural space debris: asteroids and comets. Both are considered to be left-over material from the formation of the planets in our solar system. Occasionally, these objects are perturbed by chaotic interaction with gravitational fields of the Sun and planets into paths that cross Earth's orbit.[2] Comets and asteroids are not always very different. Both can occupy the same types of orbits as illustrated by the fact that some of the Earth-crossing asteroids are actually burnt-out comets.[3] The primary differences have to do with their composition and origins. As you'll see in the following discussion these differences have an effect on the detection problem.

The Comets. A comet, unlike an asteroid, contains a large quantity of various *ices*. Common ices would include materials such as water, methane, ammonia, carbon dioxide, hydrogen and nitrogen.[4] The ices act as a glue to hold the comet together; thus comets are often thought of as *dirty snowballs* containing a mixture of rock and metals all held together in a frozen mass. As such they would be physically more fragile than an asteroid made of solid rock (which is important if you want to deflect one). As they orbit the Sun and the ices boil away, the core of the comet will be weakened. Over time, it will lose all of its ices leaving only rock or metal. Because of this process, comets are responsible for two magnificent astronomical displays: the comet with its tail as seen in Figure 2-1, and some well-known annual meteor showers.



Source: David Irizarry.

Figure 2-1. Artist Rendering of Comet With Tail

The most visible difference between an asteroid and a comet is the *tail*. As a comet approaches the Sun, solar radiation vaporizes the ices on the surface of the *nucleus*, forming a luminous cloud around the nucleus called the *coma* which blends into the tail.

The tail always points away from the Sun since it is made up of vaporized material being blown away from the nucleus by the solar wind. The length and brightness of the tail can vary considerably since the ablation rate of the comet material varies with the composition of the nucleus, distance from the Sun and orientation of the nucleus. As the comet passes perihelion (closest approach to the Sun) it loses a lot of its ices and gravitational forces will severely stress the nucleus. Eventually, due to loss of the ices, the comet will break up, or it will lose so much material that it will no longer be capable of generating a bright tail.

It's the slow disintegration of a comet that produces many of our annual meteor showers. As the ices in the nucleus warm and subsequently vaporize, they leave behind the rock which is itself eventually ejected from the surface. Therefore, in the path of a comet, clouds of debris begin to form. Over time, debris can become distributed (albeit unevenly) around the orbit.[5] This effect is extremely important since these clouds of debris form the *streams* that are the source for at least some of our annual meteor showers. Streams will be discussed in more detail later.

The Origin of the Comets. The origin of comets is unknown. No one has ever seen or irrefutably proven the existence of a single source of new cometary debris; however, it seems certain a source does exist. Short-period comets can not survive more than a few tens-of-thousands of years before the Sun boils away their ices. Thus, a supply of comets must exist someplace in deep space where the Sun can not destroy them. The most accepted theory today proposes the existence of a cloud of icy debris at the very edge of the Sun's gravitational influence. At this great distance, the accretion process that created the planets some 4,800 million years ago did not happen. Material in the outer reaches of the solar system combined with leftover debris ejected by the planets to form a spherical cloud of debris around the solar system called the *Oort cloud,* which consists of somewhere between 10^{12} and 10^{14} potential comets. Occasionally, for reasons not yet fully understood, debris from this cloud (comets) are sent sunward where they may eventually hit one of the planets.

Types of Comets. Comets are classified as either long, intermediate or short period, where period is defined as the time it takes the comet to orbit the Sun. Cometary orbits are often different than those of the asteroids. They are usually highly elliptical and are often inclined at large angles to the orbit plane of the planets. The significance is that, unlike the asteroids, comets could approach the Earth from almost any direction and at very high velocity. Therefore, to find them you would have to continuously survey the entire sky.

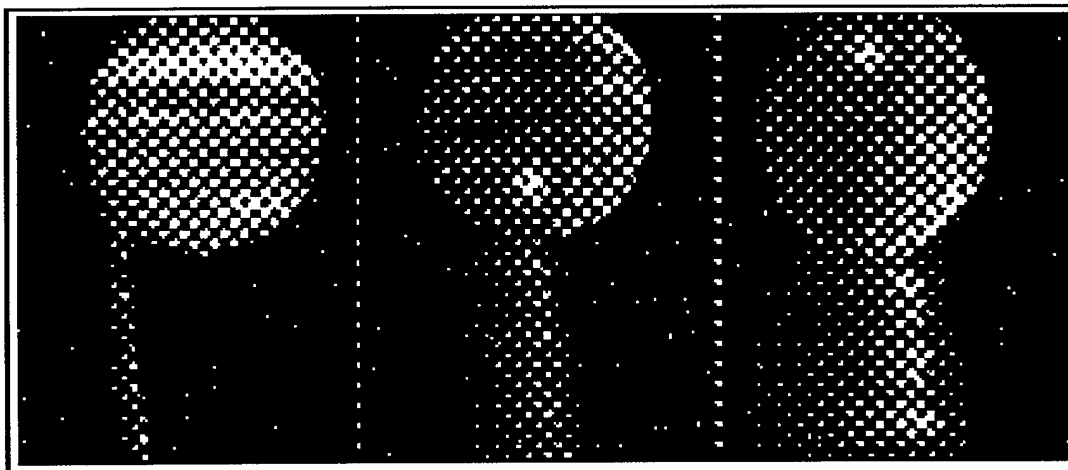
Table 2-1. Some Short-Period Comets and Their Orbital Periods

Comet Name	Period (years)
Encke	3.30
Schwassman-Wachmann 3	5.35
Giacobini-Zinner	6.59
Halley	76.03
Swift-Tuttle	119.60

Source: *Comets and Meteor Streams, Vol 2,* Porter.

Short-period Comets. To simplify our discussion, we will combine the traditional short and intermediate period comets into the category of *Short-period comets.* Though called short-period comets, periods range from only a few years up to 200 hundred years. The number of short-period comets in our solar system is unknown but is believed to be on the order of 15,000 with a diameter greater than 100 meters.[6] The number of these that are Earth-crossing is estimated to be about 10-20% of all short-period comets or about 3,000.[7] Unfortunately, only a small portion of these have been discovered and have known orbits.

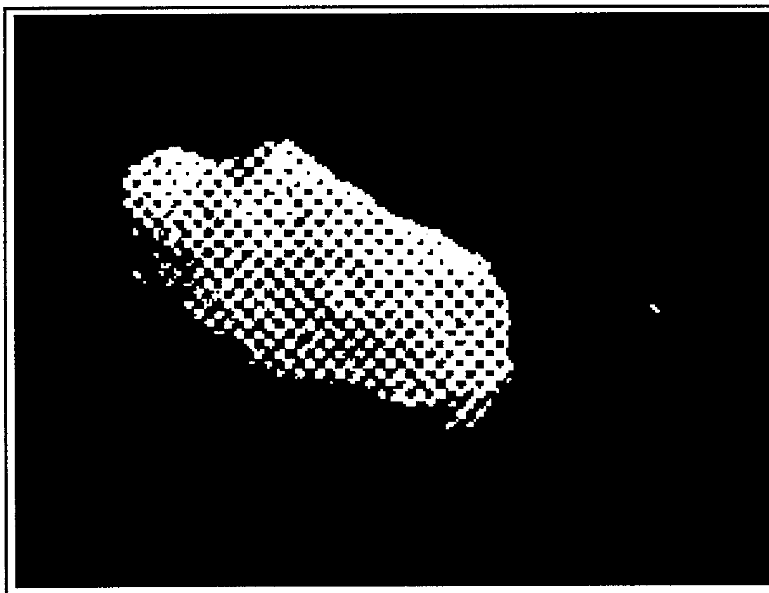
While the orbits of short-period comets are more stable than many in *the long-period* class, their orbits are still subject to perturbations by the planets and collisions with other minor solar system objects. Comet Shoemaker-Levy 9 is a prime example of the drastic orbit changes that can occur when a comet has a close encounter with one of the planets. Some time ago, Shoemaker-Levy 9 was captured by Jupiter where it orbited in a highly elliptical orbit until 8 July 1992 when Jupiter's tidal forces tore it apart.[8] One orbit later, on 16 July 1994, pieces of the fragmented comet began colliding with Jupiter sending fireballs rising out of Jupiter's atmosphere and leaving dark scars that were visible from small Earth-based telescopes.[9] A similar impact on Earth would be disastrous.



Source: David A. Seal, Paul W. Chodas and Donald K. Yeomans of JPL.

Figure 2-2. Artist Rendering of a Fragmented Shoemaker-Levy 9 Impacting Jupiter

Long-period Comets. Long-period comets consist of all comets with a period greater than 200 years. As with the short-period comets, the number of long-period comets is not known. Its likely that there are literally trillions in the solar system, waiting in the Oort cloud. Approximately 700 are known to have passed through the inner solar system and about half of them had Earth-crossing orbits.[10] The total population of long-period comets is hard to characterize for two reasons. First, its difficult to find and catalog them. Comets are most visible when they are close to the Sun. The long-period comets will spend most of their time in deep space where very little Sun light will reach them. Thus, most of the population is far enough out in space that we can't see them. Secondly, the orbits will be greatly affected by the outer planets, especially Jupiter. For example, comet 1910 I has a calculated period of 3,910,000



Source: NASA, Galileo Photo.

Figure 2-3. Asteroid Ida (56 Km Long) and its Moon (1 km Diameter)

years.[11] Little credence should be placed in calculations of such an orbit since before it can return to the inner solar system (assuming that it will return) it is likely that its orbit will be perturbed. In fact, it will probably be difficult to recognize 1910 I if it reappears since its orbit may be changed so much that it would be indistinguishable from a *new* comet. There are potentially many thousands of comets within the solar system with such long periods that we will never be able to say with confidence that we know where they all are. If only a fraction of these are Earth-crossing they could pose a significant risk.

The Asteroids. There are three very general groups of asteroids that need to be addressed: planet-crossing, main belt and extra-belt asteroids. Of these, the planet-crossing bodies are of greatest concern since they frequently cross Earth's orbit; thus they offer the greatest probability of impact. The main belt and extra-belt bodies do not pose an immanent threat since they stay well beyond Earth's orbit; however, the chaotic gravitational interaction between the planets and the asteroids may perturb them into Earth-crossing orbits sometime in the future.[12]

Table 2-2. Titius-Bode Sequence Predicted Planet at 2.8 AU from Sun

Planet	Series	Titius Series Value	Distance From Sun in AU
Mercury	0	0.4	0.39
Venus	3	0.7	0.72
Earth	6	1.0	1.00
Mars	12	1.6	1.52
	24	2.8	
Jupiter	48	5.2	5.20
Saturn	96	9.6	9.54

Source: *Cosmic Impact*, John K. Davies

Main Belt Asteroids. In 1772, a German professor named Johann Daniel Titius found an interesting mathematical relation between the sequence of numbers: 0, 3, 6, 12, 24, 48, 96 and the orbits of the planets.[13] Notice that in this series each number is double the previous one (except for the second). If the number 4 is added to each number in the series the resulting new series gives the ratios of the distances of the planets from the Sun. If you define the distance from the Earth to the Sun as 1 Astronomical Unit (AU) and divide by 10 the series gives the distance of each planet from the Sun in AU. The series is nearly perfect for all planets through Uranus. The significance of this is that Titius, and later a German Astronomer named Johann Bode, noticed that planets existed at each of the predicted locations except 2.8 AU. The discovery of Uranus in 1781 by William Herschel at almost exactly the orbit predicted by the Titius Series (mean orbital distance from the Sun 19.6 AU) started a search for the *missing planet* at 2.8 AU.

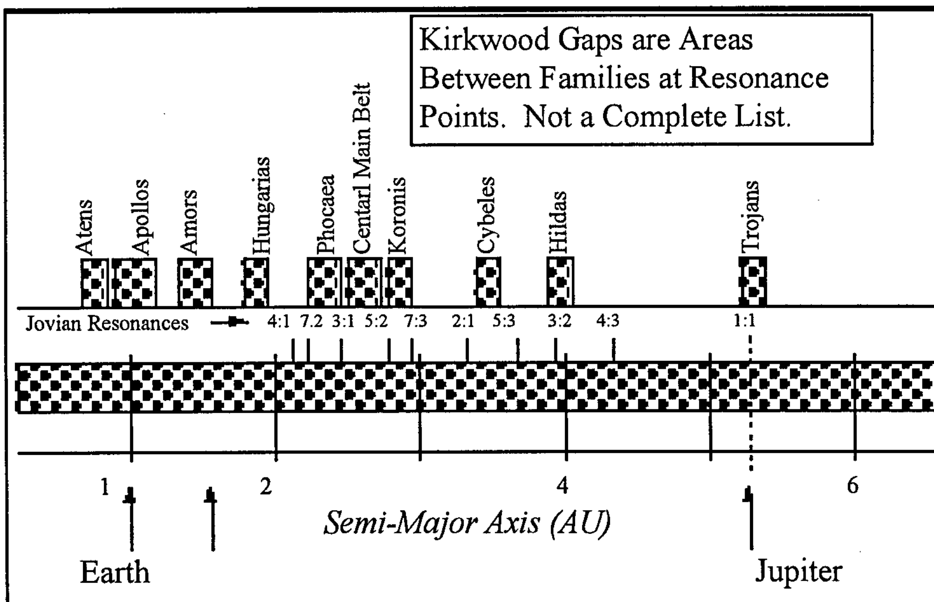
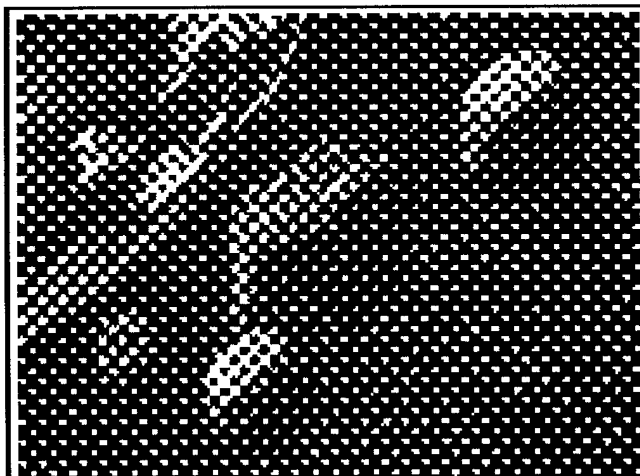


Figure 2-4. Relative Locations of Some Families and the Kirkwood Gaps

In 1801 an Italian astronomer Giuseppe Piazza accidentally discovered Ceres at 2.77 AU. The search for the missing planet would probably have ended there; however another astronomer named Heinrich Olbers found another object in the same area. The object was named Pallas; the second body in a region that has come to be known as the asteroid belt. For reasons that are still not clearly understood the region between Mars and Jupiter contains many *planetesimals* rather than a single planet. The most accepted explanation is that the gravitational field of Jupiter created a disturbance that prevented the debris from coming together to form a planet.[14]

Further study has shown that the belt itself isn't just a random collection of objects. There's a definite structure which was discovered by Daniel Kirkwood in 1857. He showed that, within the belt, there were no asteroids with an orbital period equal to an even fraction of Jupiter's period.[15] He explained this by saying that all objects in the belt receive a gravitational "tug" by Jupiter. For most of the objects, this tug occurs at different places in their orbits so the effects cancel out. For those with a period equal to a fraction of Jupiter's orbit, they receive the tug at the same place each time; so, these objects will eventually be ejected into a new orbit. Thus, the Kirkwood gaps represent unstable regions referred to as *resonances*. Any object in or very near one of these regions is will be ejected by Jupiter. A small disturbance, such as a collision by another asteroid, could perturb such an object enough to send it into a new orbit possibly ejecting it from the main belt entirely. This is at least a small part of a larger process which is apparently resupplying the Earth-crossing asteroid complex.[16]

Extra-Belt Asteroids. In 1918, K. Hirayama put forth the theory that clumpings of asteroids are *related* in that they could have formed as a result of the breakup of a larger parent body by catastrophic collision.[17] He called these clusters of asteroids *families*. A partial listing of these families and their approximate semi-major orbit axes is shown in Table 2-3. There is much discussion about the nature of asteroid *families*, their boundaries and the membership of certain objects.[18] For the purposes of this paper we use the term very loosely to refer to existing clusters of asteroids in similar orbits in order to convey the general distribution of asteroids in the solar system rather than their origins in terms of parent bodies. In other words, we do not claim that the objects in a particular family all came from the break-up of a single larger object. They only have similar orbits. As can be seen from Table 2-3, asteroids are not limited to the main belt. There are families of asteroids outside the main belt as well as a few that can cross Earth orbit.



Source: Artist, Joe Legeckis.

Figure 2-5. Artist Rendering of Asteroids Approaching a Planet

Table 2-3. Major Asteroid Families and Groups

Major Asteroid Orbital Families and Groups	Location	Approximate Semi-Major Axis of Orbit (AU)	Earth Crossing Orbit At Present?
Atens	These asteroids orbit inside Earth's Orbit. Their aphelion distance is approximately 1 AU.	1.0	Yes
Apollos	These asteroids have aphelion's in the asteroid belt (though there are exceptions). Orbits are unstable. Can evolve into Amors.	1.1	Yes
Amors	Very similar to the Apollos. Can evolve into Apollo orbits.	1.4	Yes
Hungarias	Orbit between Mars and Main Belt.	1.9	No
Phocaea	Form inner main belt between 7:2 and 3:1 resonance with Jupiter.	2.4	No. Potentially resupplies Earth-crossing groups.
Central Main Belt	Center of main belt between the 3:1 and 5:2 resonances.	2.8	No. Potentially resupplies Earth-crossing groups.
Koronis	Central main belt between 5:2 and 7:3 resonance.	2.9	No
Cybeles	Beyond main belt, between 2:1 and 5:3 resonances with Jupiter.	3.4	No
Hildas	Beyond main belt, at 3:2 Jupiter resonance.	4.0	No
Trojans	Two separate swarms share Jupiter's orbit at the L4 and L5 Lagrangian points.	5.2	No. Orbits are stable unless perturbed.

Like the main-belt asteroids, the extra-belt asteroids do not pose a threat to Earth in their present orbits. All of the main-belt and extra-belt asteroid families occupy relatively stable orbits well outside Earth's orbit. However, the existence of unstable orbit zones (the Kirkwood gaps) close to their orbits means that a small disturbance (such as a collision with another asteroid) that kicks the asteroid into one of these unstable zones can result in its ejection into one of a myriad of possible new orbits. Some of these could eventually evolve into Earth-crossing orbits.[19]

The Trojan asteroids are perhaps the most unique family in the extra-belt region. Unlike other families who define their own orbits, the Trojans share Jupiter's orbit. They are able to do this because of the existence of two regions of stable libration in Jupiter's orbit.[20] These points are called libration or Lagrange points (labeled L4 and L5) after J. L.

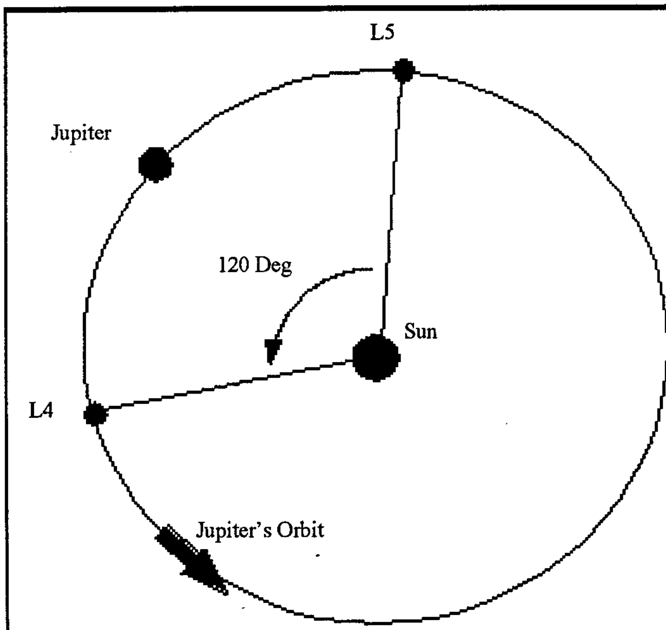
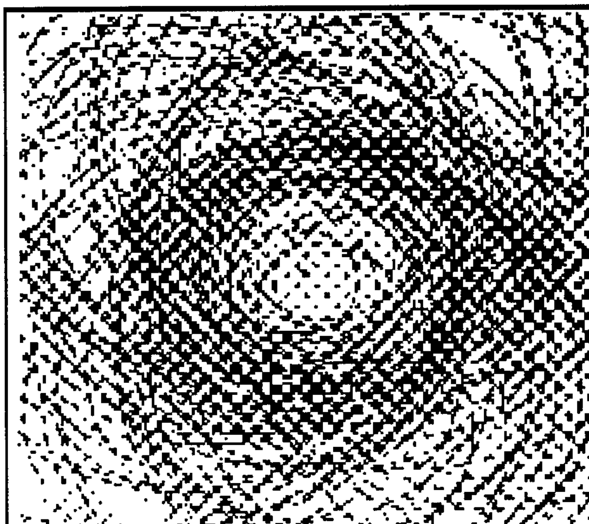


Figure 2-6. Location of Trojan Asteroids at L4 and L5 Lagrange Points

Lagrange who predicted their existence years before the first Trojan's were found. L4 is located 60 degrees ahead of Jupiter and L5 is located 60 degrees behind. Although the their orbits are stable, a relatively small disturbance from collision with another asteroid or the close passage of a large comet could kick an asteroid out of the stable region and send it into a new orbit with unpredictable results.

Earth-crossing Asteroids. The final group of asteroids we need to discuss are those in Earth-crossing or Earth-approaching orbits. The families that make up this group are the Atens, Apollos and Amors, often collectively referred to as the AAAO's. If an asteroid is going to hit Earth in the near future it will probably come from one of these families. In fact, the mean lifetime of one of these asteroids is very short; only about 10^7 or 10^8 years.[21] While a few million years seem like a long time, it is nothing when compared to the age of the Earth (~ 4,800 million years). The short lifetime



Source: Dr. Richard P. Binzel of MIT.

Figure 2-7. 100 of the Largest Earth-crossing Asteroid Orbits Overlaid on Earth s Orbit

reflects the reason for our studying the natural space debris threat. All of these objects will either hit one of the inner planets or will be gravitationally ejected from the inner system by a near miss (out of the inner system or into the Sun). Somewhere between 20% and 40% of the over 3,000 AAAO's will ultimately hit Earth.[22] Many are larger than a kilometer in diameter (big enough to cause global extinctions).[23] To date, the largest Earth-crossers known to exist are about 8 km in diameter.[24]

In 1979, it was estimated that there are 100 Atens, 700 +300 Apollos and 1,000 to 2,000 Amors.[25] As of 1989, only 128 asteroids from all three families had been found and only 61 had orbits sufficiently well defined to receive permanent catalog numbers.[26] Thus, we have found less than 1% of the asteroids that could threaten Earth. Given such a discrepancy one might question the validity of the 1979 estimates. A detailed discussion of how the estimates were derived is well beyond the scope of this paper; however, there is significant evidence that the estimates are at least close to the true number, and perhaps even a bit low.[27] The most likely reason for the discrepancy lies in the inherent difficulty of finding the AAAO's (due to their small size and orbit geometry's), combined with the fact that very few resources have been devoted to looking for them. The resource problems will be discussed in later chapters; however it is important to note that the two problems cannot be separated. The AAAO's present some very difficult challenges compared to the asteroids in the other families. These challenges are, at least in part, responsible for the small size of the present search effort. Creative, cost effective ways of doing the job must be found if we are to find these objects in a reasonable period of time.

The AAAO Orbits. The Atens are defined as asteroids having orbits who's semi-major axis is less than that of Earth (1.0 AU).[28] The Amors are defined as having orbits that approach Earth's (perigee distance ~1 AU) but never cross within its semi-major axis.[29] The Apollos, by definition, have orbits that cross Earth's and have a perihelion distance less than Earth's semi-major axis.[30] While this is a concise definition it does little to convey to the layman the basic orbit geometry. The distinction between the Atens, Apollos and Amors is important since their respective orbit geometry's present different problems for a detection system (which will be discussed in a later chapter). Since the AAAO orbit definition's are based on an understanding of the semi-major axis and its relation with other parameters a brief review of key orbit elements is in order.

Figure 2-8 shows a typical elliptical orbit. Notice that *perihelion* is defined as the point in the orbit that is closest to the Sun and *aphelion* is the point farthest from the Sun. The semi-major axis (a) is the distance from the center of the ellipse to perihelion or aphelion. Eccentricity (e) defines the *flattening* of the ellipse where,

$$e = CS / a \tag{1}$$

The perihelion and aphelion distances can be found from,

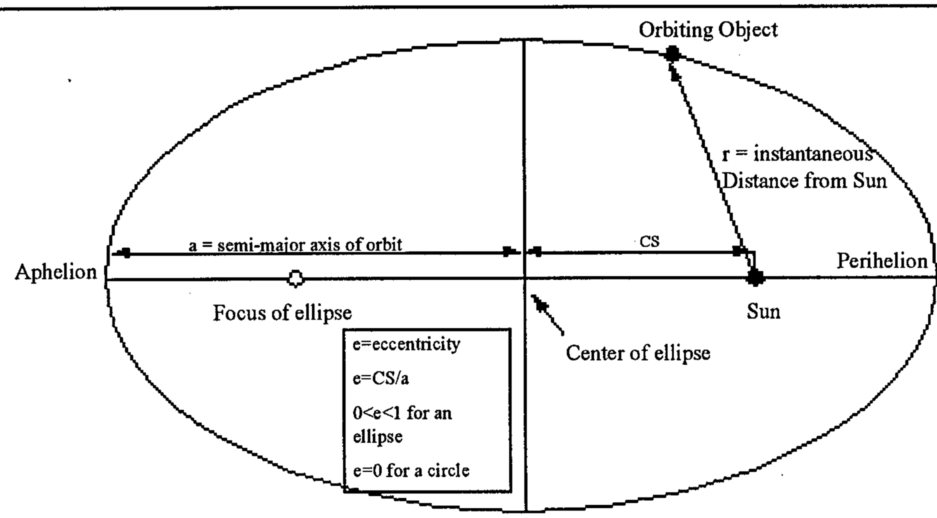


Figure 2-8. Basic Elliptical Orbit Geometry

$$r = \frac{a(1-e^2)}{1+e\cos\nu} \qquad (2)$$

where ν is the angle between vector r and the perihelion point.[31] Thus, we can easily determine the object's closest approach to the Sun by calculating r for $\nu = 0°$. The equation becomes simply,

$$r_{perihelion} = a(1-e) \qquad (3)$$

likewise, for aphelion (ν=180°) the equation becomes,

$$r_{aphelion} = a(1+e) \qquad (4)$$

Given only the elements a and e, Equations (3) and (4) can be used to determine whether the object is in an orbit that crosses or comes close to Earth's orbit. An object who's orbit takes it close to Earth's ($r_{perihelion}$ or $r_{aphelion}$ ~ 1 AU) or that crosses Earth's orbit is a potential impactor. However, it does not mean the object will hit. It is only one of several conditions that must be met before an object can hit Earth. To determine whether a collision will take place, other factors must be considered. Three significant considerations are: timing, orbit inclination and the gravitational effects of the Earth and other planets along the object's orbit.

Timing is important because we must determine whether the Earth will be near-by when the object crosses Earth-orbit. If the Earth isn't there, obviously, no impact can occur. Inclination will effect the amount of time an object can remain close to Earth orbit. In general, if the object's orbit is inclined with respect to Earth's orbit, the object will pass close to Earth no more than twice per orbit. The most difficult factor to model is the effect of the planets on the object's orbit. Each planet, especially Jupiter, will perturb the orbit making precise orbit calculation and impact prediction difficult.

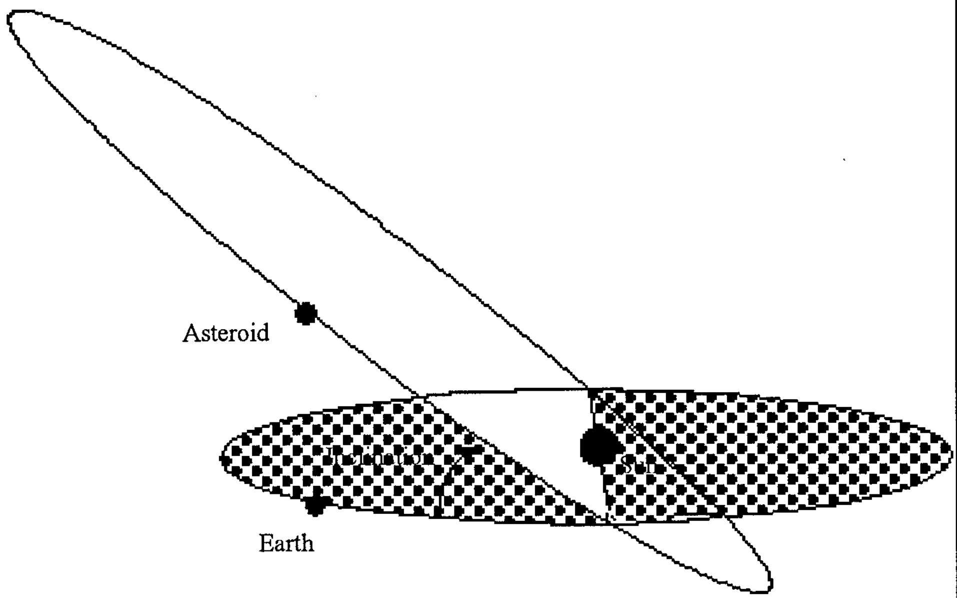


Figure 2-9. Earth-crossing Orbit with Inclination

In order to predict an asteroid impact, precise knowledge of its orbit is required. Further, the orbit parameters must be updated periodically to account for perturbations to its orbit. With this data in hand the orbit can be calculated precisely enough to determine whether the object will collide with Earth; however its extremely difficult to determine where on Earth the object will hit.

Representative orbits for the AAAO's are shown in Figure 2-10, Figure 2-11 and Figure 2-12 below. Keep in mind that the families are comprised of many asteroids who follow similar but not identical orbits. Each family has members with widely varying orbit elements, especially inclination and eccentricity.[32] Table 2-4 shows orbit elements for the namesake asteroids for each Earth-crossing asteroid family. Again, these should be considered as representative only.

Table 2-4. Orbit Elements of Earth-crossing Asteroids For Which Families Are Named

Asteroid	a (AU)	e	i (Deg)	$r_{perihelion}$ (AU)	$r_{aphelion}$ (AU)
Aten	0.97	0.182	18.9	0.79	1.15
Apollo	1.47	0.560	06.3	0.65	2.29
Amor	1.92	0.435	11.9	1.08	2.76

Source: Lucy-Ann McFadden and others. "Physical Properties of Aten, Apollo and Amor Asteroids," in Asteroids II. Eds. Richard P. Binzel, Tom Gehrels and Mildred Shapely Matthews. Tucson Az: The University of Arizona Press, 1988.

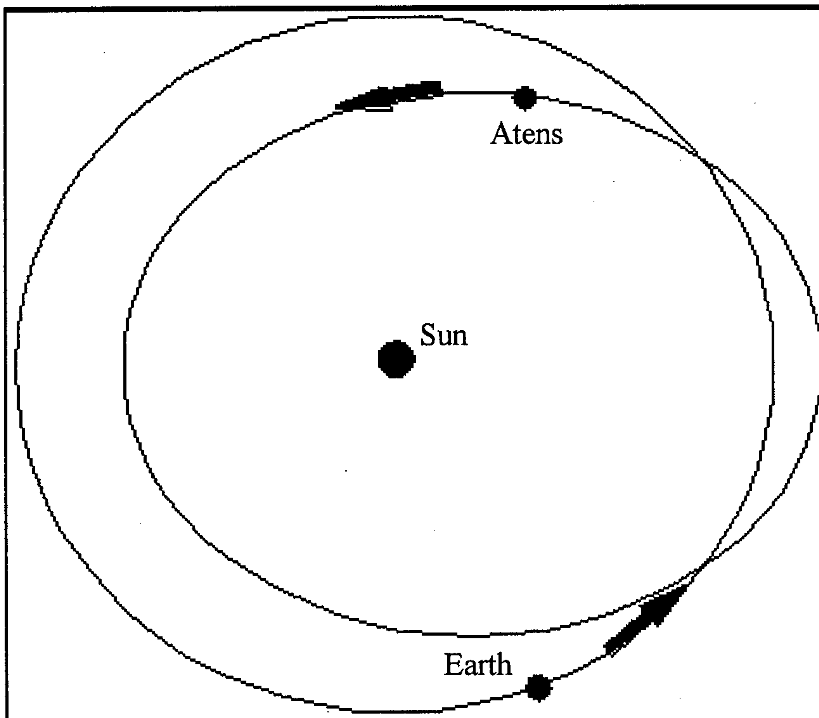


Figure 2-10. Typical Earth-crossing Orbit of Atens Asteroid Family

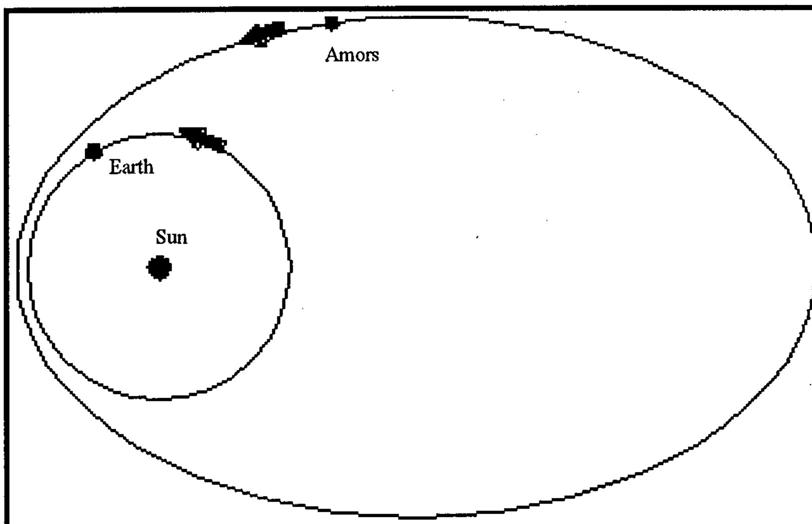


Figure 2-11. Typical Earth-approaching Orbit of Amor Asteroid Family

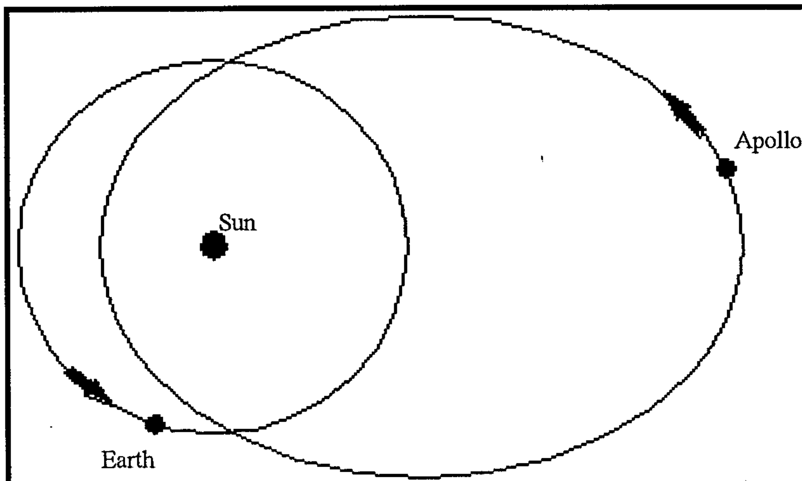


Figure 2-12. Typical Earth-crossing Orbit of Apollo Asteroid Family

Table 2-5. Definitions of Some Common Space Debris Terms

Object	Definition
Planetesimal	Asteroids with diameters of 10-1000 km. Generally this term is used to refer to the debris from which the planets formed.
Asteroid	An object, largely devoid of ices, ranging in size from 1 meter to 1000 Km in diameter.
Bolide	A large meteor, usually in the 1-50 meters diameter range that fragments or detonates while passing through the atmosphere.
Meteoroid	Essentially a small asteroid. Sizes range from micro-meters to a meter.
Meteor	The light, heat and sound phenomena accompanying the passage of a meteoroid through the atmosphere.[33]
Meteorite	The solid object that survives passage through the Earth's atmosphere.

Meteors and Meteor Streams. Before entering into a discussion of meteors and their streams there are some terms that we need to define to avoid confusion. There are three terms related to meteors that people often confuse: meteorite, meteoroid and meteor. A meteorite is the solid object that survives entry through the Earth's atmosphere. A meteoroid is the name of the object while still in space. The only difference between an asteroid and a meteoroid is size. There is no clear definition of size for either of these objects; so, for this paper we will use the definitions presented in Table 2-5. Finally, meteor, is the name given to the effects produced by a meteoroid as it passes through the atmosphere, leaving a brief streak of light in the sky. Like the asteroids and other Sun-orbiting debris, meteoroids of all sizes travel at speeds frequently exceeding 26 km/sec with respect to Earth.[34] One stream, the Leonids, can exceed 71 km/sec with respect to Earth.[35] At such high speeds, friction between the object and the air molecules generates enough heat to raise the surface temperature to over 3000°F, vaporizing material on its surface.[36] It's the hot, vaporized material and air mixture (called plasma) that is responsible for the bright incandescent trail behind the meteoroid. Generally, aerodynamic heating begins about 100 km altitude and complete disintegration occurs above 6 km; however, many are able to survive entry.[37] Factors that allow meteoroids to survive are: composition, size, entry velocity, entry angle and fragmentation.[38]

Composition is important because it determines how much heat and stress the meteoroid can take. Meteoroids made of ices or stone seldom survive entry; whereas iron and other metallic objects often do. Size is an important factor because a large object can lose a lot of its material and still retain physical integrity. Conversely, very small objects (in the millimeter size range) have a better chance of surviving because their mass is low compared to their cross-sectional area.[39] Thus, they are able to dissipate energy and slow down without vaporizing. Meteoroids of this size usually don't fall to Earth immediately. Instead, they remain suspended high in the atmosphere, usually about 90 km above the Earth.[40] While suspended, water often condenses and freezes around them. If many of these ice-coated particles are trapped in the same region of the atmosphere they can cause *noctilucent clouds* that glow long after sunset.

Many of the meteoroids raining down on Earth come from *streams*. Meteor(oid) streams are three dimensional rings of dust and debris in orbit around the Sun. Like asteroids and comets, the orbits of some of these streams cross Earth's orbit. Whenever the Earth passes through or near one of these streams it gets pelted with debris creating a meteor shower. Over long periods of time (greater than 10^5 years), the debris in these streams will break down into very fine particles and spiral into the Sun (due to interactions with the solar wind).[41] Thus, on an astronomical time-scale, meteor streams are a transient phenomenon.

Table 2-6. Some Well-known Meteor Showers and Their Parent Objects

Shower	Approximate Date of Shower	Typical Number of Meteors per Hour	Parent Body
Eta Aquarids	May 2-7	18	P/Halley
Perseids	July 27-August 16	65	P/Swift-Tuttle
Orionids	October 17-21	10	P/Halley
Taurids	Oct 25-Nov 25	10	P/Encke
Leonids	November 16-19	15	P/Temple-Tuttle
Geminids	December 7-15	55	Asteroid 3200

Source: *Cosmic Impact*, John K. Davies

Meteor showers are named according to the constellation from which the meteors appear to originate. The exact point from which they emanate is called the radiant point. The radiant point is merely an illusion caused by the viewers perspective; the same effect that makes railroad tracks appear to converge in the distance. The orbits of the Earth and the debris streams change little from year to year; therefore, each time the Earth passes through the stream the debris appears to come from the same position relative to the star background; thus the radiant point for a given stream does not change much.

The origin of meteor streams is still being debated. However, it seems there are at least two mechanisms at work: the disintegration of comets as they orbit the Sun and the transport of debris from the asteroid belt by collision-induced injection into one of the unstable Jupiter resonances discussed earlier.[42] Both phenomena contribute to the formation of meteor streams, though it seems comets are the most significant contributors.

While meteoroid sized objects produce some impressive displays in the night sky they pose no threat to life on Earth. In fact, given the rather low rate that meteoroids normally hit the Earth, they pose very little threat to space assets. However, some interesting new theories regarding the distribution of debris within several Earth-crossing streams indicates the nominal impact rate (called flux) can periodically increase by a factor of 10,000 times.[43] Called meteor storms, these high impact fluxes would endanger our spacecraft.

The Natural Space Debris System: A Summary

The purpose of the preceding background material was to familiarize the reader with the general distribution of debris in the solar system, methods of delivery to Earth and to convey the complex and dynamic nature of the *natural debris system.* For many years, people considered natural space debris to be a static phenomena. The lunar craters clearly showed impacts were once common. However, most believed the planets had long ago hit or ejected most of the debris; thus, remaining debris would be in a stable orbit and the resulting Earth-impact rate very low (and would remain low) compared to times past. We now know that this model is incorrect.

Debris (asteroids, comets and meteoroids) is continually being supplied to the inner solar system. Further, the rate of supply, especially from the Oort cloud is not constant; therefore the risk of an object hitting the Earth varies significantly over a long period of time. As discussed above, the primary sources of new debris are the asteroid belt and the Oort cloud.

The consequence of perpetual debris influx into Earth-crossing orbits is that the Earth will forever be in danger of hitting an asteroid or comet, and we will continually pass through meteor streams that endanger our space assets. Furthermore, the danger is not constant. It is generally accepted in the scientific community that, at least over long periods of time, the cometary impactor flux in the vicinity of Earth varies significantly.[44] Finally, there may be other short period variations that have not yet been identified. If so, then we may one day have to contend with a sudden influx of comets for which we are not prepared.

Notes

[1] David Morrison. Chairman of the Asteroid Detection Workshop (Spaceguard Survey), NASA Ames Research Center. "Statement Given House of Representatives, Committee on Science, Space and Technology, before the House Sub-Committee on Space. 24 March 1993. Note: Our selection of an upper bound size is notional only. Our analysis is not constrained by an upper limit. However, the Spaceguard survey shows that the number of Earth crossing asteroids greater than 10 km diameter is very small (see Chapter 6 for more discussion).

[2] Richard Greenberg and Michael C. Nolan, "Delivery of Asteroids and Meteorites to the Inner Solar System" *Asteroids II:* Ed. Richard P. Binzel, Tom Gehrels and Mildred Shapley Matthews (Tucson AZ: The University of Arizona Press, 1988), 786.

[3] John K. Davies, *Cosmic Impact* (New York: St Martin's Press, 1986), 66.

[4] J.G. Porter, *Comets and Meteor Streams, The International Astrophysics Series* (London: Chapman & Hall LTD., 1952), 8.

[5] M. Beech, Peter Brown and J. Jones, *The Potential Danger to Space Platforms from Meteor Storm Activity* (University of Western Ontario: Departments of Astronomy and Physics, London, Ontario, Canada), 5, 28 July 1994 (revised 26 October 1994).

[6] David Morrison (editor). *The Spaceguard Survey: Report of the NASA International Near-Earth-Object Detection Workshop.* NASA Office of Space Science and Applications, Solar System Exploration Division, Planetary Astronomy Program of Jet Propulsion Laboratory/California Institute of Technology, Pasadena California. 25 January 1992, Chapter 3, 16.

[7] Ibid.

[8] J. Kelly Beatty and David H. Levy, "Awaiting the Crash," *Sky & Telescope*: (January 1994), 42.

[9] J. Kelly Beatty and Stuart J. Goldman, "The Great Crash of 1994: A First Report," *Sky & Telescope*: (October 1994), 18.

[10] Morrison, Chapter 3, 16.

[11] Porter, 36.

[12] Davies, 65-66.

[13] Ibid., 46-49.

[14] Ibid., 44.

[15] Ibid., 50-51.

[16]Richard P. Binzel, "An Overview of the Asteroids" *Asteroids II:* Ed. Richard P. Binzel, Tom Gehrels and Mildred Shapley Matthews (Tucson AZ: The University of Arizona Press, 1988), 7.

[17] Ibid., 7-8.

[18] Clark R Chapman and others, "Asteroid Families: Physical Properties and Evolution" *Asteroids II:* Ed. Richard P. Binzel, Tom Gehrels and Mildred Shapley Matthews (Tucson AZ: The University of Arizona Press, 1988), 386-413.

[19] Binzel, "An Overview of the Asteroids," and J. Bell and others, "Asteroids: The Big Picture," *Asteroids II:* Ed. Richard P. Binzel, Tom Gehrels and Mildred Shapley Matthews (Tucson AZ: The University of Arizona Press, 1988), 941-942.

[20] Eugene M. Shoemaker, Carolyn S. Shoemaker and Ruth F. Wolfe, "Trojan Asteroids: Populations, Dynamical Structure and Origin of the L4 and L5 Swarms," *Asteroids II:* Ed. Richard P. Binzel, Tom Gehrels and Mildred Shapley Matthews (Tucson AZ: The University of Arizona Press, 1988), 487-489.

[21] Lucy-Ann McFadden, David J. Tholen and Glenn J. Veeder, "Physical Properties of Aten, Apollo and Amor Asteroids" *Asteroids II*: Eds. Richard P. Benzel, Tom Gehrels and Mildred Shapley Matthews (Tucson, AZ: The University of Arizona Press, 1989), 443.

[22] Morrison, Chapter 3, 15. Note: Recent studies indicate some AAAO's are thrown into the Sun through gravitational interaction with the planets; however, we consider this part of the gravitational ejection process because no matter where they go, they are ejected from the AAAO orbit.

[23] Clark R. Chapman and David Morrison, "Impacts on the Earth by Asteroids and Comets: Assessing the Hazard," *Nature* Vol 367: 35 (6 January 1994).

[24] Morrison, Chapter 3, 15. Note: Largest objects are 1627 Ivar and 1580 Betulia with 8 km diameters.

[25] McFadden and others, 443.

[26] Morrison, Chapter 3, 15.

[27] J.G. Hills and Peter J.T. Leonard, "Earth-crossing Asteroids: The Last Days Before Earth Impact," to be published in *Astronomical Journal* (January 1995), Draft Document dated 18 August 1994, 9. Note: Hills and Leonard believe the Atens are

underrepresented among Earth-crossing orbits; thus, estimates of the population are also probably too low.

[28] McFadden and others, 443.

[29] Ibid.

[30] Ibid.

[31] Peter Duffett-Smith, *Practical Astronomy With Your Calculator 3rd Edition.* (Cambridge: Cambridge University Press, 1988), 104.

[32] McFadden and others, 445-447.

[33] Peter Brown, International Meteor Organization, (University of Western Ontario, London Ontario Canada), Personal Correspondence. March 1995.

[34] O. Richard Norton, *Rocks From Space* (Missoula Montana: Mountain Press Publishing Company, 1994), 14.

[35] M. Beech and P. Brown, "Space-Platform Impact Probabilities-The Threat of the Leonids" *ESA Journal.* 18: 66 (1994).

[36] Ernst J. Opik, *Physics of Meteor Flight in the Atmosphere* (New York: Interscience Publishers, Inc., 1958), 105. and Norton, 47. Note: Opik indicates the maximum temperature is closer to 2000 deg F, while Norton (the newer source) gives 3000 deg F as the max.. We choose to use the newer value.

[37] Norton, 47 and 49-51.

[38] Norton, 49-51.

[39] Note: The relationship between cross-sectional area and mass is normally expressed in terms of a ballistic coefficient, which is simply the ratio of mass to cross-sectional area.

[40] Norton, 15.

[41] Porter, 77. Note: Small particles are slowed down by a combination of pressure of solar radiation and relativity effects, (now called the Poynting-Robertson effect), and to a lesser degree, the retarding force caused by the absorption and re-emission of heat.

[42] Richard Greenberg and Michael C. Nolan, "Delivery of Asteroids and Meteorites to the Inner Solar System" *Asteroids II:* Eds. Richard P. Binzel, Tom Gehrels and Mildred Shapley Matthews (Tucson AZ: The University of Arizona Press, 1988), 786 & 792-793.

[43] Beech and others, 3.

[44] Paul R. Weissman, "The Cometary Impactor Flux at the Earth" *Geological Society of America.* Special Paper 247: 172-174 (1990).

CHAPTER 3

A Brief Overview of Impact Theory

Impact theory, sometimes referred to as the Shiva Theory (after the Hindu god of destruction), postulates that Earth experienced many large impacts over the last 500 million years.[1] Further, at least some of these impacts upset Earth's ecological system so badly that entire species of plants and animals were driven to extinction. The most famous extinction in the fossil record is called the K/T event, named for the boundary between the Cretaceous and Tertiary periods during which the dinosaurs died out.[2] The K/T extinction was the first to be associated with extraterrestrial impacts.

The subject of dinosaurs seems an unlikely topic for a military research paper; however, their fate could hold a great deal of relevance for those who strive to maintain the security of our society, especially if we wish to learn the lessons of history. While debate continues to rage over the cause, duration and periodicity of the recorded extinctions, it is clear that many extinctions coincide with large impacts.[3] That is, large impact craters have been found, dated and determined to temporally correspond to known extinction events. This doesn't prove the impacts caused the extinctions but the coincidence is worth investigating. As we will show, there is strong evidence suggesting at least one impact (K/T) could have created severe global ecological damage, perhaps sufficient to cause extinctions. If such an event happened today, it would cause massive loss of life and probably lead to the collapse of our society.[4] For the first time in the history of the world, we have the knowledge and tools available to prevent such a catastrophe. If impacts of this magnitude can happen again, someone needs to give thought to defense and risk mitigation. Who is more capable of meeting this challenge than the US military?

In the following pages we present a brief summary of what has been learned from the geologic record regarding past asteroid and comet impacts on Earth as well as potential ties between these impacts and mass extinctions.

Mass Extinctions and the Geologic Record

Geologists and Paleontologists have recognized for many years that, according to the fossil record, various species of plants and animals have become extinct in relatively short periods of time (see Figure 3-1 and Figure 3-3). Most notable of these extinctions

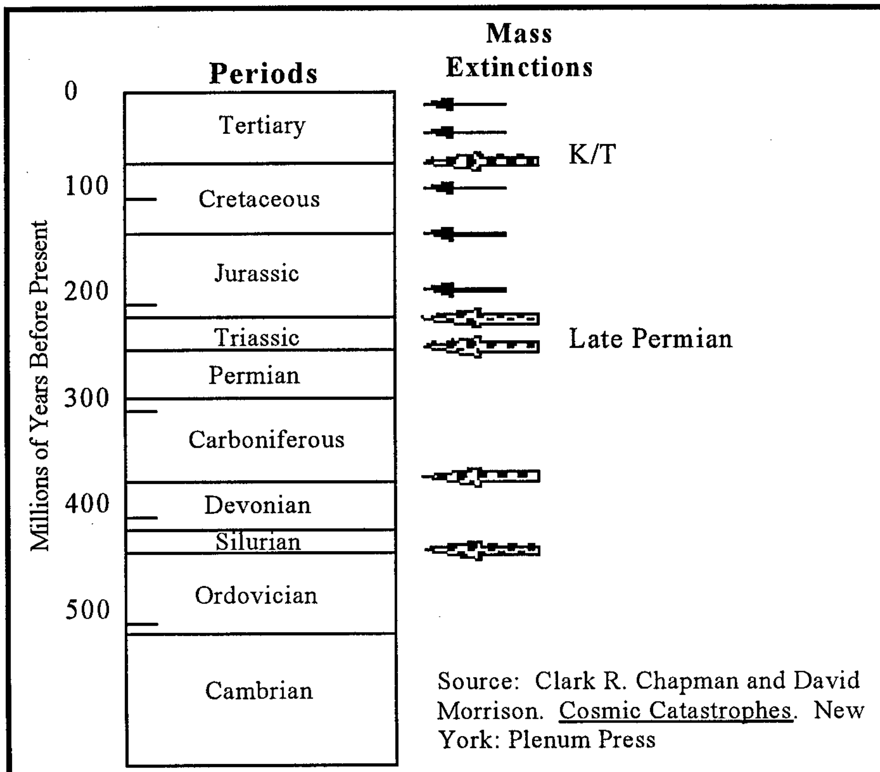
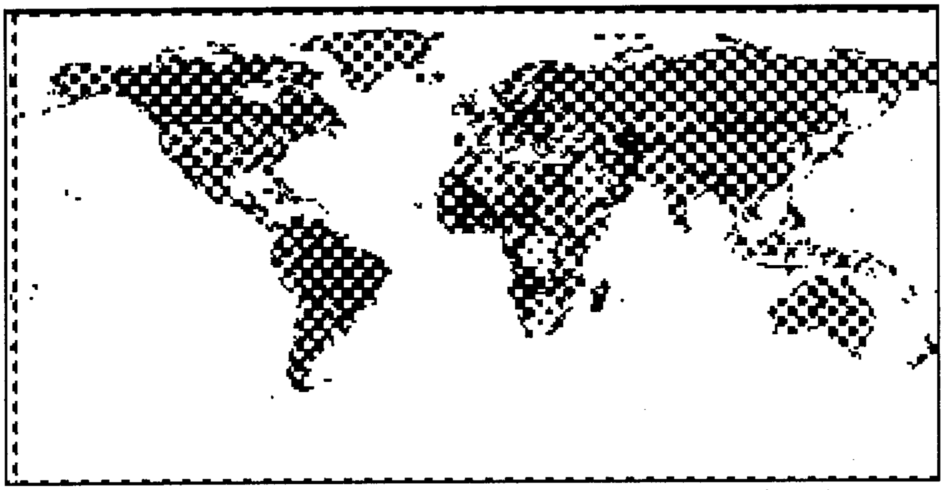


Figure 3-1. Mass Extinctions in the Geologic Record



Source: Sharpton and Grieve. "Perspective on the Evidence at the K/T Boundary," *Global Catastrophes in Earth History*, USGS Special Paper 247, 1990.

Figure 3-2. Dots Show Approximate Position of Known Impact Sites

are the dinosaurs. What happened to them? Thousands of dinosaur species existed during the Mesozoic era; yet at the transition between the Cretaceous and Tertiary periods, all of the dinosaurs died. What we don't know is how quickly they died out or what caused it in the first place. Of course, the main reason for striving to understand the extinction process is the hope that we may be able to avoid their fate. Will whatever killed the dinosaurs and countless other species happen again? The answer may lie in the rocks around us. The problem is learning to read them.

Evidence of Periodic or Recurring Extinctions

Analysis of the geologic record hints that mass extinctions on Earth may be cyclical.[5] The evidence is somewhat crude and subject to interpretation; thus scientists have been unable to agree on the cycle's period. In fact, some claim that there's no evidence of any periodicity.[6] Many people have conducted detailed studies of the fossil record in an attempt to find evidence that would lead them to the cause of the mass extinction, but there is still a long way to go before periodicity can be proven. Unfortunately, as far as we are concerned it may not make any difference who is right. Periodic or random, large impacts do occur. To the uninitiated, the arguments may be somewhat confusing; therefore this is probably worth further explanation.

The side that argues in favor of periodicity believes there is a bombardment cycle with a period of 26 to 32 million years. Within this group are many other factions that differ as to the cause of the period (more on this later).[7] As for those that argue against periodicity, most agree that large impacts have occurred many times in Earth's past, but they believe the bombardment is random. Whether periodic or not, the frequency of major impacts indicated by the geologic record and the theoretical analysis shown in Figure 3-4

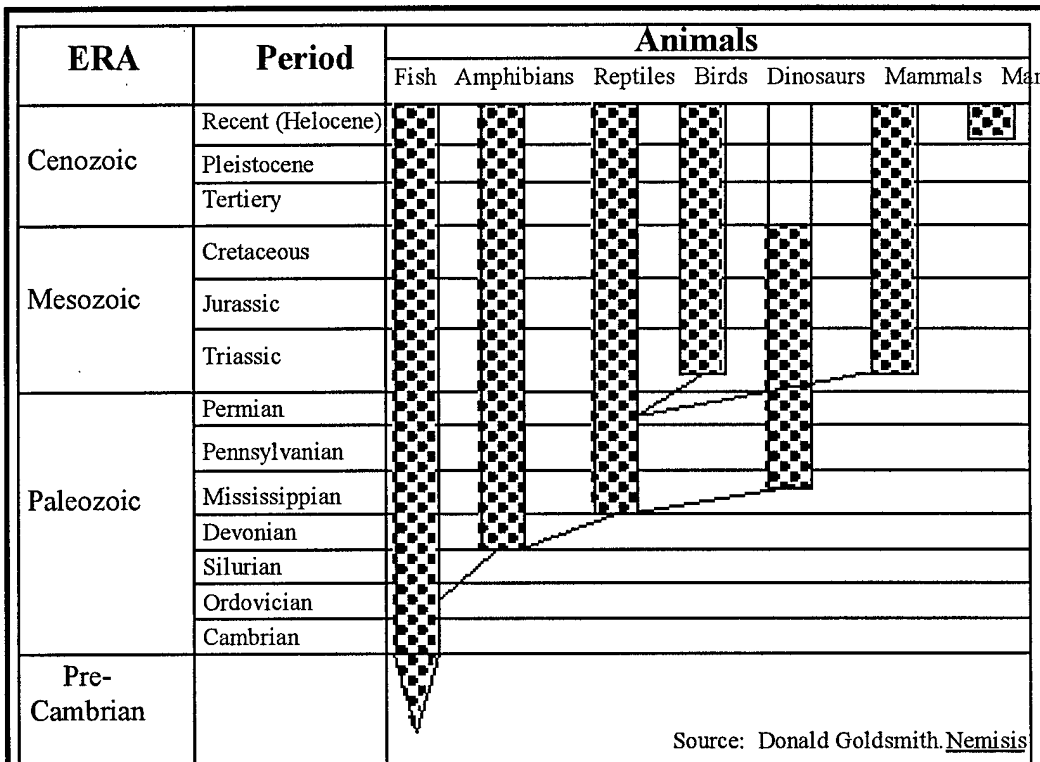


Figure 3-3. Approximate Time Scale of Life on Earth According to Fossil Record

gives us reason for concern. Everything we know about the natural debris system (Chapter 2) and Earth's past tells us impacts happen all too often. Both the periodic and random impact models show dramatic variations in the impact rate. The most favored theory explaining the variations says that Earth is occasionally subjected to comet showers wherein large numbers of comets enter the inner solar system, some of which hit Earth.

Comet Showers. The role of cometary impactors in creating mass extinctions on Earth has gained new momentum due to two relatively new pieces of information: introduction of the periodic comet storm theory and the discovery of impact signatures in the K/T layer of the geologic record by Alvarez (et al).

In 1981, J.G. Hills theorized the existence of *comet showers* wherein periodically large numbers of new comets would be injected into the planetary system resulting in a high rate of Earth impacts.[8] A study of the extinction record on Earth conducted by Michael Rampino suggests that 5 major and 19 minor mass extinctions have occurred over

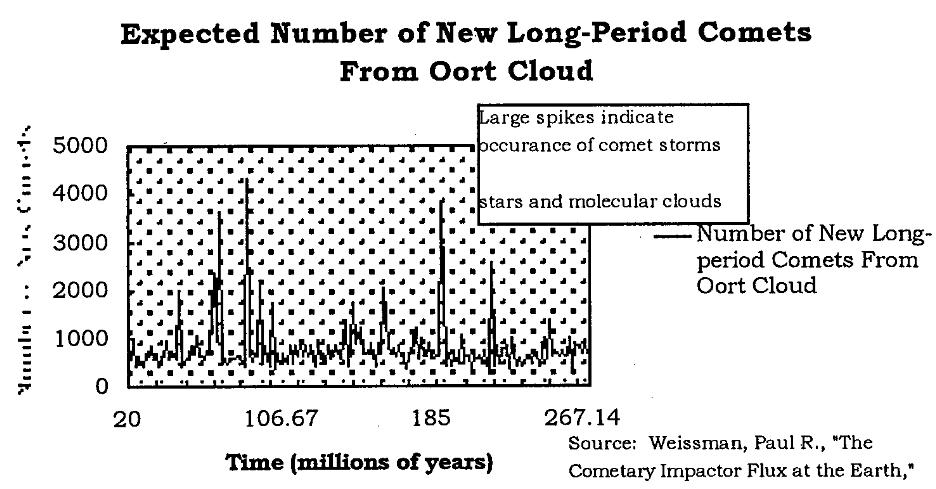


Figure 3-4. Theoretical Occurrence of Comet Storms as Calculated by Weissman Using Monte-Carlo Analysis of Random Star and Molecular Cloud Passages

the last 540 million years.[9] There's no direct evidence that these extinctions were caused by impacts, but there is an interesting correlation between impact signatures in the geologic record and six extinctions: the Pliocene (2.3 million years ago), the Late Eocene (26 million years ago), Late Cretaceous (65 million years ago), the Late Triassic (203 million years ago) and the Late Devonian (365 million years ago).[10] The mechanism responsible for comet showers has not been confirmed nor has the periodic comet shower theory. Paul Weissman in this 1990 paper came to the conclusion that there is no evidence of a periodic (26-32 million year cycle) influx of comets and there is no evidence of an increased influx at this time.[11] Instead, he believes intense, random showers occur as a result of close stellar passages (another star passing close to our solar system) stirring up debris in an inner layer of the Oort cloud. He estimates that ~17% of all existing Earth impact craters greater than 10 km in diameter were due to random cometary showers. On the other hand, the analysis performed by Raup and Sepkoski showing a strong correlation to a 26 million year period is hard to fault.[12]

The debate over the existence of periodic, intense comet showers continues. While it is true there is no exact correlation with the current interpretation of the extinction record as argued by Rampino, Raup and Sepkoski, there are some interesting facts that need further exploration. For example, Weissman points out that data suggests recent craters on the Moon appear to cluster in a non-random fashion at 10 $\pm$ 5 million years and 30 + 10 million years ago. Also, the ages of meteorites found on Earth tend to cluster at about the same times in the past.[13] In the absence of other explanations, these data indicate storms could have happened at those times. These inconsistencies seem to leave the question of periodic storms open for debate.

The main problems with the periodic comet storm theory seems to be: the lack of a credible mechanism to create the required period and inaccuracy of extinction dates making the period hard to determine.

Problems Determining Periodicity--Potential Mechanisms. Several theories have been suggested, all of which involve some as yet undetected force disturbing the Oort cloud and injecting comets into the inner solar system. Some of the leading theories are presented in following pages.

Nemesis. The Nemesis theory suggests that our solar system is actually a binary system with two suns: the one we see and another brown or red dwarf star that we can not see. As the theory goes, the dwarf star is orbiting in an elliptical, possibly highly inclined orbit with a period of about 26 million years. The question one must ask is: how could a second star go undiscovered for so long? The answer must be that it is too small to support nuclear fusion as the Sun does (does not emit light), and it must spend most of its time very far away. Knowing that the star is not luminous allows scientists to bound its mass. Another factor that helps determine its size is the fact that two large bodies in orbit will move around a common point in space proportional to their respective masses. Therefore, Nemesis would have to be small enough that it would only slightly disturb the Sun's motion with respect to the stars. Otherwise, we could detect Nemesis by watching the Sun's movement. No such movement has been observed. These two bits of information indicate Nemesis must have a mass between 0.005 and 0.12 solar masses.[14] The next question is whether an object with this mass could possess the required orbit. The orbit is dependent on the object's mass, and since Nemesis' orbit must be stable to have existed since the formation of the solar system (~4.5 billion years), scientists performed an analysis to see if a theoretically stable orbit could be found with a period of ~26 million years. The answer is yes; stable orbits fitting the required parameters do exist.[15] While interesting, it doesn't prove the existence of Nemesis. It simply fails to eliminate it as a possibility. Recent analysis of the Nemesis theory by critics of the periodicity argument have been unable to find any major flaws. If our sun had a brown dwarf companion, it would be, by no means, unusual. Many such systems are known to exist.[16]

Of all theories advanced so far, Nemesis is the most acceptable to critics but its existence is far from certain. Some scientists are working to change that. The Berkeley group calculated that the last periodic extinction was 12-14 million years ago; thus, if it exists, Nemesis should be near aphelion.[17] Though Nemesis would not emit light, it would emit heat; so it would be detectable using infrared sensors. Surveys conducted by the Extreme Ultraviolet Explorer Satellite, NASA's IRAS satellite and several ground based instruments have so far failed to find any sign of Nemesis.[18]

Passage Through the Galactic Plane. Our solar system occupies space in one of the Milky Way galaxy's spiral arms, about three fifths of the way out from the galactic center. As the Sun orbits the galactic center, it bobs up and down through the plane of the galactic disk every 33 million years. Besides stars and planets, the galactic disk contains a lot of dark matter in the form of molecular clouds. These clouds, some with masses exceeding 10 million times the mass of our sun, stay mostly within the plane of the disk.[19] This theory postulates that passage of our solar system through the plane puts us close to large molecular clouds who's gravity could disturb the Oort cloud enough to send cometary material in toward the planets.[20] Success of the theory hinges on the existence of these dense molecular clouds.

Some clouds are known to exist, the closest being in the direction of the constellation Orion about 1,600 light years distant.[21] However, Thaddeus and Chana of Columbia University believe the clouds are not bunched together tightly enough to influence the Oort cloud.[22] Stothers and Rampino of the Goddard Institute for Space Studies in New York point out there is a solution to the apparent deficiency.[23] If our sun traveled a bit farther above and below the galactic plane than presently thought, the molecular cloud theory could work.[24] Critics agree, but remain skeptical since there's no evidence to support the increased motion. If the theory should turn out to be correct, we may get confirmation soon since the solar system is now passing through the galactic plane. In fact, some have suggested that we may now be in the midst of a comet shower.[25] If so, the cratering rate record would support this model.

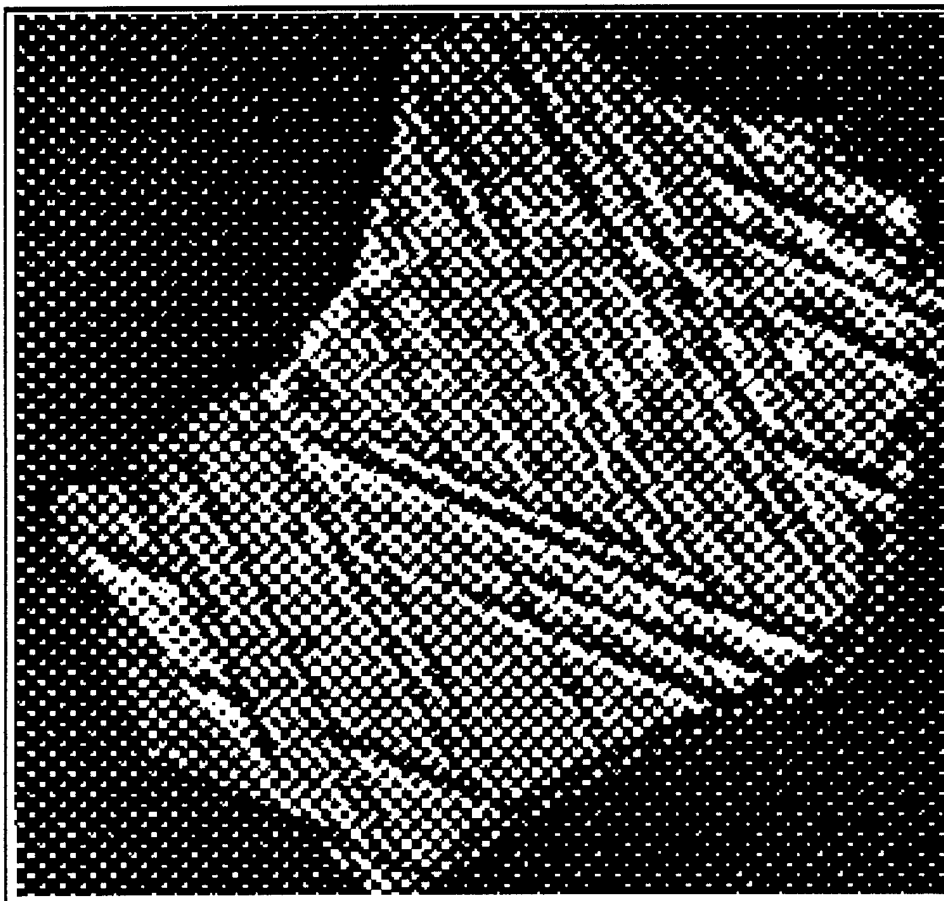
A Tenth Planet. Whitmire and Matese of the University of Southwestern Louisiana suggested that a tenth planet located 100-150 AU from the Sun and having a mass equal to 1 1/2 times that of Earth (called Planet X) could create a sufficient disturbance in the Oort cloud to dislodge comets and send them sunward.[26] In order to fit the 26 million year half-period suggested by the fossil record, the planet's orbit would have to be eccentric and highly inclined to the ecliptic, probably about 45°. The problem with Planet X is that it would have to be big enough to clear a gap in the Oort cloud of comets, while being small enough to avoid disturbing comets on either side of the gap. Otherwise, Planet X would be unable to produce a burst of comets (a storm). Instead, it would send a steady stream of comets in toward the Sun. According to Scott

Tremaine of the University of Toronto, Canadian Institute for Theoretical Astrophysics, there is no single mass that can meet both criteria.[27] It seems, at least for now, that the Planet X theory won't work.

Problems Determining Periodicity—Accuracy of Dating. The analysis determining the periodicity of extinctions performed by Raup and Sepkoski used extinction data for a subset of 3,500 marine animal families.[28] In past studies, the authors had found the data to be noisy in that it contained some amount of false information; therefore they filtered data they thought to be bad. In the end, their analysis found a strong correlation to a periodic extinction cycle of 26 million years, with especially severe extinctions every 250 million years. Unfortunately, even the authors admit that the resulting periods are highly dependent on the quality of the data.[29] Small inaccuracies in the dating of extinctions, inclusion of extinction data occurring from non-periodic effects, etcetera, will lead to significantly different results.[30] Even a small difference in the calculated period, say 30 vice the predicted 26 million years, will make it hard to determine the cause of the periodicity. Unfortunately, no one has found a way to solve the accuracy problem. Some hope to resolve the issue by finding a cause for periodic showers before proving showers are periodic (i.e., finding Nemesis). Admittedly, this is a backward approach, but as unlikely as it is, it may be more practical that trying to interpret the data.

Impact Signatures and the K/T Event. In the late 1970s, scientists found the first evidence linking the disappearance of the dinosaurs with a large impact; an impact that caused such severe changes in Earth's ecosystem that half of the genera living at that time died.[31] The evidence supporting a mass extinction at the end of the Cretaceous has, so far, proven irrefutable. Core samples taken from around the world show the same phenomena of mass death in a wide variety of species.[32] The evidence linking the extinctions to impact of a comet or asteroid is also very strong. Though it has been challenged many times over the last 15 years, the impact theory still stands as the best explanation for the evidence at hand. Most scientists now believe an impact is the only viable explanation.[33]

The impact connection was first presented by Luis Alvarez (et al.) in his 1980 paper "Extraterrestrial Cause for the Cretaceous-Tertiary Extinction."[34] Dr. Alvarez studied a clay layer bridging the K/T periods in the Umbrian Apennine Mountains, near Gubbio Italy.[35] The layer, now referred to as the Gubbio layer, contains an unusual concentration of Iridium. The Iridium content in the Gubbio layer was about 30 times higher than expected.[36] Subsequent samples of the K/T transition layer taken elsewhere have shown concentrations as much as 160 times normal.[37] This is a significant discovery because, as early as 1952, it was recognized that Earth's crust was deficient in Platinum metals (Platinum, Iridium, Osmium and Rhodium) due to their concentration in the Earth's core during planetary formation. This knowledge led Pettersson, Rotschi and later Goldschmidt, to suggest concentrations of these elements would be greater in meteoritic debris; thus deposits containing elevated levels of Platinum metals could be correlated to a large influx of extraterrestrial material (impact events).[38] Subsequent analysis of sedimentary layers on Earth as well as numerous meteorites has substantiated this hypothesis.[39] NSD often does contain higher levels of these metals. However, there are terrestrial mechanisms that could be responsible for the deposit of Platinum metals in various surface layers. For example, volcanoes could do the job.[40] So why are geologists



Sources: Bruce F. Bohor, U.S. Geological Survey. "Shocked Quartz and More"

Figure 3-5. Photo of a 0.75 mm Shocked Quartz Grain from K/T Boundary Clay at Teapot Dome, Wyoming. Clearly Shows Two Sets of Planar Deformations.

and paleontologists convinced the Iridium came from an impact? The answer lies in the recognition of other impact signatures in the same layer: shocked quartz and charcoal-soot.

Shocked quartz is a name used to describe quartz grains that have multiple sets of planar deformation features. These features have been produced in laboratories under pressures of 100-250 kb, and have been noted at nuclear detonation sites and known impact craters.[41] No other mechanism for the formation of shocked quartz has been identified; thus, it is considered the most reliable indicator of a large impact event.[42] Shocked quartz has been found in abundance in the K/T layer as well as in several other extinction layers.[43]

An appreciable amount of charcoal and soot has also been found at several sites within the K/T layer. Further, along with the carbon, other compounds (retene and carbon isotopes) indicative of forest fires were found.[44] The global distribution of these materials could only happen if the smoke plumes were intense enough to reach the stratosphere.[45] The only known explanation for the existence of such a large amount of globally distributed soot would be a wildfire covering a very large area, perhaps an entire continent.[46] In the next chapter we'll discuss the potential for impacts igniting forests. As you'll see, a large fire would be consistent with the impact of a large comet (not an asteroid).

The next logical question would be: if the K/T extinction was caused by a large impact (~10km diameter), where is the crater? Several sites have been postulated but the current favorite is just off the coast of Yucatan Mexico in the Chicxulub basin.[47] The underwater crater was initially located by a Mexican oil drilling operation and subsequently confirmed by a gravimetric survey and other studies. It seems clear that a crater definitely exists at Chicxulub; however the exact size is in dispute. Estimates range from 170 to 300 km diameter. It remains to be seen whether the crater can be conclusively linked to the K/T event. It seems to fit the bill but the debate is far from over.

Summary

The geologic record is the oldest history book in the world. In various ways, it documents the evolution and passing of countless life forms as well as many catastrophic changes in the ecosystem. While we are still learning to read it, some things are clear. Mass extinctions have happened several times in the past. At times, (K/T) as many as half the genera alive at the time of change died. Further, there is a growing body of evidence that suggests large impacts have occurred and will probably continue to occur. Whether they are connected to the extinctions is arguable but not critical to our discussion. Man need not be threatened with extinction in order for us to deem the potential effects unacceptable. As we will show, the impact of an object large enough to form the Chicxulub crater would kill many millions of people and endanger society regardless of where it hit.

Notes

[1] Donald Goldsmith, *Nemesis* (New York: Walker and Company, 1985), 8.

[2] V.L. Sharpton and Peter Ward (Editors), "Global Catastrophes in Earth History; An Interdisciplinary Conference on Impacts, Volcanism, and Mass Mortality" *Geological Society Special Paper 247* (Boulder CO: Geological Society of America) 301-563. Note: The K/T event is also sometimes referred to as the C/T event. The most accepted notation is either K/T or Cretaceous/Tertiary.

[3] V.L. Sharpton and R.A.F. Grieve, "Meteorite Impact, Cryptoexplosion and Shock Metamorphism; A Perspective on the Evidence at the K/T Boundary" in "Global Catastrophes in Earth History: An Interdisciplinary Conference on Impacts, Volcanism and Mass Mortality," Eds. Virgil L. Sharpton and Peter D. Ward, *Geological Society of America Special Paper 247*, (1990), 305-308.

[4] Clark Chapman and David Morrison, "Impacts On The Earth By Asteroids And Comets: Assessing The Hazard," *Nature*. 367: 34-36 (6 January 1994).

[5] Michael R. Rampino and Richard B. Stothers, "Terrestrial Mass Extinctions, Cometary Impacts and the Sun's Motions Perpendicular to the Galactic Plane," *Nature.* 308: (1984), 709-720.

[6] Paul R. Weissman, "Cratering Theories Bombarded," *Nature. 314*: 17-18 (1985).

[7] Michael R. Rampino and Bruce M. Haggerty, "The Shiva Hypothesis: Impact Crises,Mass Extinctions, and the Galaxy," *Earth, Moon & Planets. Special Volume*: Pre-publication copy, pages 11-12 (3 March 1995) and Paul R. Weissman, "Cratering Theories Bombarded" and Weissman. "The Cometary Impactor Flux at the Earth." Note: Discussions in these papers highlight the two sides of the argument. These are representative articles only. Other authors have expressed other variations on the theme.

[8] J.G. Hills, "Comet Showers and the Steady-State Infall of Comets From the Oort Cloud," *Astronomical Journal, Vol 86*: 1730-1740, (1981).

[9] Michael R. Rampino, "Impact Crises and the Mass Extinctions: Towards a General Theory" *Presentation at the American Geophysical Union Fall Meeting* Moscone Center, San Francisco, CA. 7 December 1994.

[10] Ibid.

[11] Weissman. "The Cometary Impactor Flux at the Earth," 171-180.

[12] David M. Raup and J. John Sepkoski Jr., "Periodicity of Extinctions in the Geologic Past," *Proceedings of the National Academy of Sciences, USA,* Vol 81: (February 1984) 801-805.

[13] Weissman, 171-180.

[14] Goldsmith.,134-144.

[15] Ibid., 136.

[16] Richard A. Kerr, "Periodic Extinctions and Impacts Challenged," *Science* vol 227:, 1452,(22 March 1985).

[17] Marc Davis, Piet Hut and Richard A. Muller, "Extinction of Species by Periodic Comet Showers," *Nature* Vol 308:, 715-717, (19 April 1984).

[18] S. Perlmutter, R.A. Muller, C.R. Pennypacker, C.K. Smith, L.P. Wang, S. White and H.S. Yang, "A Search for Nemesis; Current Status and Review of Theory" in "Global Catastrophes in Earth History: An Interdisciplinary Conference on Impacts, Volcanism and Mass Mortality," Eds. Virgil L. Sharpton and Peter D. Ward. *Geological Society of America Special Paper 247*, (1990), 87-91. and Weissman, "Cratering Theories Bombarded,"18.

[19] Goldsmith, 122.

[20] Richard D. Schwartz and Phillip B. James, "Periodic Mass Extinctions and the Sun's Oscillation About the Galactic Plane," *Nature* Vol 308: 712-713, (19 April 1984).

[21] Goldsmith, 122.

[22] Kerr, 1451.

[23] Michael Rampino and Richard B. Stothers, "Terrestrial Mass Extinctions, Cometary Impacts and the Sun's Motion Perpendicular to the Galactic Plane," *Nature* Vol 308: 709-712, (19 April 1984).

[24] Kerr, 1451-1452.

[25] Weissman, "Cratering Theories Bombarded,"18.

[26] Daniel P. Whitmire and Albert A. Jackson IV, "Are Periodic Mass Extinctions Driven By a Distant Solar Companion?," *Nature* Vol 308: 713-715, (19 April 1984).

[27] Kerr, 1452.

[28] Raup and Sepkoski, 801.

[29] Ibid., 801, 805.

[30] Goldsmith, 61-64.

[31] Luis Alvarez, Walter Alverez, Frank Asaro and Helen V. Michel, "Extraterrestrial Cause for the Cretaceous-Tertiary Extinction," *Science* Vol 208: 1095, (6 June 1980) and Goldsmith, *Nemesis:* 8.

[32] Sharpton and Grieve, 301-305.

[33] Ibid.,301.

[34] Alvarez and others, 1095-1108.

[35] Ibid., 1096.

[36] Ibid., 1095.

[37] Ibid., 1095.

[38] V.M. Goldschmidt, *Geochemistry* (New York: Oxford University Press, 1954).

[39] Alvarez and others, 1096.

[40] D.L. Finnegan, T.L. Miller and W.H. Zoller, "Iridium and Other Trace-metal Enrichments From Hawaiian Volcanoes" in "Global Catastrophes in Earth History: An Interdisciplinary Conference on Impacts, Volcanism and Mass Mortality," Eds. Virgil L. Sharpton and Peter D. Ward. *Geological Society of America Special Paper 247:* 111 (1990).

[41] Bruce F. Bohor, "Shocked Quartz and More; Impact Signatures in Cretaceous/Tertiary Boundary Clays" in "Global Catastrophes in Earth History: An Interdisciplinary Conference on Impacts, Volcanism and Mass Mortality," Eds. Virgil L. Sharpton and Peter D. Ward. *Geological Society of America Special Paper 247:* 335-341, (1990).

[42] Ibid.

[43] Ibid.

[44] Wendy S. Wolbach, Iain Gilmour and Edward Anders, "Major Wildfires at the Cretaceous/Tertiary Boundary" in "Global Catastrophes in Earth History: An Interdisciplinary Conference on Impacts, Volcanism and Mass Mortality," Eds. Virgil L. Sharpton and Peter D. Ward. *Geological Society of America Special Paper 247:* 391-396, (1990).

[45] Ibid., 394.

[46] Ibid., 395-398.

[47] V.L. Sharpton and L.E. Marin, "How big is the Chicxulub Impact Basin, Yucatan, Mexico?" *Presentation at the American Geophysical Union Fall Meeting.* Moscone Center, San Francisco, CA. 7 December 1994.

CHAPTER 4

Natural Space Debris Effects

Natural debris effects are determined by the energy content of the potential impactor and the manner of energy dissipation during impact. As you will see in the following pages, asteroids and comets are essentially kinetic energy *weapons,* meaning that they inflict damage much the same way as any projectile. However, because of the extremely high levels of energy involved and the variety of environments this energy may be transferred to, the effects are much more complicated and varied than one might expect. To begin, lets start with a discussion of the energy available at impact.

Impact Energy

The destructive potential of an object is directly related to the energy it possesses at impact, though as we will discuss in following sections, the actual damage done will depend on many other factors. Objects colliding with the Earth will strike with very high kinetic energy. Kinetic energy is defined simply as the energy a body with mass possesses by virtue of its being in motion. The destructive effect is much like that of a bullet fired from a gun. From basic physics we calculate kinetic energy for a non-rotating body as,

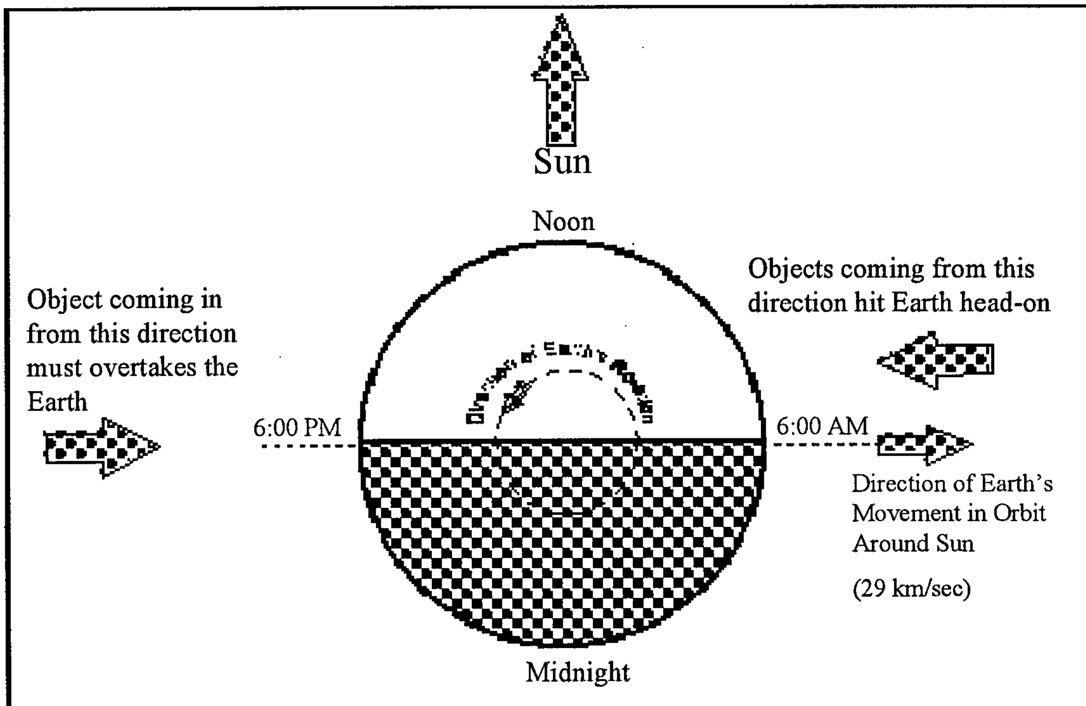
$$K.E. = 1/2 \cdot 10^6 mV^2 \qquad (5)$$

Where

K.E. = energy, joules
m = mass, kg
V = impact velocity, km/sec

Before proceeding it is important to note that impact velocity, V is measured *relative* to the Earth.[1] To determine the impact velocity you must know the object's orbital velocity at the point (in its orbit) of projected impact, the Earth's velocity at the same point, the impact geometry and the acceleration that will be produced by the Earth's gravity. Accounting for acceleration due to Earth's gravity (see endnote), the impact velocity will be,

$$V_{impact} \cong \sqrt{11.2^2 + V^2_{\Delta Earth}} \tag{6}$$



Source: Richard O. Norton. ***Rocks From Space.***

Figure 4-1. Impact Geometry

where $V_{\Delta Earth}$ (km/sec) is the difference between the Earth and object's orbital velocities.[2] The orbital velocity of the object and the Earth are determined by their respective orbits. Once the object's orbit elements and position are determined through observation, the velocity with respect to the Sun is given by

$$V = \sqrt{1.32712438 \cdot 10^{11}\left(\frac{2}{r} - \frac{1}{a}\right)} \tag{7}$$

where r and a are defined as in Equation (2) for the object's position in orbit at the time of impact.[3] Units for r and a are kilometers for this equation and V will be given in km/sec. Figure 4-1 and Figure 4-2 illustrate the basic impact geometry. For objects in prograde orbits (those orbiting the Sun in the same direction as the Earth), a portion of their velocity will be canceled out by the Earth's motion, resulting in lower impact velocities. On the other hand, those in retrograde orbits, where their velocities are added to that of

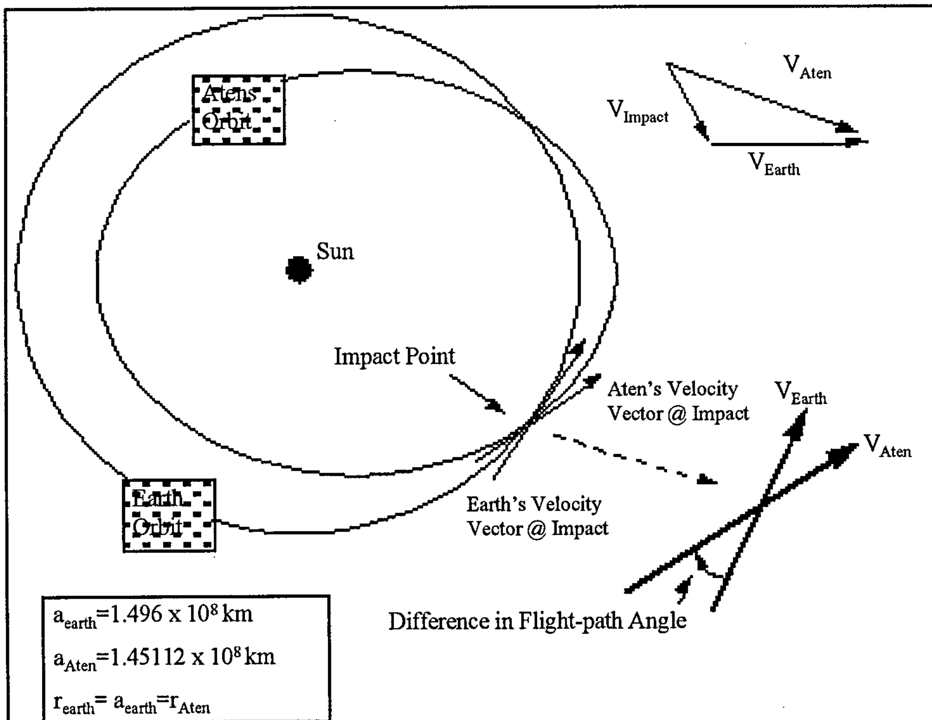


Figure 4-2. Aten Asteroid-Earth Impact Example

Earth, will generally have much higher impact velocities. The figures show the geometry in an overly simplified, two dimensional fashion for clarity. They do not convey the full range of possible impact angles nor do they allow for orbit inclination and differences in flight path angles at impact. Objects (especially comets) could conceivably hit from any angle; not just from behind or head-on. Even though the actual geometry will be more complex, this simple model allows us to determine a rough approximation of the impact velocity.

As an example, let us estimate the impact velocity of asteroid Aten discussed in Chapter 2, Table 2-4 and Figure 2-10. For Aten to hit Earth, it must be at a point in its orbit where $r = 1$ AU = 149.6 x 10^6 km since that is Earth's distance from the Sun if we assume Earth's orbit is circular (a reasonable assumption since the actual eccentricity is 0.0167). Aten's velocity from Equation (7) is 29.32 km/sec, and because it is in a prograde orbit, a portion of its velocity will be canceled out by Earth's motion (see Equations 8-10). Aten's orbit is inclined 18.9° with respect to Earth's; thus the relative velocity (V_{AEarth}, Equation 10) must be found by vector addition.

$$\vec{V}_{Earth} = 29.8\hat{X} \tag{8}$$

and,

$$\vec{V}_{Aten} = 29.32\cos(i)\hat{X} - 29.32\sin(i)\hat{Z} \tag{9}$$

where i = inclination = 18.9°.

$$\left|\vec{V}_{Earth} - \vec{V}_{Aten}\right| = \sqrt{2.06^2 + 9.5^2} = 9.72 \text{ km/sec} \tag{10}$$

Earth's orbital velocity is 29.8 km/sec, so just before acceleration by Earth's gravity the relative velocity from Equation (10) is 9.72 km/sec. Using Equation (6) we find the impact velocity accounting for the acceleration would be,

$$V_{impact} = \sqrt{11.2^2 + 9.72^2} = 14.83 \text{km/sec} \quad (6)$$

In this example, ignoring the actual intersecting flight path angles causes the estimated impact velocity to be too low. Shoemaker (et al) shows the actual impact velocity to be 16 km/sec, but our answer is close enough for our purposes.[4] The reader should note that a 14.83 km/sec impact velocity is very low relative to many other asteroids because the Atens asteroids are in orbits very similar to that of Earth.[5] Their orbits are similar, so their orbital velocities are never very different. This would not necessarily be the case for asteroids in the other families or for comets. Their impact velocities could be much greater.

Given that we have estimated the impact velocity for Aten we can continue the example to estimate its kinetic energy at impact. We have the impact velocity and now need to determine the mass. From observations, Aten's diameter is approximately 0.9 km.[6] Its composition is not available; however, objects in the Atens family have been analyzed and have surface compositions ranging from the common stony type to the differentiated metal variety.[7] The respective densities would be 3,000 kg / m^3 and 7,200 kg / m^3. More than likely, Aten is largely stone; therefore, we will assume, $\rho = 3{,}000$ kg / m^3. Mass, *m*, is defined as,

$$m = \rho \cdot Volume_{sphere} \quad (11)$$

Many asteroids are not spherical but for simplicity we assume Aten is a sphere with volume,

$$Volume_{Aten} = 1 / 6 \pi D^3 \tag{12}$$

where D is Aten's diameter in meters. Using Equations (11) and (12) we find that the mass of Aten is about 1.15 X 10^{12} kg. Restating Equation (5),

$$K.E. = 1/2 \cdot 10^6 m V_{impact}^2 \tag{5}$$

we can now calculate the kinetic energy, K.E. = 1.3 X 10^{20} Joules. One Megaton of TNT is generally considered equal to 4.2 X 10^{15} Joules; therefore, the impact of Aten would release energy equal to more than 30,000 megatons of TNT or 1,500, 20 megaton bombs; more than enough to create global catastrophe.[8]

As you can see from this simple example, the energy released by impact is tremendous. With the possible exception of our density estimate, all of our calculations were conservative in that they yield a lower kinetic energy than an object such as Aten would actually possess.

Impact Effects

Using only a few simple calculations we have shown that the destructive potential of natural space debris is considerable. Even so, the destructive power is so far beyond human experience that it's hard to comprehend. Relating a large impact to a nuclear detonation is the best analogy available in terms of energy but, short of full-scale nuclear war, even that pales in comparison. Large impact events are rare when measured against a lifetime; thus, none of us has had the misfortune of experiencing one. However, there is one modern impact we can study: Tunguska.

Tunguska. On 8 June 1908 at a few minutes past 7 a.m., a pale blue fireball appeared in the southern sky moving rapidly northward over Siberia leaving a thick trail of dust suspended in the air.[9] At 7:14 a.m., the object exploded about 6 km above the Siberian forest creating a column of flame and smoke more than 20 km high. The impact site was sparsely populated but because of the massive destruction there are reports of a few deaths. Several eyewitness accounts have been recorded over the years (most made many years after the event, having been passed down verbally). These accounts go far to convey the ferocity of an asteroid impact. An unnamed Siberian farmer reported,

> When I sat down to have my breakfast beside my plough, I heard sudden bangs, as if from gunfire. My horse fell to its knees. From the north side above the forest a flame shot up. Then I saw that the fir forest had been bent over by the wind, and I thought of a hurricane. I seized hold of my plough with both hands so that it would not be carried away. The wind was so strong it carried soil from the surface of the ground, and then the hurricane drove a wall of water up the Angora.[10]

Eyewitness accounts as gathered and reported by Roy A. Gallant in 1994 include,[11]

> The sky has split apart. When the fire appeared it became so hot that one couldn't stand it. S. Semenov's shirt was as if set on fire. When the loud explosion was heard he was hurled to the ground across a distance of three sazhens (an old Russian length of measure of about 2 meters).
> M. Kosolapov said that he felt 'as if someone had burned my ears.' A hot wind blew past us. The ground and all the huts trembled, causing the sod packing to fall from the ceilings. The glass was blasted out of the window frames.
>
> Akulina was thrown up into the air as if flying. The old man Vasiliy, son of Okhchen, was thrown into the air as he slept. He flew for 12 meters until he was hurled into a tree, which broke his arm so that the bone was sticking out. He soon died. In a state of shock Ivan Yerineev lost his tongue. The hunting dogs disappeared.
>
> God in his displeasure with us tore the sky apart. In the nomad camp of Ivan Dzhenkoul all 200 reindeer in a single instant were incinerated. All of his stores of furs, food, and other goods were likewise destroyed.

Because the impact area was so remote, the explosion went largely unnoticed by most of the world except for a few scientific monitoring stations. The blastwave was so powerful that it registered on a recording barometer at Potsdam near Berlin at 5:54 a.m. as it spread outwards from the explosion site.[12] The same wave registered again in Potsdam the following day having circumnavigated the globe reaching Potsdam 25 hours later. Also, Russian scientists at the Irkutsk Magnetic and Meteorological Station 893 miles away detected seismic waves beginning at 7:18 a.m. that continued for over an hour. The following night brought an unusual, bright light display which continued for several weeks. Eyewitnesses remembered,

> It was exceptionally bright in Europe and western Siberia, and in the south of Russia it was reportedly possible to read a newspaper at midnight without the help of artificial lights.[13]

The precise nature of the object that caused the destruction of over 2,000 square kilometers of Siberian forest is still debated. Investigation of the impact site showed that the object did not create a crater in the Earth and no pieces of the object larger than dust have ever been found.[14] For a time, it was thought that it must have been a comet; thus, nothing larger than dust would be expected since the object (made mostly of dust and ice) would be destroyed before it could hit the ground. The comet's tail could also explain the strange lights in the night sky. Subsequent work by Christopher Chyba showed that a comet could not penetrate deeply enough to cause the damage noted. His work indicates the most likely culprit was a stony asteroid about the size of a football field.[15] Others, such as Hills and Goda, believe that an object around 80 meters in diameter would have been sufficient.[16] The asteroid traveling at about Mach 45 created a shock wave in front of it as it entered the atmosphere (Figure 4-4). This shock wave resulted in a pressure gradient across the asteroid (essentially vacuum behind and many atmospheres in front). When the gradient exceeded the strength of the object's material (stone in this case) the object shattered and exploded.[17] Destruction of the object didn't end the event. The shock wave continued to propagate toward the ground. The entry and detonation of the object (probably a comet) heated the air to several thousand degrees. It was the superheated air and shock wave that slammed into the Siberian forest, flattening and burning trees for hundreds of kilometers. The effect is very similar to that of a nuclear detonation (without the radiation).

The Tunguska region was isolated and largely unpopulated. If the object had hit in a densely populated area, or in a coastal area the damage would have been much greater. As the world becomes more populated, the potential for death and destruction from such events is increasing. As we'll discuss later, Tunguska sized events (~12 Megatons) are expected to happen about once every one to two hundred years. Tunguska happened 87 years ago this June. Statistically, we could be due for another assault very soon.

The value of the Tunguska example is that it not only shows us how much damage a small asteroid or comet can do, it also gives us a case study from which to learn how the damage is done. Impact effects can be divided into two groups: direct and indirect. As we'll discuss, most damage will be done by indirect effects.

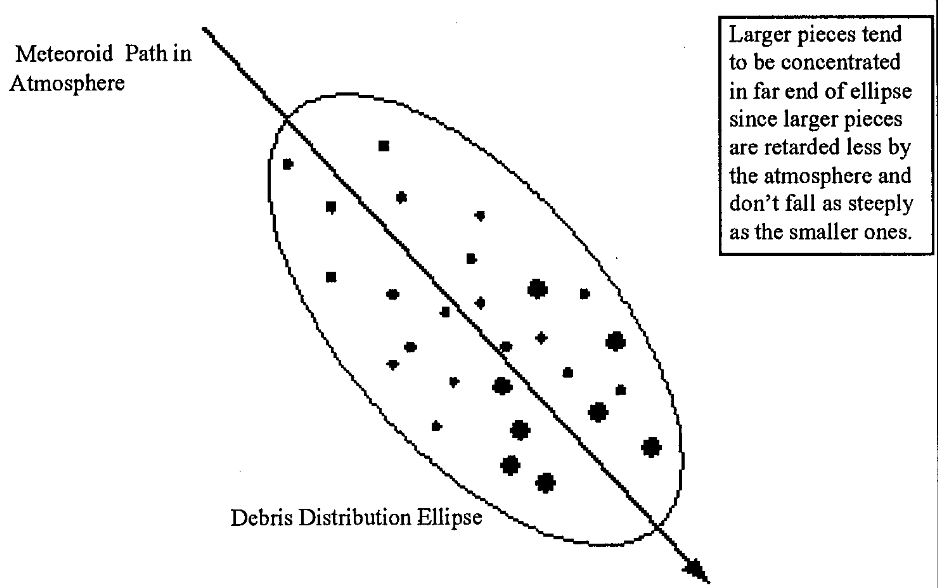
Direct Impact Effects. Direct impact effects are those created by the object physically slamming into the surface (creating craters). This can happen as a result of an object hitting in one piece or could result from a shower of smaller debris if the object breaks apart. Thus, a single asteroid could produce multiple direct impact sites or an enlarged impact zone where a swarm of debris hits the Earth.

While direct effects are important, especially if the crater's footprint encompasses a populated area, it's not the main cause of destruction. Depending on the nature of the impactor, its kinetic energy and where it hits, other indirect effects may be more important.

Indirect Impact Effects. As shown by the Tunguska impact, the object doesn't have to actually hit the Earth's surface to cause damage. Depending on where and with what energy an object hits the Earth, there are several serious indirect effects that must be considered when attempting to understand the damage such an event could cause. Blast waves (overpressure), tsunamis, earthquakes, global impact winter, fires, hypercanes and EMF pulses are among the more significant and well studied effects that must be addressed.

Blast. The breakup of an object in the atmosphere is called *fragmentation.* Fragmentation is a common occurrence in meteors as well as larger objects like Tunguska.[18] As the shock wave (pressure gradient) across the object exceeds the strength of the material, the central body will shatter creating many smaller pieces.
Figure 4-3 shows the typical distribution of debris for a meteoroid after fragmentation.

Besides scattering debris or creating multiple impact sites, fragmentation greatly increases the aerodynamic cross-section. Before the object fragments, a shock wave exists with full ram pressure at the stagnation point in front of the object, to near vacuum at the edges of the wave (and behind the object). After fragmentation, the shock wave will continue to see the swarm of pieces as a single object until the radius of the swarm is equal to about two times the object's initial (before fragmentation) radius.[19] Once that is exceeded, individual objects will form their own shock waves and either descend independently or fragment further. The increase in aerodynamic cross-section without an increase in mass results in a significant and rapid increase in aerodynamic braking. That means more of the object's energy will be dissipated in the atmosphere than would be true for an object that did not fragment. Hills and Goda found that for an asteroid with a typical impact velocity of 22 km/sec, the atmosphere will absorb more than half of the energy for stony objects with diameters less than 220 meters and for iron objects of less than 80 meters.[20] At first glance, this sounds like a good thing. After all, it's the atmosphere that protects us from the smaller objects by absorbing and dissipating their kinetic energy. The less energy an object has when it reaches the surface, the smaller the crater. As indicated by Equation (14), the diameter of the crater (D_{crater}, km) is directly influenced by the amount of kinetic energy remaining when the object hits the surface



Source: Rosks From Space, O. Richard Norton

Figure 4-3. Typical Meteorite Debris Field

($K.E._{impact, surface}$ in megatons).[21]

$$K.E._{impact,surface} = K.E._{total} - K.E._{absorbed,atmosph.} \quad (13)$$

where,

$K.E._{total}$ is given by Equation (5)
$K.E._{absorbed, atmopsh}$ is the energy absorbed by the atmosphere before impact
$K.E._{impact, surface}$ is the energy remaining at impact

and

$$D_{crater} = \left(\frac{K.E._{impact,surface}}{0.952 Mtons} \right)^{1/3} \quad (14)$$

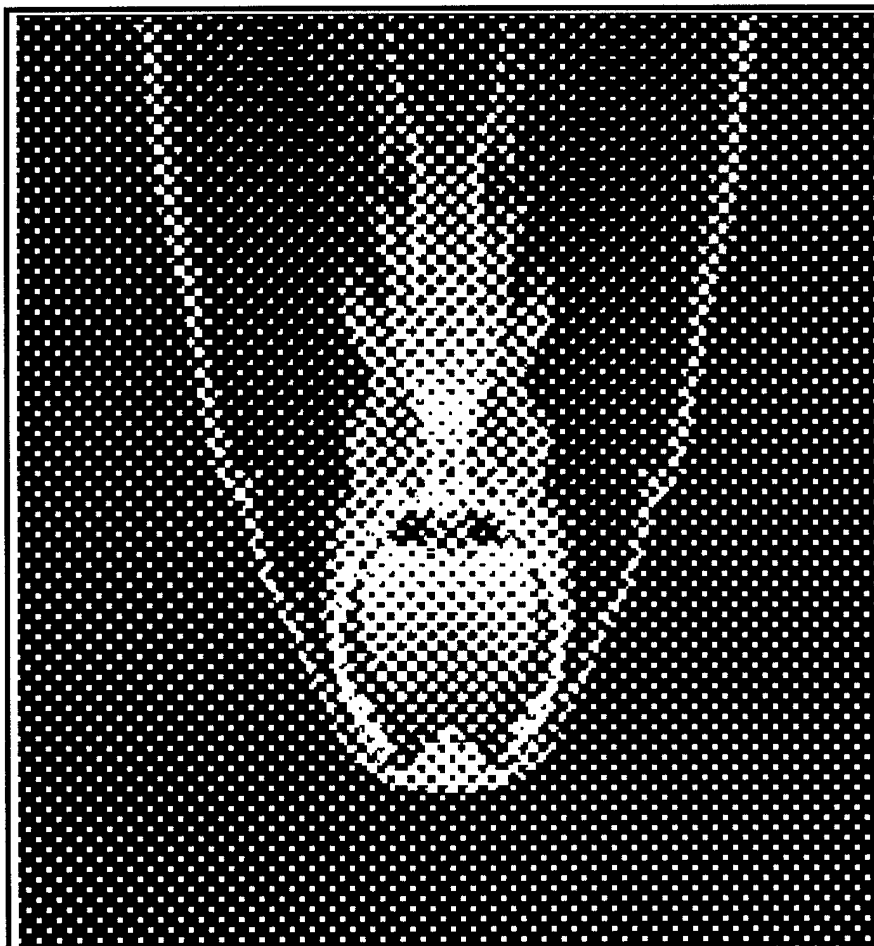
However, while the size of the crater decreases due to atmospheric energy absorption, the size of the blast damage area increases (due to the shock wave).[22]

As seen in the Tunguska impact, even if $K.E._{impact, surface}$ goes to zero, meaning all the energy has been absorbed by the atmosphere, considerable damage will still occur. The damage results when the shock wave hits the ground creating an overpressure pulse equal to 4 psi or greater.[23] Such a pulse is capable of knocking down trees and destroying most buildings. The maximum diameter of the blast zone ($D_{Blast Zone}$ in km) is given by Equation (15).[24]

$$D_{BlastZone} = 15 \left(\frac{K.E._{absorbed,atmosph}}{Mtons} \right)^{1/3} \quad (15)$$

Where $K.E._{absorbed, atmosph}$ is in megatons. The important thing to note is that, as Hills and Goda point out, the diameter of the maximum zone of destruction created by the blast wave could be as much as three times greater than it would have been if all of the energy had been expended by striking the Earth. In other words, for objects greater than ~56 meters in diameter, the atmosphere is no longer able to effectively protect the surface. In fact, it amplifies the destructive effect of the impactor.

It is worth noting that for large impactors (those with total kinetic energies above 1 giga-ton) the blast would be large enough to blow off most of the atmosphere within the line-of-sight.[25] Further, as the air rushed in after the blast to fill the void, additional pressure pulses would be produced. Obviously, the resulting destruction would be



Source: Dr. Mordecai-Mac-Low, NASA Ames Research Center.

Figure 4-4. Simulation of a Bolide Passing Through the Atmosphere

devastating. Surprisingly, the diameter required to cause such destruction is relatively low. For a typical stony asteroid moving at 20 km/sec only a 240 meter diameter is required. Just three times larger than the Tunguska asteroid.

Tsunamis. A tsunami is a wave produced by a large disturbance at sea: essentially a tidal wave. Tsunamis and tidal waves can be produced by *any* large disturbance in the ocean. Volcanic activity and earthquakes are the most common causes; however a large asteroid impact in the ocean would also generate a tsunami.

Unlike our previous discussion of blast effects, in order for an asteroid to create a tsunami it must physically hit the water. Therefore, the energy absorbed by the atmosphere must be less than the total energy of the object. On land, the amount of kinetic energy remaining after passage through the atmosphere determined the size of the crater. When the impact is in water, this energy will instead displace water creating deep ocean waves. The effect is much like the ripples you see when you toss a rock into a pond. As the asteroid hits the water it pushes the water out of the way creating the first giant wave. As the asteroid passes, water rushes in behind to fill the void. The sudden inrush of water creates additional waves. Thus, a series of deep water waves are produced, expanding outward at several hundred km/hr from the impact site.

The height of an average tsunami is ~40 times higher than the deep water wave that produced it.[26] Hills and Goda calculated the height of the deep water wave that would be created by the impact of a stony asteroid 1,000 km away. A typical asteroid moving at 22 km/sec with a diameter of 240 meters would create a wave about 5 meters high. If an average tsunami is 40 times higher than the deep water wave, we would expect a tsunami of about 200 meters high.

An asteroid with a diameter of 200 meters or greater hitting anywhere in the Atlantic (independent of its composition) would produce tsunamis over 200 meters in height that would hammer the European and American Atlantic coasts, eventually traveling all the way around the world's oceans.[27] Smaller, but still significant waves would continue to hammer the coasts every two minutes or so until the wave motion damped out. This periodic action would tend to force the water farther inland than a single tidal wave, resulting is extreme inland flooding.[28] If the wave hit the coast near a river, it would propagate up the river flooding everything in its path. For example, if a large asteroid hit in the Gulf of Mexico, the resulting tidal wave would travel all the way up the Mississippi river (though the height of the wave would not remain constant). In regard to the Atlantic coast, Hills and Goda offer an interesting observation:

> These numbers are very disturbing to the authors. Perhaps the legendary tale of the lost civilization of Atlantis, which was said to be on the Atlantic coast and was engulfed suddenly by the ocean was due to such a tidal wave. It is somewhat surprising that there were no widespread coastal settlements along the Atlantic until after 800 AD when the Vikings settled and fortified numerous towns along the Atlantic coast. The niche that they exploited may have been opened by a previous disaster whose institutional memory had been lost.[29]

Because of the large populations that live along coastal areas, tsunamis may be the most destructive impact effect of all.

Earthquakes. In order to produce an earthquake, the object must physically strike the Earth's surface. If the impact is in water, the object must hit the ocean floor. In other words, a crater must be produced. That means that the initial diameter of the object must be greater than ~200 meters before earthquakes become a significant concern.[30] Most of the impact energy will go into forming the crater; thus very little goes into the quake. Asteroids with diameters much less than 200 meters give up significant portions of their energy to the atmosphere; so the resulting quakes will be small.

For stony asteroids with diameters greater than 200 meters, the Richter scale magnitude (M) of the resulting earthquake is given by Hills and Goda as,

$$M = 7.9 + 0.7\left[3\log_{10}\left(\frac{R}{100meters}\right) + 2\log_{10}\left(\frac{V}{20km/\sec}\right) + \log_{10}\left(\frac{\rho}{3g/cm^3}\right)\right] \quad (16)$$

where,

R is object's initial radius in meters
V is the object's velocity in km/sec. When R>100 the atmosphere slows the object only slightly thus the impact velocity is approximately equal to the initial velocity
ρ is the material density of the object in g/cm^3. For stony asteroids ρ=3 g/cm^3

Though somewhat long, this equation provides a simple means to estimate the magnitude of an earthquake resulting from impact. Since $\log_{10}(1) = 0$ we can see that a 100 meter radius, stony asteroid traveling at 20 km/sec will cause an earthquake of 7.9 on the Richter scale. The same object with a 120 meter radius would cause an 8.1 quake. The equation takes into account only the quake induced by the impact energy. It does not account for the release of energy stored in the rocks below or near the impact site. If the object were to strike an area that commonly experiences earthquakes (near an existing fault line) it's possible that a large impact induced quake could trigger a *normal* quake.

Global Impact Winter. Most people living today are familiar with the concept of *nuclear winter*. Global impact winter is very similar. An asteroid or comet impact will release dust into the atmosphere during impact. For small objects or those made primarily of dirt and ice (comets), the amount of dust that can be put into the atmosphere is limited by the mass of the object because such objects will be destroyed before they reach the surface. For larger objects, those with diameters greater than 200 meters, debris from the crater will be thrown into the atmosphere along with the object's material. The dust must get into the upper atmosphere where it can remain suspended for days or weeks, and in sufficient quantities to block out a big percentage of the sunlight, before impact winter can occur. The dust is lofted by the large mushroom cloud that results from the tremendous heat at the impact site. The cloud, because of the heat, is very buoyant and will not be constrained by the atmosphere; therefore it will continue to rise until it escapes the atmosphere where it will spread out and form a layer at the top. Any dust carried with the cloud will be trapped in this layer and settle out slowly by diffusion.[31] Hills and Goda found that any comet or asteroid that releases more than 150 megatons of dust will produce a uniform global dust layer.[32] Such a layer may not be thick enough to cause mass extinctions but it could have an effect on crop yields if it happened at the peak of the growing season. Denser layers would result from larger impacts.

The K/T impact event probably created a global impact winter although some believe that a large impact would generate enough greenhouse gasses to cause global warming instead.[33] Geologists have found a 2 cm thick layer of dust that settled evenly all over the world at the boundary between the Cretaceous-Tertiary periods. The layer contains a high amount of Iridium (an element rare on Earth but common in many comets) as well as grains of shocked quartz (that result from impact events). This dust was all in the atmosphere at some time and probably took weeks or months to settle. Given the quantity and composition of the material, it's likely that the Earth was completely dark for a long period of time after the impact. This could have caused some species to die out. Significant darkening and cooling of the Earth would have to occur before this dust would become a real concern. Hills and Goda found that an impactor of 0.6 to 1 km diameter would be required to induce the onset of global impact winter.

Fires. Tremendous heat is produced by impact. This is true regardless of whether the object is destroyed in the atmosphere or physically hits the surface. If the impact occurs within the line of sight of a forested area, fires may result.[34] These fires may turn into wildfires capable of destroying very large areas. The potential for fire depends greatly on whether the impactor is a comet or an asteroid (density is the key). Comets are much more likely to start fires because they expend their energy higher in the atmosphere than the denser asteroids.[35] The high altitude release of energy allows the resulting heat to effect a larger area of the surface. Further, the shock wave will take longer to reach the surface. In nuclear tests it was found that the shock wave would, at least temporarily, extinguish the fire.[36] If the shock wave takes longer to arrive, the fire will have time to expand and grow hotter; thus, when the shock finally arrives the fire is extinguished but reignites.

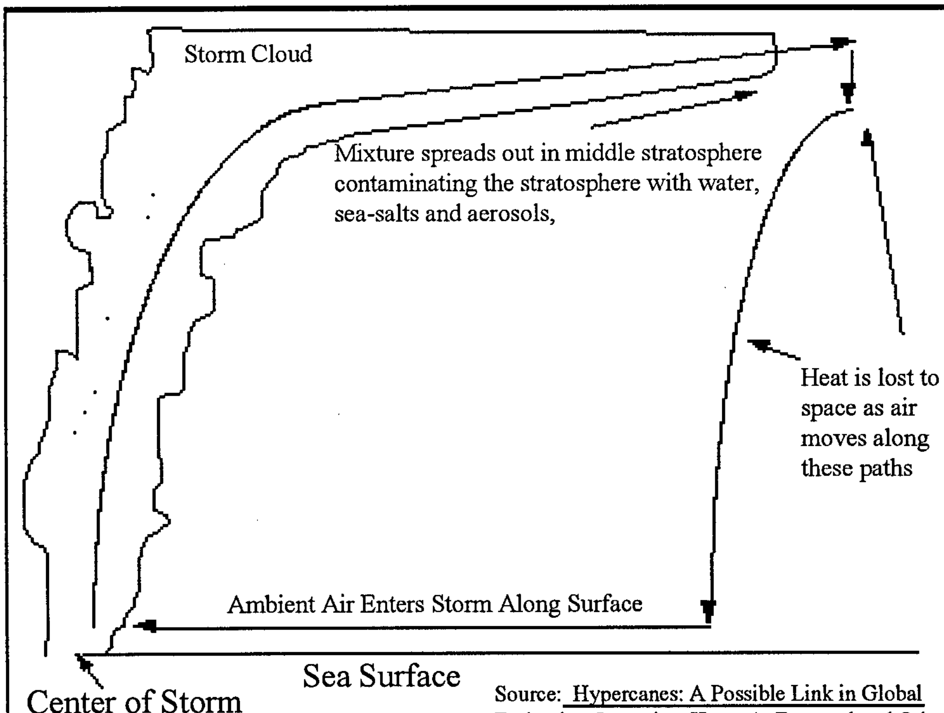
Hills and Goda found that stony asteroids and comets greater than ~80 meters in diameter will create sufficient heat to ignite pine forests. Deciduous forests could be ignited by slightly smaller objects. Note that these values are consistent with the Tunguska impact. While the pine trees at Tunguska were charred by the heat of the air blast, they did not burn because the shock wave (presumably) extinguished the fire shortly after it started.

Hypercanes. The creation of *hypercanes* by a large, ocean impact event was first proposed by Kerry A. Emanuel at the American Geophysical Union conference in 1994. Hypercanes are essentially runaway hurricanes that would cause havoc on the surface and along coastlines, but more importantly, would inject large amounts of sea water and aerosols into the atmosphere causing global climate changes.[37] Although hypercanes could occur naturally under conditions similar to hurricanes, they would be very rare because several conditions must prevail to get one started. One of the most important factors is the water temperature. Emanuel (et al) found that the water temperature must be in excess of 45°C. While this could happen naturally in some areas of the tropics, it is not very likely. However, a large impact could generate enough heat to create the necessary conditions. The minimum sized object required to generate a hypercane has not been calculated but its somewhere between 200 meters and 14 km. Obviously, an impactor less than 200 meters would loose much of its energy in the atmosphere and would be unable to heat the water. Calculations show that a 14 km diameter asteroid hitting the Earth at 20 km/sec would heat the rock in the crater on the ocean floor to about 1000°C; literally boiling the water in the vicinity of the crater.[38] Since hypercanes are theoretically possible without an impact event, it stands to reason that the minimum impactor size would depend on the ambient conditions at the time of impact. The larger the object, the less dependent the formation of a hypercane would be on ambient conditions; thus it would be more likely to form.

Once formed, a hypercane acts much like a Carnot heat engine, transferring heat from the sea surface to space as shown in Figure 4-5. As the air rapidly rises in the center of the storm it will carry with it water, sea-salts and aerosols. The presence of water in the normally dry stratosphere could result in global cooling. Aerosols and chlorine (from salt) will attack the ozone layer leading to a significant depletion of the shield that protects the Earth's surface from the Sun's ultraviolet radiation.[39]

Electromagnetic Energy Generation and Electrophonics. As a bolide enters the atmosphere it looses kinetic energy at rates upwards of tens of gigawatts.[40] The process by which the object sheds its energy is still not completely understood. We know some is converted to heat and light since we can see them streak across the night sky. But if meteors, (referring to objects of all sizes that enter the atmosphere at high speed), are capable of converting kinetic energy to light and heat, why couldn't they also generate energy in other parts of the electromagnetic spectrum? Evidence suggests that they do.

One of the first indicators that meteors generate other forms of electromagnetic



Source: Hypercanes: A Possible Link in Global Extinction Scenarios, Kerry A. Emanuel and Others,

Figure 4-5. Function of Hypercane

energy came in the form of sound. For many years people have reported hearing strange sounds from meteors as they streaked across the sky. Sounds that are heard at the same time the streak is seen. Anyone who has ever seen a meteor flash across the sky knows that they only last a few seconds or less. A large iron meteoroid entering the atmosphere at ~38 km/sec with a diameter of 0.3 meters will encounter its atmospheric retardation point at an altitude of about 16 km.[41] At the retardation point, the atmosphere has absorbed the object's entry velocity so it begins to free-fall and will cease to emit light. Therefore, the meteors are generally tens of kilometers from the observer when they are seen. Like a lightening flash in a thunderstorm, several seconds should elapse between the meteor streak and any sound heard by an observer. Yet people continue to report sounds occurring *simultaneously*.

Perhaps the earliest scientifically documented case of what we have now come to call *electrophonics*, happened in August of 1783 over Great Britain.[42] Sir Charles Blagdon, an army physician, collected observation reports from a large meteor that appeared high over the Shetland Islands. Passing quickly over much of England, it separated into two pieces over Lincolnshire and proceeded toward Paris. As it passed Lincolnshire and Kent, a loud thump was heard by many observers. Other observers reported a loud hissing sound attended the meteor as it passed. Doctor Blagdon noted the apparent impossibility of the sound and light appearing simultaneously but was unwilling to discount the testimony of the observers. The nature of meteors, as rocks entering Earth's atmosphere, was not understood until 1803; thus the doctor was unable to explain the cause of the noises.[43] The literature is replete with similar accounts.[44] A more recent example is the Great New South Wales Bolide of 7 April 1978 where numerous witnesses reported hearing strange sounds while the meteor was still is sight.[45]

For years, meteor researchers speculated that the sound must be caused by ELF/VLF radiation emitted by the meteor being transduced into sound by the objects in the observers immediate area.[46] However, until recently, no definitive process had been identified whereby the electromagnetic radiation would be produced.[47] In 1980, Colin Keay presented a theory that described a process whereby ELF/VLF radiation could be produced. Keay explains that a large meteor is surrounded by an ionized plasma region as it passes through the atmosphere. This plasma interacts with the Earth's magnetic field in the turbulent wake behind the meteoroid to produce strong electromagnetic waves at a frequency of around 3 kHz.[48]

It then follows that only meteors sufficiently large to penetrate the atmosphere enough to produce turbulent wake will generate radio waves. A typical bolide of magnitude -13 (~100 kg object mass) could generate about 2.5 megawatts of power in the ELF/VLF portion of the spectrum.[49] Depending on the object's composition and entry velocity, the minimum diameter required to produce significant radio emissions would probably be less than 0.1 meters.

Given the amount of energy that could theoretically be produced, the potential for disruption of electronic systems cannot be ignored. A lack of real data has made it impossible to correlate the entry of a bolide with effects (sound or electrical disruption) on the ground; however, evidence exists which indicates ELF/VLF pulses from bolides could create problems for terrestrial electrical systems.[50] For example, shortly after midnight on 20 October 1994, a bright fireball descended over central Michigan. Moving southwest to northeast, hundreds of eyewitnesses reported brilliant flashes and electrophonic effects. One witness in Jackson Michigan heard a loud noise and noted that the power went out in Jackson at the same time.[51] It is well known that large EMF pulses can induce current in long power and communication lines, so if meteors can create high power pulses, the mechanism for their causing interference or damage does exist. While it is not clear that the meteor was the cause of the power outage, the coincidence, especially in the presence of electrophonic reports, is interesting. Reports of similar incidents gathered over the last few decades support the hypothesis that ELF/VLF pulses, or other as yet unidentified mechanisms, are responsible for the outages.[52]

Given the small meteor size required to produce ELF/VLF energy, such events have the potential for happening frequently. While it seems not every large meteor generates electromagnetic radiation, some obviously do. Data reported by Chapman and Morrison indicates fireballs with diameters on the order of 0.1 meters or larger could happen daily. As we become more dependent on electrical and electronic systems the potential for interference by fireball energies could become significant.[53]

The Effect of Meteor Storms and Meteoroid Impact on Space Vehicles

Meteoroid impact effects on space vehicles are simpler than the Earth-impact scenarios we just finished discussing, in that there are fewer ways the energy can be transferred to the object being hit. Using our previous definitions of direct and in-direct effects, all space impact effects result from direct impingement of the impactor, or ejecta from the impact site. When an object strikes a spacecraft it will behave much like a supercharged bullet; expending all of its energy against the surface it strikes. However, the end effect on the satellite's mission is highly dependent on where the object hit the vehicle and how much energy it contained (i.e. how much damage was done). To assess the damage effects of meteoroid impact we will consider two different size ranges: dust (less than ~1mm diameter) and debris greater than 1mm in diameter. Material in a meteor stream will cover the gamut.

Dust in the Stream. Any ionized gas or particles in Earth orbit, (whether from the Sun, Earth, man-made materials, or a natural debris stream) will have a long term negative effect on satellite thermal and optical surfaces. Through a process referred to as *sputtering,* materials can be deposited on sensitive surfaces (such as thermal blankets) causing undesirable changes in their properties. There is probably very little gaseous matter in meteor streams because it would be blown away by the solar wind. What little may be present would not represent a major threat to our space assets. The combination of ions and gasses from the Sun and Earth's atmosphere are much more significant.

Dust and small debris the size of a grain of sand will severely pit surfaces. In the case of optical, solar array and thermal radiator surfaces, this will lead to a loss of efficiency for the effected surface. When the properties degrade beyond their design margin, spacecraft function will be degraded. In the case of optical surfaces like horizon sensor or star camera lenses (used for attitude determination) a small amount of pitting of the optics can completely disable the sensor.

Debris Greater than 1 mm. The effects of small debris varies widely. As the debris size increases beyond the millimeter range, it will possess enough energy to begin doing real damage (significant penetration and cratering). As shown in Figure 4-6, even a very small meteoroid has considerable energy. To help put the numbers in context consider

this: a bullet fired from a 44 Magnum has energy equivalent to only 0.000534 kg of TNT, (240 grain bullet at 0.54 km/sec), while a meteoroid roughly the size of a pea (0.75 cm) will have energy equivalent to about 0.3 kg of TNT, over 500 times more energy than the bullet. [54] The diameter of the *crater* created at impact on an aluminum target is given by,[55]

$$D = 1.081 m^{0.4} V^{0.88} \tag{17}$$

where D is in centimeters, m is in grams and V is in km/sec. Further, the depth of penetration (T) in the same target is roughly, [56]

$$T \approx 0.62D \tag{18}$$

In the example above, (assuming both projectiles are spherical) the bullet would create a crater in the target ~1.9 cm in diameter, with a depth of ~1.2 cm. The meteoroid would do much more damage. Its crater diameter will be ~32.4 cm with a potential penetration

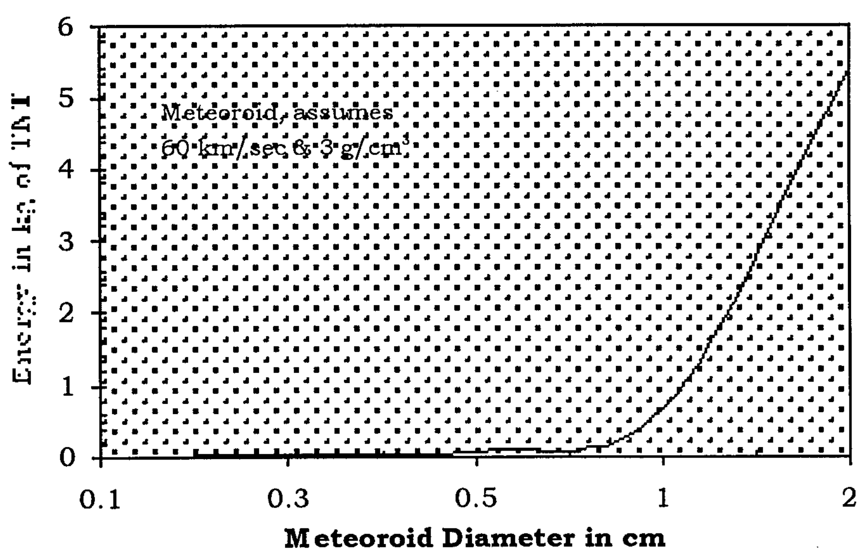


Figure 4-6. Meteoroid Energy

depth of ~20 cm. While the bullet would penetrate the skin and inner compartments of most satellites without difficulty, a meteoroid larger than a centimeter could penetrate several compartments or even pass completely through the vehicle since the Whipple effect (see end note) of the outer layer would not necessarily be adequate to vaporize an object of this size.[57] The reader should note that the bullet example is intended to help put the destructive potential of stream meteors into perspective. The equations used were intended for meteoritic debris (density 1 gm/cm^3), not low velocity, high density objects such as a bullet. However, in all cases, the energy comparisons are valid.

The difference between man-made (Earth orbiting) and meteor stream debris is nearly as dramatic as the bullet example. Figure 4-7 shows the energy difference between a Perseid meteor and a piece of man-made debris. During discussions with the space debris community we frequently observed a lack of concern for natural meteor streams.

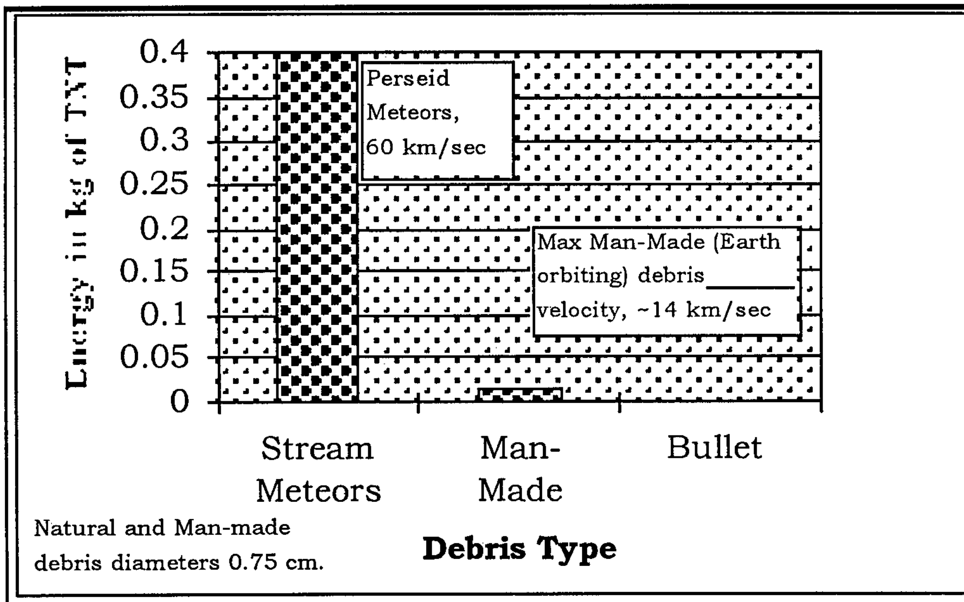


Figure 4-7. A Comparison of the Energy Content of Man-Made and Meteor Stream Debris. Bullet Energy Too Low to Show On Graph.

While we agree that the accumulation of man-made debris in Earth orbit is a major issue, we would also like to point out that the meteor streams contain much more energetic material. If an impact does occur, the potential for damage from stream meteoroids is greater than from Earth-orbiting debris (given equal masses).[58]

The effect of a strike of the magnitude shown in Figure 4-7 on the satellite's mission depends entirely on what gets hit. If the body of the vehicle is spared and only a protruding attachment suffers an impact, (like a solar panel) the effect might be limited to partial loss of power (assuming only a few cell strings are broken). If pressure tanks for propulsion are punctured, it is possible the vehicle will spin out of control. Puncture of some types of batteries could cause a similar effect, as well as loss of power storage

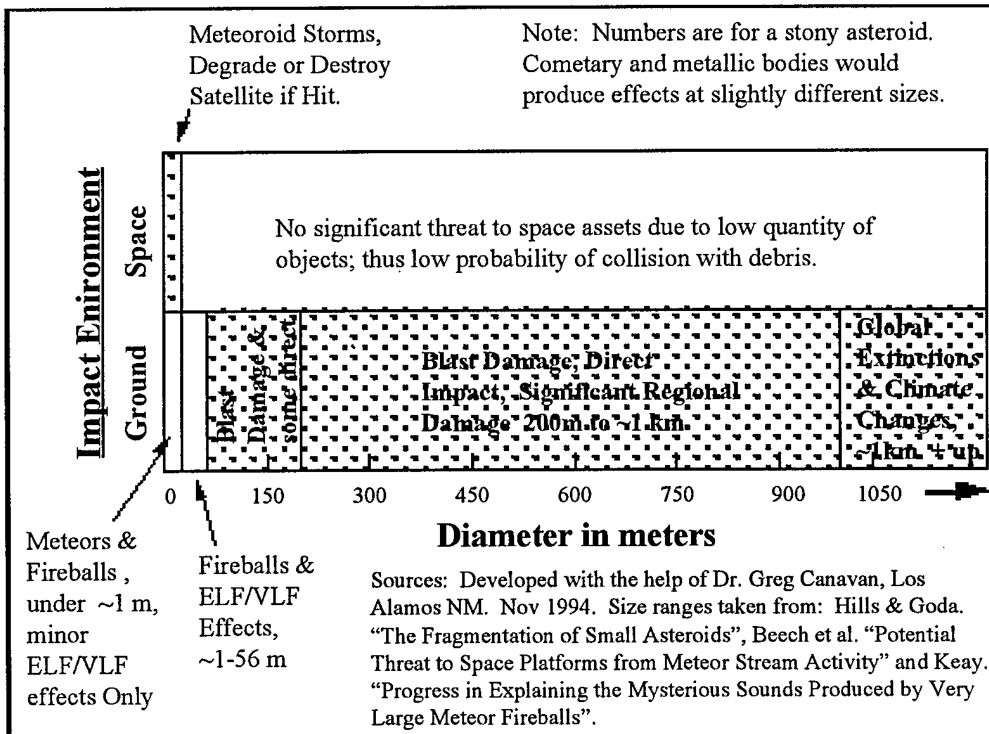


Figure 4-8. Spectrum of Natural Space Debris Effects

capability. Even if nothing vital is directly hit, ejecta from the impact area (vaporized metal) can create short-circuits in nearby electronic components, especially in areas where high voltages (~60 volts) are present. In any case, odds are good that the spacecraft will be severely damaged if not completely destroyed.

Summary of Effects

Figure 4-8 summarizes the NSD effects for various impactor diameters. For more detail on specific effects refer to previous pages.

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[21] Ibid., 1138-1139.

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[49] Keay, 347 and Personal Correspondence. 1 November 1994.

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[51] Peter Brown, Dept. of Physics, International Meteor Organization-FIDAC, University of Western Ontario, CANADA. "Meteorite Fall and Bright Fireball Over Michigan, 20 October 1994, 0553 UT" Electronic Message. 15:45:52 CST, 20 December 1994.

[52] Colin Keay Department of Physics, University of Newcastle, New South Wales, Australia. Personal Correspondence. 1 November 1994. and Mary F. Romig and Donald L. Lamar, 33-53.

[53] Chapman and Morrison, 367.

[54] Edward Matunas, *American Ammunition and Ballistics*, (Tulsa Oklahoma:Winchester Press, 1979), 77 and Martin Beech and Peter Brown, "Impact

Probabilities on Artificial Satellites for the 1993 Perseid Meteoroid Stream," *Mon. Notices of the Royal Astronomical Society,* 262: (1993) L35-L36.

[55] M. Beech, P. Brown and J. Jones. "The Potential Danger to Space Platforms from Meteor Storm Activity," to be published in *Quarterly Journal of the Royal Astronomical Society January 1995*, Received 28 July 1994, revised 26 October 1994 with updated Figure 2, December 1994, 16.

[56] Ibid.

[57] Darren S. McKnight, "Orbital Debris—A Man-made Hazard," *Space Mission Analysis and Design 2nd edition.* Eds. Wiley J. Larson and James R. Wertz. (Torrance CA and Boston: Microcosm and Kluwer Academic Publishers Jointly, 1992), 761-763. Note: Whipple bumpers are thin shields place between the spacecraft skin and space. When meteoroids hit, they are vaporized by the shield; thus do less damage to the spacecraft. Whipple bumper effect provided by vehicle skin not sufficient to break up impactors greater than 1 cm on average pg. 762. Whipple bumpers are discussed in more detail in Chapter 6.

[58] Ibid., 759. Note: Earth orbiting objects are constrained to velocities below escape velocity (~11.2 km/sec) and thus max. relative velocities between satellite and debris of ~14 km/sec.

CHAPTER 5

Natural Space Debris: Clarifying Risk, Hazard and Threat

This chapter, and the one that follows, state that NSD threatens all elements of modern society, and that there is good reason for concern. Further, the threat and associated risk to life and property are sufficiently great to warrant some reasonable levels of mitigation based on sociologists' estimation of the public's threshold for acceptable risks. To better understand the NSD threat, we must first define several key terms that we will be using throughout the paper. In addition, because we have found that the public's perception of the threat is confused and generally wrong, we need to bring the reader up to speed on the way the NSD threat has historically been presented. We do this in the hope that past mistakes can be avoided in the future.

Terms Defined

During our investigation of various NSD risk analyses, risk communication methods and general assessments of the NSD threat, we found inconsistent and often interchangeable use of the terms: *hazard*, *risk*, and *threat*. We offer the following definitions and will try to adhere to these throughout our paper.

Hazard. We define *hazard* as the end consequence of an NSD impact. In other words, it's what happens as a result of the various impact effects we discussed in Chapter 4. For example, the effect of a 200 meter diameter asteroid slamming into the ocean near a coastline would include blast damage and the generation of a tsunami (among other effects). The hazard posed by such an event is determined by the effect, or combination of effects present. Further, there may be more than one hazard associated with each effect. Consider the possible hazards associated with a tsunami; we would expect drowning, drinking water contamination, and severe property damage to name just a few.

Risk. Risk is defined as the likelihood that a particular hazard will occur.[1] In other words, *risk* is the probability that a hazard will happen within a particular period of time. People frequently and incorrectly use the terms hazard and risk interchangeably. An analogy used by Dr. Keith Smith serves to illustrate the difference between hazard and risk:

> Two people crossing the ocean, one in a ship and the other in a rowboat both face the same hazard (death by drowning). However the risk (probability of drowning) is substantially different. If the drowning occurs, in either case, it would be considered a disaster. Therefore a disaster can be seen as the realization of a hazard.[2]

Applying this analogy to the NSD impact problem, we find that risk is the probability that we will be subjected to a hazard or a set of hazards resulting from an impact.

Threat. We define *threat* as the relationship between hazard and risk. It can be likened to a product of the two, notionally depicted in Figure 5-1. Thus, the threat is

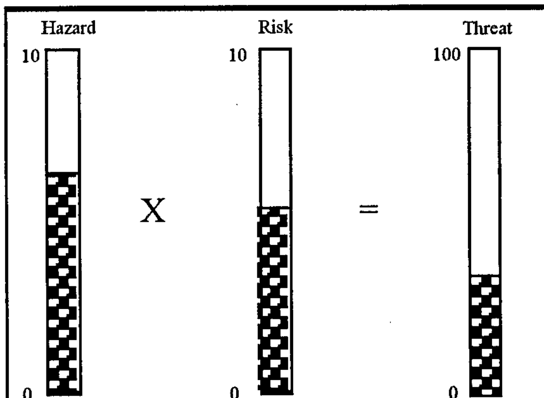


Figure 5-1. Threat is a Product of Hazard and Risk.

considered extreme only if both hazard and risk are also extreme. Consider the following analogy, the probability of getting hit by at least one rain drop while walking in a rain storm would be very high; however, the hazard associated with getting hit by a rain drop is very low. Therefore the threat posed by that raindrop is also very low.

Conveying the Threat Message

Historical Representations of the NSD Threat. Historically, the NSD threat has been presented as simply the risk (probability) of getting hit by an asteroid (or meteoroid in the case of spacecraft). The relationship between risk and hazard is seldom clearly defined. Thus, the true NSD threat really has not been rigorously defined, and perhaps for good reason. The fact is, it is very difficult to accurately and yet simply portray the threat. There are so many variables to consider that no one model is capable of doing the job, or at least, so far no one has found one. Figure 5-2 illustrates the myriad of things that must

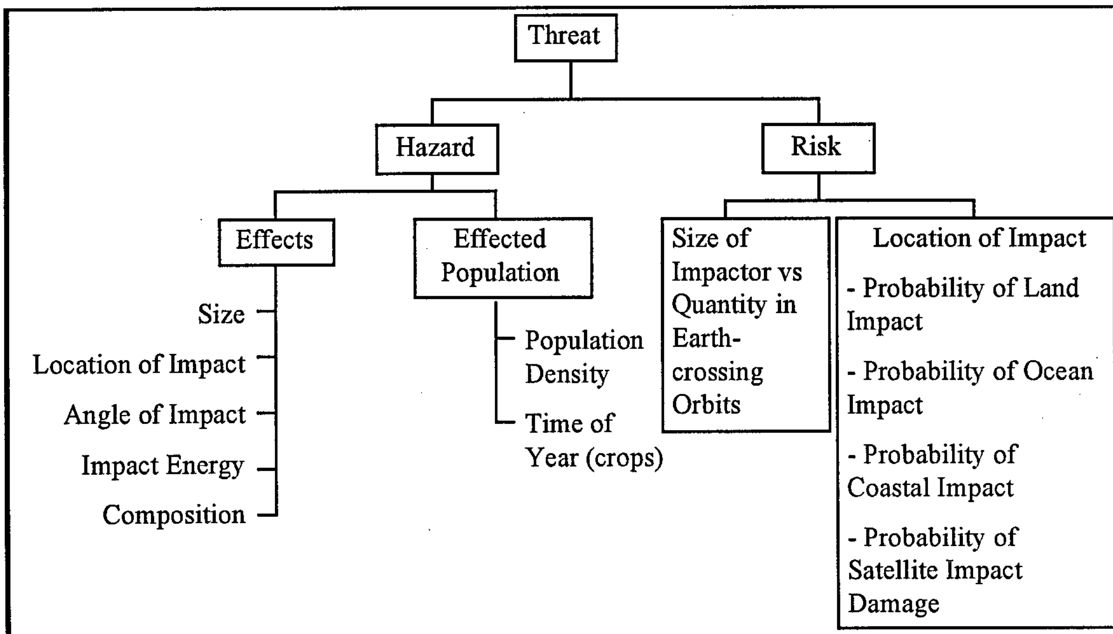


Figure 5-2. Variables Affecting Threat Determination

be considered in order to determine the threat. It is hardly surprising that people have found so many ways of modeling it, and perhaps why they vary so much in their final assessments.

In the past, NSD risk estimates have suffered from a severe lack of credibility in the eyes of the public, and it's this lack of credibility that has given rise to what is commonly called the *giggle factor* (a name given to the involuntary giggles that often accompany NSD discussions). There are two key factors responsible for the creation of this Pavlovian reflex: the public's perception of the *reasonableness* of the risk assessments, and wild variations in the purported risks.

The Reasonableness Test. The reasonableness test that a person might apply to a risk assessment will vary according to the background and experience of the individual. Everyone has a slightly different perception of what is reasonable. For example, to say that the risk of a person being killed by an asteroid is one in 6×10^7, may be ineffective if that person does not understand scientific notation. Likewise, saying that one's risk of dying as a result of an asteroid or comet impact is equal to that of dying in an airplane crash, is equally ineffective, since most people are aware of catastrophic airline accidents while essentially no one alive today has ever seen a person killed by an asteroid impact. Blindly comparing NSD risk to other disasters without explaining how the numbers were derived serves to undermine the credibility of the NSD threat. Those who seek to inform the public about NSD must realize that everyone will perform their own reasonableness test on the information given. We must take care to carefully explain the models and ensure that we never sensationalize or overstate the threat. Once credibility is lost it is very difficult to recover.

Part of the reason people are reluctant to believe the advertised risks is that those who cry that the sky is falling are often perceived by the public to have hidden agendas or motives[3]. For example, the analysis indicating the highest level of NSD threat to date, was performed by Chapman (Planetary Science Institute) and Morrison (NASA); two astronomers with a vested (professional) interest in creating new NSD programs. That does not mean their assessments are incorrect or inflated, their analyses are very well substantiated. The problem is that their risk assessment might be discounted by the public to some degree because they are not seen as being impartial.[4] In this situation the scientists reporting the risk appear to be salesmen rather than objective reporters of truth. This presents a serious dilemma wherein the most capable and appropriate source is perceived to be the least objective and potentially most biased.

Variations in Historical Risk Assessments. To begin our research, we reviewed a variety of papers and books to see what level of NSD risk was being *advertised.* We had hoped to find some degree of consensus; instead we found that each author used significantly different methods and assumptions that ultimately led to substantially different conclusions.

The predominate method of assessing the NSD risk was to relate the statistical probability of individual death as a result of an asteroid impact. The probabilities reported (shown in Table 5-1) varied from one chance in three thousand, to one chance in one hundred billion. Some authors determined the risk on a *death per event* basis; whether death occurs as a result of actual impact or due to environmental ramifications caused by the impact. Others determined the risk as a function of current world population and the size of the asteroid impacting Earth. In most cases, they assume an even distribution of the world population across the globe, and then calculate the likelihood of death from being in the asteroid's footprint when it impacts Earth. This method does not take into consideration any secondary effects caused by the impact (blast, tsunami, fire, earthquake, etcetera). A review of Table 5-1 clearly shows the problem. With such widely varying risks it is not surprising people don't know what to believe.

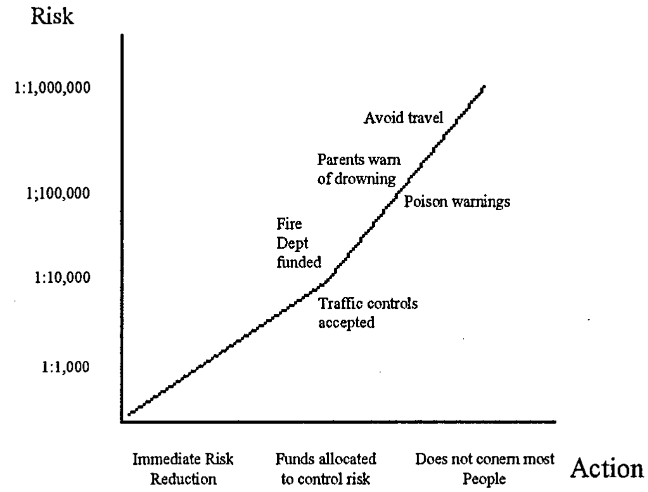
Table 5-1. Various Authors Have Put Forth Widely Differing Risk Assessments Regarding Natural Space Debris

AUTHOR	HAZARD	TO	RISK
Slovic[5]	death	100,000 persons/year	0.000006
Dinman[6]	death	person per year	1 in 100 billion
Kletz[7]	death	person per year	6×10^{-7}
Chapman & Morrison[8]	catastrophic impact	earth per 100 years	1 in 10,000
Chapman & Morrison[9]	death	person per event	1 in 3,000-250,000

Another, more manageable problem, is the presentation format. They are all slightly different, so it's difficult with the information provided to directly compare the risk numbers. For example, Slovic (sociologist), reports the annual fatality rate per 100,000 persons at risk for meteorite impact to be 0.000006.[10] According to Dinman (medical doctor) the same risk is about 1 in 100 billion.[11] Kletz (industrial safety engineer) articulates the risk as being about 1 in 6 million[12]; and Morrison and Chapman (astronomers) place the risk of dying from an asteroid impact as high as 1 chance in 3,000 and as low as 1 chance in 250,000 per event, which may occur in a given century.[13] Time frames, the parameter being measured, what is at risk, and how the risk is annotated all differ. These differences, along with the asymmetrical comparison of hazards (risk to planet, risk to person, and risk to person per event) confuse readers and reduce the likelihood of effectively communicating risk levels.

A final problem with the historical risk assessments is the apparent use and propagation of antiquated data. We found, for example, that risks published as recently as 1992 in Smith's *Environmental Hazards*, were tertiary source material from an original table of risk comparisons, by Dinman and Kletz, which had no cited source for meteorite data.[14] Dinman, who was writing about the acceptability of risk, cited Kletz who when writing about risk in the work place had failed to cite a source for data he used[15]. Additionally, Kletz's article was written fifteen years earlier, when less was known about the asteroid and comet populations. Further, Slovic unrealistically characterizes the NSD risk in terms of one piece of debris per person; thus ignoring deaths that could be caused by indirect effects. The bottom line is that a large number of the existing and frequently quoted NSD risk numbers are incorrect. We will discuss this further in the next chapter, but for now just let us say that the most accurate and well substantiated risk assessment is that of Chapman and Morrison.[16]

Defining an Acceptable Level of Risk. Once we have an assessment of the NSD threat, the next step is to decide whether threat mitigation is necessary and warranted. In order to do that we need to have some way to gauge at what point people become sufficiently concerned to take action. Sociologists suggest that a risk of death around one chance in a million is the public's threshold for concern.[17] Beyond the one in a million scenario, people are likely to consider the situation as either an act of God, or as being no real threat to them personally, and therefore not worth the effort to manage.[18] NSD has been portrayed as having a level of risk both above and below this threshold. Looking



Source: Dinman, 1980.[19]

Figure 5-3. There is a Relationship Between Risk and Efforts People are Willing to Make to Reduce or Control the Risk.

back to Table 5-1, there seem to be valid arguments that would support a concern (risk at 1 in 3,000), as well as a lack of concern (risk at 1 in 100 billion). However, if we ignore the questionable assessments and use only those of Chapman and Morrison (which we believe to be valid), we find that the risk of death does exceed acceptable levels.

Action Thresholds. As stated previously, the general public perceives risks that threaten their lives in a ratio of one chance in a million to be a threshold for concern.[20] Beyond the one in a million scenario, people are likely to see the disaster as an *act of God* and dismiss their ability to alter the course of events. However, their willingness to take concrete action also has a variety of thresholds (depicted in Source: Dinman, **1980.**

Figure 5-3). The greater the perceived risk, the greater the mitigation effort. From the figure, we can see that the public will begin to allocate significant funds for mitigation when the perceived risk is somewhere between 1 in 20,000 and 1 in 200,000. Again, based on Chapman and Morrison's numbers, an individual's chance of death from NSD is within this range; thus we conclude that the public would support an NSD threat mitigation program.

Summary

Our investigation of several commonly quoted NSD risk assessments showed that nearly all were essentially unsubstantiated. Further, the extremely wide variation in the reported risks have led, over time, to public apathy regarding the NSD threat. However, newer assessments done by Chapman and Morrison are well substantiated and could be used to re-educate the public as to the real threat. With that information, perhaps in time we will be able to rebuild the credibility of those who advocate some reasonable mitigation measures and convince the public that NSD is worth paying attention to. In the next chapter, we will take a more detailed look at the NSD risk (as developed by Chapman and Morrison) as well as the overall NSD threat.

Notes

[1] Keith Smith, *Environmental Hazards: Assessing risk and reducing disaster* (New York: Routledge, 1992), 6.

[2] Ibid.

[3] Note: Personal interview with Dr. Dennis Mileti, Hazards Center, Univ. of Colorado, Boulder, 29 Nov 94.

[4] Ibid.

[5] Paul Slovic, "Informing and Educating the Public About Risk," *Risk Analysis 4:* 407, (1986).

[6] Bertram D. Dinman, MD, "The Reality and Acceptance of Risk," *Journal of the American Medical Association 244:* 1227, (1980).

[7] Trevor A. Kletz, "The Risk Equations: What risks should we run?" *New Scientist*, 12 May 1977, 321.

[8] Clark R. Chapman and David Morrison, "Impacts on the Earth by asteroids and comets: assessing the hazard," *Nature* 367: 33, (1994).

[9] Ibid., 39.

[10] Paul Slovic, "Informing and Educating the Public About Risk," *Risk Analysis 4*: 407, (1986).

[11] Dinman, 1227.

[12] Kletz, 321.

[13] Clark R. Chapman and David Morrison, 39.

[14] For example, in a book published in 1992, Dr. Keith Smith, a professor of Environmental Science at the University of Stirling, cites Bertram Dinman, MD as a source for the involuntary risk of death by meteorite as being 1 in 100 billion. Dinman's article was published in 1980, and his source for the meteorite risk was cited from Trevor Kletz, a senior research associate and Petrochemicals Division Safety Advisor at ICI Wilton. Kletz does not cite a source for his data. Each of the aforementioned is considered expert in their field, however, in an effort to make their respective points, they have propagated outdated estimates of the NSD threat into the medical, sociological, industrial, and engineering communities. By illustration, it would be as if Dr. Chapman were to use risk assessments of death due to cigarettes, non seat belt use and heart disease with data from the 1940s in making his case for the NSD threat.

[15] Kletz, 321.

[16] Clark R. Chapman and David Morrison, 34.

[17] Dinman, 1228.

[18] Ibid.

[19] Dinman, 1227-1228.

[20] Ibid.

CHAPTER 6

The Natural Space Debris Threat

We have defined the natural space debris threat to be a function of the undesirable effects NSD could have on Earth (hazard) and the likelihood (risk) of these effects occurring. The interdependent nature of modern society makes it inherently vulnerable to NSD effects (or any other large disaster). Significant damage to any part of the world, or any element of society will create ripples that will be felt everywhere. For example, a medium-sized impact in the Middle East could completely destroy the oil fields. Even though the impact effects are confined to this one region, the consequences would be global. Thus, we cannot adequately define the NSD threat only in terms of the potential loss of human life or the total destruction of civilization, (which are the historically *typical* threat assessment methods). Rather, we need to realize that there are many additional threat elements that must be considered in order to understand the *total threat*. On the surface, this may sound like a purely academic discussion; however, the accurate definition of the threat is absolutely crucial if we are to convince civilian and military leaders that mitigation measures are warranted. In fact, we believe the main reason that an NSD defense program does not already exist is that current threat models are inadequate.[1]

Most of this chapter will be devoted to discussing a conceptual NSD threat model. However, as we discussed in Chapter 5, *threat* consists of both risk and hazard (hazard was presented in Chapter 4). So before jumping into the threat model, we will present an up-to-date assessment of the NSD risk.

Estimating the Amount of Debris in Earth-crossing Orbits

By estimating the approximate number of earth crossing asteroids it is possible to estimate the risk posed to Earth by NSD. One need only look at the Moon to see that impacts are not uncommon (Figure 6-1). The Earth and Moon have traveled around the Sun together for millions of years and have endured much the same rain of debris. If not for the effects of erosion and geological activity, the Earth's surface would look very similar to that of the Moon. Unlike Earth, the Moon has no atmospheric shield to fragment incoming objects or destroy smaller objects. Therefore, every piece of debris reaches the surface and leaves its mark. Over time, craters have piled upon craters to the point that it is nearly impossible to tell precisely how much debris has hit the Moon by simply counting craters. Fortunately, even naked-eye observation of the Moon shows the entire surface is not cratered. The so called *man-in-the-moon* feature, consisting of three large maria (also known as the lunar seas), has relatively few craters; thus it is easier to

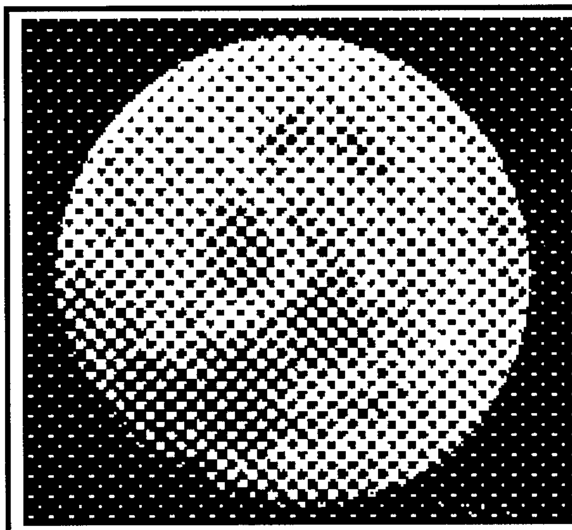


Figure 6-1. Crater and Lava Flows on Moon

count the impacts in these areas. Analysis of material brought back by the Apollo missions shows that these maria are made of solidified lava that flowed out from deep under the lunar crust to fill large basins. It's possible that even these basins were, in fact, large craters.[2] The significance of the maria is that they erased the cratering record over large areas. Thus, if we know the age of the Moon's surface and the lava in the maria, we can determine the cratering rate by comparing the number and sizes of craters in the maria with those elsewhere on the surface.

In theory, an accurate assessment of the existing population of Earth-crossing debris could be derived from the lunar record. However, in practice, there are some significant problems that must be overcome. First, there is the problem of determining the age of the Moon and the maria. Fortunately, lunar material brought back by Apollo provided a means to accurately measure these; thus one error source has been virtually eliminated. The second problem, counting craters, is proving more difficult to overcome.

On the *original* lunar surface, the craters are so numerous that it is hard to tell how many have been obscured by subsequent impacts. In addition, impact often results in debris being thrown out of the crater. This debris subsequently impacts the surface, creating what are called *secondary* impact craters. It's very hard to separate the primary and secondary impact craters.

Scientists have made some effort to compensate for these uncertainties but even so, they represent a significant source of error.[3] Combining the lunar impact record with observations of asteroids over the past several centuries and craters discovered on Earth, scientists derived an estimate of the number and sizes of Earth-crossing asteroids as a function of diameter.[4] As you can see in Figure 6-2, there are approximately 150 million

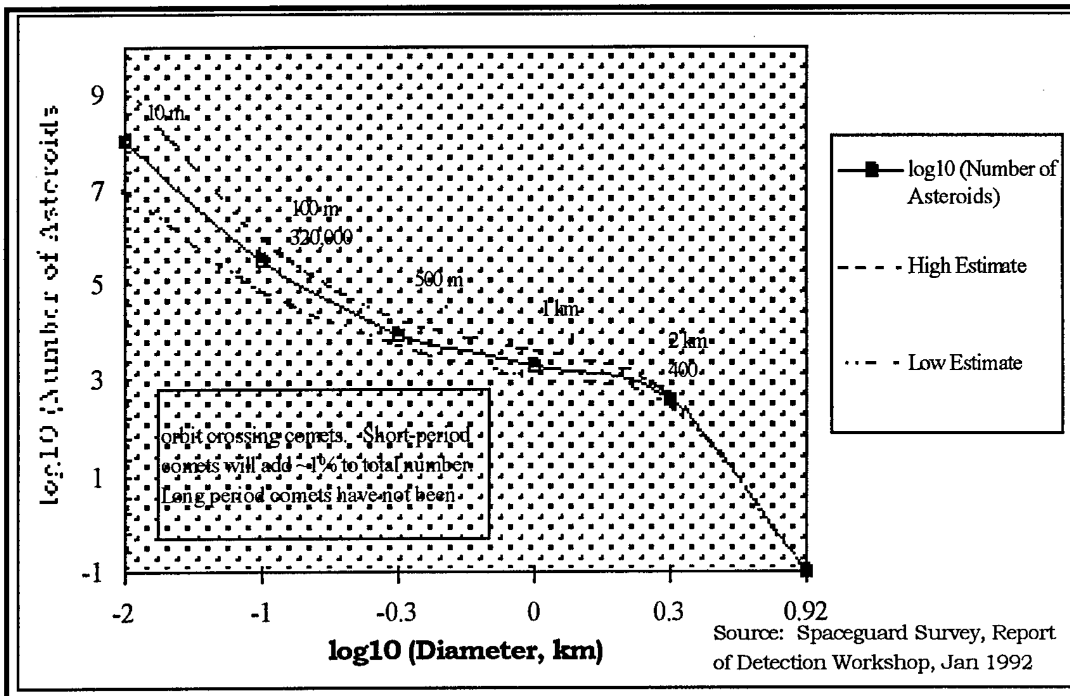


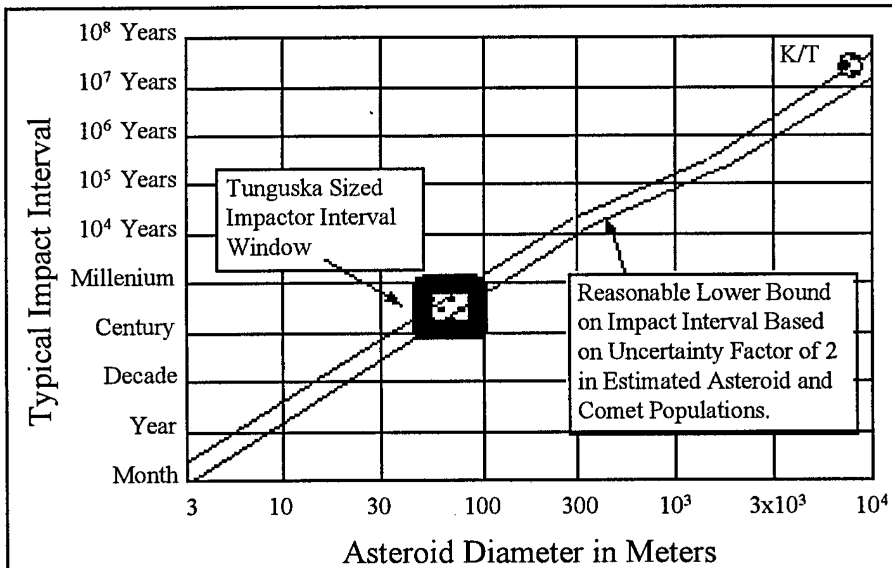
Figure 6-2. Number of Earth Crossing Asteroids by Size

Earth-crossing asteroids with a diameter of 10 meters or greater and there are approximately 2,100 asteroids with a diameter of 1 km or greater. The broken lines illustrate the uncertainty factor associated with these estimates. The uncertainty factor must be considered when discussing the NSD threat since it directly effects the calculated probability of impact for various sizes of debris (i.e. the assessed risk as a function of impactor diameter).[5]

In addition to the uncertainty in the number of Earth-crossing asteroids reflected in Figure 6-2, there are other sources of natural space debris which are not included in the figure.[6] Of particular concern are the comets. The number of comets that have Earth-crossing orbits is unknown, but it is estimated that they would equal about 5-10% of the asteroid population.[7] In addition, comets are much more dangerous than asteroids because they are generally larger and move at higher velocities. Asteroids and comets pose slightly different threats and present a different challenge for a detection and tracking system as we will discuss in subsequent chapters.

Risk of Terrestrial Impact

As we just established, the probability of an asteroid or comet hitting Earth can be derived from estimates of the total Earth-crossing object population. Chapter 5 illustrated that there are many different ways of presenting the NSD risk, some of which are not very meaningful to a layman. One of the more effective methods (shown in Figure 6-3) illustrates the risk from all Earth-crossing objects as a function of impactor size. This curve, which was used by Spaceguard, is widely accepted as accurately depicting the NSD risk. However, as shown in Figure 6-2, there are significant uncertainties associated with the Earth-crossing object population. Therefore, there should be a corresponding



Source: Derived from Chapman and Morrison, Impact on the Earth by Asteroids and Comets: Assessing the Hazard. Based on work by Shoemaker, A.Rev. Earth Planet. Sci. 11, 461-494 (1983). Lower Bound Added.

Figure 6-3. Typical Intervals Between Impacts

uncertainty in any terrestrial impact risk assessment. Though we have not attempted to determine the precise value of uncertainty, we believe a factor of two would be reasonable given that the debris population estimates could be off by as much as a factor of two for objects over 0.5 km diameter and as high as 15 for smaller debris.[8] Thus, we added the lower line to Chapman and Morrison's graph to illustrate an upper limit on the probability of impact (risk range). The importance of defining a *risk range* is two-fold. First, we want to highlight the fact that there is an uncertainty associated with any probability prediction. Second, when discussing the merits of a threat mitigation system, this level of uncertainty is a very important part of the decision process. Generally, to be conservative you would use the highest predicted risk as your basis for evaluation. This is a slightly different approach than that used in the Spaceguard Survey, where, in most cases, the nominal values seem to have been used.[9] Throughout the remainder of this paper, we will use the lower bound values of impact interval as a *conservative estimate* of the NSD risk.[10]

In Search of an NSD Threat Model

Currently, no universally accepted model of the NSD threat exists.[11] One reason, as Figure 5-2 illustrates, is the large number of variables affecting threat determination. Other reasons, including the interchangeable and often erroneous use of threat-related terms, public perception of the threat (i.e. the *giggle factor*), as well as a lack of consensus on the best parameters with which to assess the NSD risk, were discussed in the previous chapter of this paper. The models that do exist have typically focused on either the *risk* of an event occurring or the *hazard* (the expected effects) that will result from an event. We

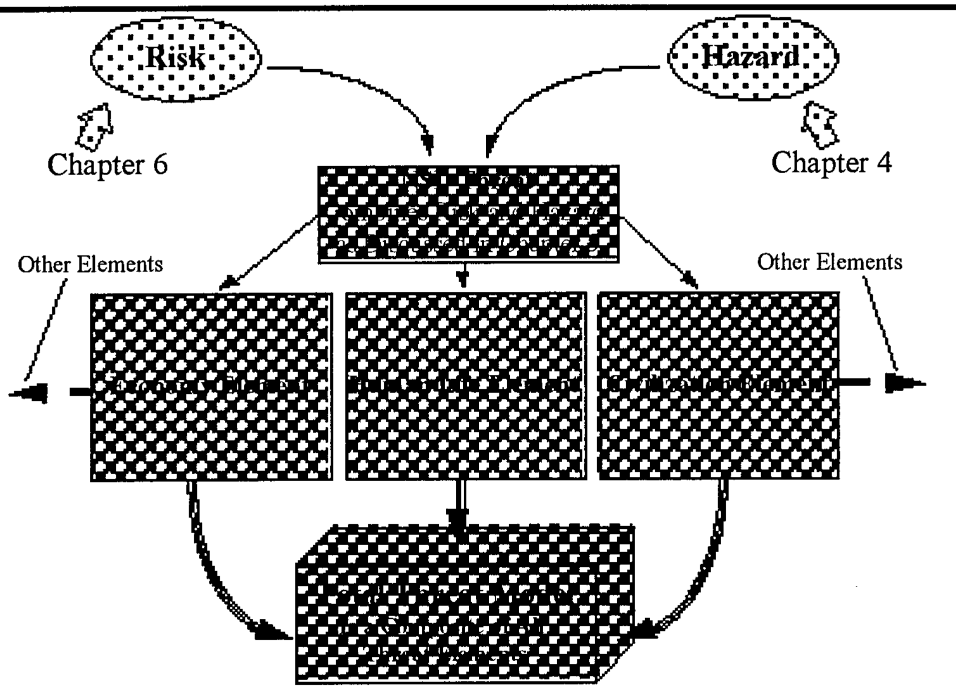


Figure 6-4. Elements of the NSD Threat Model

believe that *an NSD threat model must consider the relationship that exists between the factors of risk and hazard.* Figure 6-4 shows the contribution that these two factors make to the NSD threat, while portraying the overall threat in terms of a variety of possible *threat elements.* The reader should note that the NSD threat to the economy, life and civilization depicted in this figure are just some of the many possible elements (food production, communication networks, environmental issues, and damage to infrastructure are others) that need to be factored into any useful threat model.

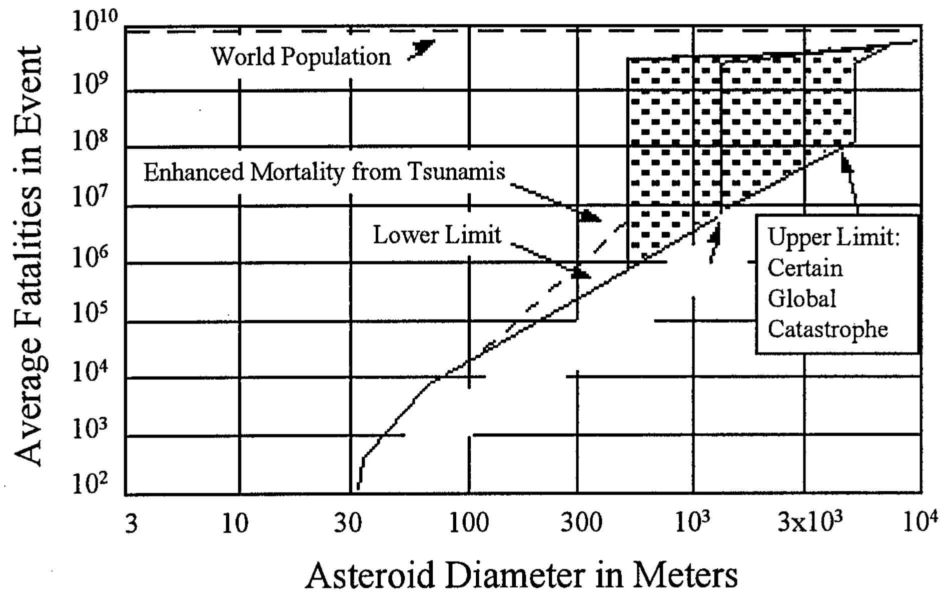
Figure 6-4 shows three elements of our conceptual threat model: civilization, life, and the economy. If the model were complete, there would be as many elements within the model as there are systems or subsystems within our society. Unfortunately, as we expand our interests to more and more elements the model quickly becomes too complicated to manage. In other words, our society consists of such a large number of interwoven and interdependent elements that we quickly find ourselves unable to assess the potential costs (life, money etc.) of damage to a given element or portion of an element. Thus, a complete threat model will probably never be possible. Still, improvements can be made by simply adding enough elements to cover the more obviously important or vulnerable aspects of modern life (such as those mentioned above).

Once the elements are chosen, the next step is to assess the threat NSD poses to each of them. This will require significant knowledge of how the elements function. For example, looking at the world economy, we would identify and map the critical nodes and linkages to other parts of society. From this information you could draw a nodal diagram that functionally depicts the world economy as a *system*. With the critical nodes and linkages identified you could then begin to assess their vulnerability to impact related effects, and from that begin to quantify the overall effect on the world economy. Obviously, this is not a simple process. Remember, this must be done for several key elements in order to ensure a reasonably clear picture of the threat.

Once the elements are modeled, we can begin to evaluate the acceptability of the threat. To do this, we must look at each element individually. As we discussed in Chapter 5, for every threat there is an associated threshold of concern at which people are willing to take concrete action to mitigate the threat. This threshold will be different for each of the elements within the model. In order to decide whether mitigation is warranted, we must determine whether the level of threat exceeds our threshold for concern in *any one* of the elements. By only addressing two or three of the possible elements, we potentially overlook threat elements in which our thresholds will be exceeded. In fact, we believe this is exactly what is happening. By focusing our attention on the threat to life and civilization we have convinced ourselves that only objects 1 km in diameter and larger are of concern. If a more complete model (many more elements) existed, we would see that the threat from small debris is significant; perhaps even greater than some of the larger asteroids and comets.[12] With that said, we will now discuss the individual elements of threat shown in Figure 6-4 with an eye toward the contribution that each makes to the overall assessment.

The Threat to Civilization. This is the most familiar and simplest of the NSD threat models. After all, the theory that the impact of Earth by large asteroids and comets puts civilization at risk is as true today as it was for the dinosaurs. It is commonly accepted that objects 1 to 2 km in size exceed the threshold at which global climate changes and other global effects could bring life on Earth (as we know it) to an end.[13] The civilization model is a simple one because the threat is easily defined, risks and hazards are quantifiable, and it is obvious that our threshold for concern is exceeded.[14] For this reason, the Spaceguard Survey focuses on objects 1 km or greater in its proposals concerning asteroid and comet detection and defense systems. Even though the risk of occurrence is low, the hazard posed by large NSD to civilization is so great that Spaceguard suggested that mitigation of the threat is warranted on that basis alone. However, as we discussed above, a threat model with a single element (survival of civilization) does not provide a complete picture of the total NSD threat. The problem with stopping here is that these results lead us to mitigation measures that focus on large objects and ignore the smaller, but more plentiful objects. A more detailed model may (we believe it will) identify a significant threat from the smaller debris. In other words, there are many other elements of society at risk from small debris that this simple model overlooks. Obviously, we would not expect the direct losses resulting from smaller debris impacts to be as grave as the loss of civilization. However, indirect losses arising mainly through second-order consequences of such an event, (i.e. the disruption of economic activity or the occurrence of health problems) represent intangible, yet very real long-term costs.[15]

Threat to Life. A second useful NSD threat model element is the one developed by Chapman and Morrison (shown in Figure 6-5). This figure illustrates the predicted mortality rates caused by an impact of an asteroid or comet as a function of the impactor's diameter. The strength of this model is that it attempts to account for the indirect effects of an impact (discussed in Chapter 4) that contribute significantly to the loss of life. As we would expect, the threat to human life increases dramatically with the size of the debris. The only major deficiency in this model, (acknowledged by the authors) is that it presumes an equal distribution of the population over the globe. Since the population is actually concentrated along coastlines, waterways and in cities; the death toll would be considerably worse if the impact happens anywhere near a population center. Of course, the converse is also true. If the impact occurred in the middle of the ocean or near the poles, the death toll could be very low.[16] Unfortunately, as the world population grows and all land masses experience increased population densities, the death toll in even small strikes will probably be significant. For example, a Tunguska-sized asteroid or comet strike would devastate an area the size of Washington DC or New York City and kill millions of people.



Source: Chapman and Morrison, Impact on the Earth by Asteroids and Comets: Assessing the Hazard

Figure 6-5. The Threat to Human Life For Various Impactor Sizes

Threat to Economy. Designing a threat model element to assess the hazard to the world's economy as the result of an NSD event is a very complex task, and to date little such work has been done. The benefit of having an economic element would be to explore the economic benefit of NSD search and defense systems *by calculating the expected losses in their absence.*[17] The economy is inextricably linked to so many facets of modern society that it is difficult to imagine any NSD event happening without some expected economic loss. This model would require extensive analysis to first determine existing linkages between the economy and the other interdependent elements of society, and then to find a way to estimate the financial losses that would result from the expected impact effects. Apparently, no such model exists. However, in our literature search, we did find one report that makes a rough assessment of potential economic losses.[18]

Unfortunately, the analysis does not contain enough detail to quantify the economic threat of debris under 1 km in diameter.[19]

Element Summary. We have introduced the concept of threat elements in an effort to show how little we understand about the potential effects of an asteroid or comet impact. Everyone realizes there is a potential for tremendous economic damage from relatively small debris; however, when the issue of mitigation comes up, it seems we always end up hearing about the end of civilization and various body counts. While these are all valid concerns, we need to remember that they represent but one small piece of the total NSD threat. In order to get a better handle on the value of an NSD defense system, we need to improve the existing threat model. One way to approach the problem would be to address other elements as we have suggested above.

An NSD Threat Model Summary

The above discussion asserts that current NSD threat models are deficient because they overlook many other threatened elements of our society. The design of a truly useful model, like the conceptual model illustrated in Figure 6-6, would therefore require a study to identify and analyze additional critical elements (of society). Unfortunately, the number of possible elements is at least equal to the number of systems and subsystems present in modern society, so effort must be limited to those critical elements demonstrating the greatest linkage to other elements. For example, in addition to elements for civilization, life, and economy; elements such as the environment or communications networks are critically important, and potentially very vulnerable.[20]

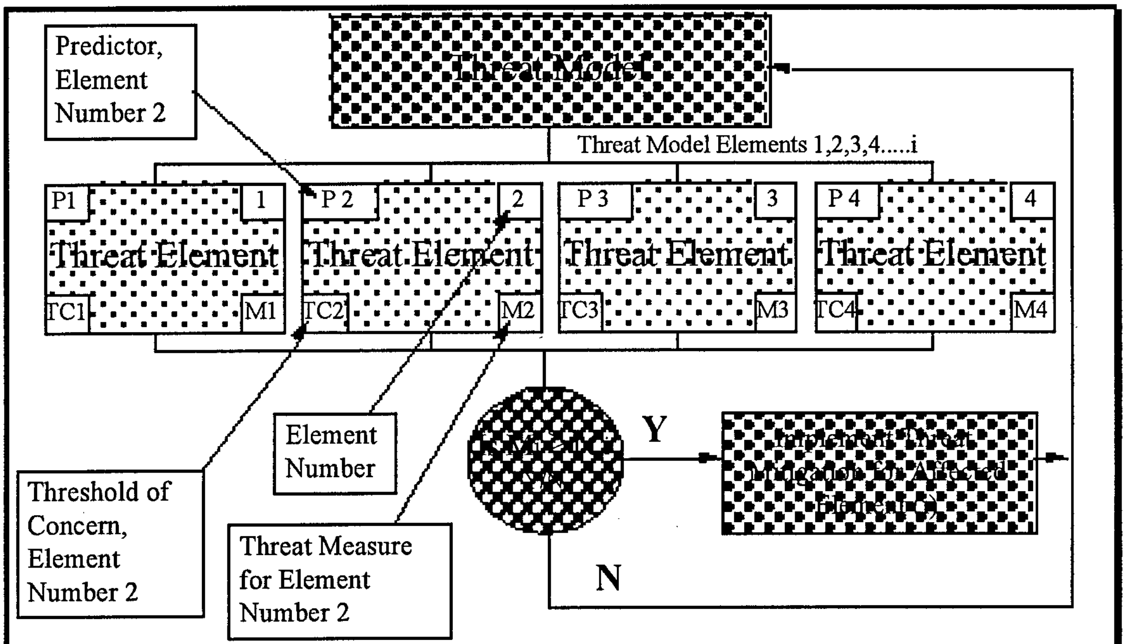


Figure 6-6. Conceptual NSD Threat Model

After selecting additional critical threat elements for analysis, we must determine thresholds for concern (TC) at which mitigation actions (for that element) would be appropriate. Using the economic element as an example, we would decide upon an allowable cost which, if it were exceeded would tell us that mitigation is required and warranted. The next step is to develop predictors and measures whereby we can determine whether the threshold of concern is exceeded. The predictor (P), is the expected effect for a given set of impact conditions. In other words, the predictor is what we believe would happen to the element for various impact scenarios. The predictor is then converted into a threat measure (M), which quantifies the effect in some way appropriate to the element being considered. We might expect, for example, the hazard resulting from a 100 meter asteroid to be the total devastation of a city (predictor), and by using nodal analysis and computer simulation modeling, determine the equivalent cost to be $100 billion and 1 million lives (threat measure). This same process would be completed for each of the critical elements under consideration. As shown in Figure 6-6, each threat measure is compared to the accepted threshold of concern for that element. If any one of the measures is found to exceed its threshold, then mitigation actions should be pursued for that element.

Mitigation measures could take two different approaches. The first would be mitigation to reduce the expected hazard. An example might be the enactment of disaster preparedness plans, storage of emergency medical supplies (as well as food and water) and the creation of dikes or sea walls to minimize the effect of a small tsunami. The second type of mitigation would seek to reduce the potential threat to the point that it no longer exceeds the known threshold of concern. In this case, a system to defend against the threat might be decided upon. If no threshold is exceeded for any of the elements, then mitigation is not required. However, the analysis process must be continued, in order to make updates to the model and to refine predictors, measures, and thresholds, resulting from changes to either the element or the threat.

The conceptual NSD threat model in Figure 6-6 is intended as a framework, within which we can begin to build a more accurate picture of the overall NSD threat. So far, we have focused entirely on the terrestrial impacts; however, there is another dimension to the NSD issue that needs to be considered: the meteor stream threat to our space assets. It is to this discussion that we now turn.

Satellites and the Meteor Storm Threat

As discussed in Chapter 2, meteor showers occur as a result of Earth's passage through a stream of debris. Clusters of debris exist in the stream and if the Earth encounters one of these clusters, the result will be an unusually intense shower, called a meteor *storm*. It is these storms that pose a threat to our space systems.

Table 6-1. Well Documented Meteor Storms Since 1799

Date	Shower	ZHR Storm	ZHR Normal Shower	Enhancement Factor (f)
1799	Leonids	30,000	15	2,000
1803	Lyrids	1,500	20	75
1832	Leonids	20,000	15	1,300
1833	Leonids	100,000	15	6,700
1866	Leonids	6,000	15	400
1867	Leonids	5,000	15	330
1872	Andromedids	8,000	10	800
1885	Andromedids	15,000	10	1,500
1933	Draconids	20,000	10	2,000
1946	Draconids	7,000	10	700
1965	Leonids	5,000	15	330
1966	Leonids	150,000	15	10,000

Source: *The Potential Danger to Space Platforms from Meteor Storm Activity,* Beech, Brown and Jones.

Meteor Storms. There is historical evidence that storms occur. In 1966, the Earth approached the debris stream produced by Comet P/Tempel-Tuttle (Leonids) only 561 days after the comet, resulting in the strongest storm ever documented. Table 6-1 shows the documented storms since 1799. Of particular interest is the fact that only the last two have taken place during the space age. It is estimated, from historical records, that there are 25 well-defined meteor streams.[21] Of these, only 11 are currently active and only four of these 11 have produced storms since 1799.[22] The fact that 14 streams (of which 6 are known to have produced storms in the past) no longer intersect Earth's orbit illustrates the dynamic nature of the debris environment.[23] While some streams are no longer a threat, others have arrived to take their place. One example of a relatively new stream is the Draconid meteor shower that takes place in October. According to Beech, Brown and Jones,

> Activity from this stream was first noted in the second decade of this century, and the stream has subsequently produced two spectacular meteor storms.[24]

The potential for single event showers, such as the Corvid meteors that were observed only once on the nights of 25-30 June 1937, also exist.

As early as 1946, it was recognized that meteors and meteor showers presented a serious threat to spacecraft. In his report to Douglas Aircraft Company in September 1946, Dr. F. L. Whipple made the following recommendations in regard to a future spacecraft with a 120 hour planned mission duration,

> As an added precaution it would be advisable to avoid launching the vehicle near the time of major recognized meteor showers. Because the severity of these showers is not predictable, it is advisable to avoid, insofar as possible, the chance of a major shower occurring simultaneously with the launching of the vehicle.[25]

By 1957, a great deal more data had been gathered and the scientific community had come to the conclusion that meteoroids were going to be a significant risk for space vehicles. In his 1957 report to the 8th International Astronomical Congress in Barcelona, Whipple made the following statement,

> This expectation of punctures to space vehicles is much greater than earlier estimates. As a consequence, the use of a *meteor bumper,* as suggested by the author seems even more important in planning space vehicles. The meteor bumper is simply a thin secondary layer of surface placed a few thicknesses of the major surface from it on the space side of the vehicle. . . . the bumper should reduce the number of punctures by a factor

> of approximately ten to one hundred times by exploding the meteoritic particle far enough away from the surface of the skin that only vapor strikes the skin. . . .[26]

In spite of this warning, today's unmanned satellites are not equipped with *Whipple bumpers* or any other significant meteor protection because the added weight is prohibitively expensive under normal (meteor activity) conditions.

In the 1950s, O.E. Berg and L.H. Meredith showed that the meteor impact rate at an altitude of 80 km was 1 per minute per square centimeter of exposed surface.[27] The size of most of the debris was probably very small, too small to puncture a satellite's metal skin, but over time it would certainly abrade the surface enough to cause significant damage. If these numbers remained constant, a satellite with 20 square meters of exposed area, in orbit 5 years, would receive 5.256×10^{11} impacts from natural meteoroids over its life. More recent rate data suggests the number of impacts for the same spacecraft would be somewhere between 1.25×10^{5} and 1.25×10^{8}, still a lot of hits for a delicate instrument to survive.[28] As discussed in Chapter 4, the effect is much like sandblasting your spacecraft. Unfortunately, the impact rate and quantity of larger particles is not constant and that is the crux of our concern.

At the time these impact rates were determined, our space program was in its infancy, thus, the only significant source for space debris was natural. Today the situation is quite different. The bulk of current debris discussions in the spacecraft community deal with the proliferation of man-made debris.[29] In fact, the man-made debris problem has gotten so bad that, most of the time, it completely dominates the near Earth orbital debris environment.[30] A significant effort is being made to sense, identify, catalog and track all man-made debris with diameters greater than 10 cm (low earth orbit, LEO) and 1 meter (geostationary orbit, GEO).[31] Currently, over 7,000 man-made objects are being tracked.[32] However, it's estimated that there exist 40,000 to 80,000 non-trackable fragments less than 1 cm in diameter in low Earth orbit.[33] With that data in mind, it's easy to see why we have tended to ignore natural background meteor rates (also called meteor *flux*).

Except at times of greatly enhanced meteor stream activity, the man-made debris does dominate the near Earth debris environment, but we need to keep in mind that we have only been in space since 1957 (Sputnik), and it has only been in the last 20 years or so that significant numbers of satellites were put into operation. On an astronomical time-scale, this a very brief period. Considering such a small statistical sampling period, it would be a mistake to assume the natural space debris environment is unchanging. Impact rates may periodically increase dramatically. In addition, if a meteoroid impact does take place, natural meteoroids have the potential to cause much more damage than man-made debris because the natural meteors are traveling two to seven times faster.[34] Although, as we pointed out in Chapter 4, every strike will not necessarily disable a satellite, (just as every bullet will not bring down an aircraft) a strike in the wrong spot (and there are plenty of these) could *kill* a satellite.

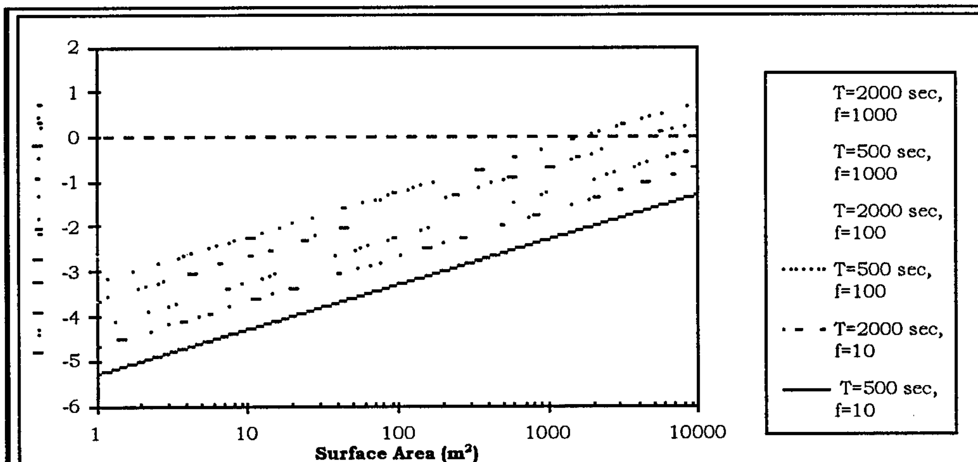
An example of the damage meteoroids can do may be found in the fate of the European Space Agency's Olympus communications satellite. On 12 August 1993 Olympus unexpectedly failed and spun out of control.[35] While no one knows for sure what happened, the incident took place during an outburst of the Perseid shower; so meteor damage is at least a strong possibility.[36] Since we are seldom able to determine conclusively the cause of a satellite failure, it is possible that impact damage is a common cause of satellite failure. In any case, during storms the potential for damage increases dramatically as we will show in subsequent discussions.

Meteor Streams. Meteor stream activity is described in terms of the Zenithal Hourly Rate (ZHR) which is defined as the number of meteors that an average observer would see for a particular shower under ideal conditions.[37] For a typical meteor shower, the ZHR varies from a few per hour to ~100 per hour.[38] At these rates, Earth's passage through the meteor stream does not present a significantly increased threat; however, during a meteor storm or outburst, the ZHR can increase by factors of 10 to 10,000 times with typical storms lasting from 1,000 (16 min) to 10,000 seconds (2.8 hrs).[39] Given an expected storm duration and intensity we can determine the probability of impact (risk). Figure 6-7 shows the predicted probability of impact for various levels of storm intensity (f) and duration (T in seconds). While calculated specifically for the Perseid stream, we will assume it is representative for all streams in the absence of better data.[40]

A spacecraft with a frontal area (cross-sectional area as seen from the stream) of 100 m^2 has a probability of impact of only ~0.06% during a normal meteor shower exposure of 500 seconds. However, the same satellite will have a 20% chance of getting hit in a moderate storm (f = 1,000). Though most of our satellites have frontal areas less than 100 m^2, we must consider that we have more than one satellite in orbit. If you assume a random distribution of vehicles, the frontal area of each can be added to derive a total exposed frontal area. For spacecraft in low Earth orbit, fewer than half will be shielded by the Earth for a typical 2,000 second (33 min) storm duration, and those in GEO will have essentially no protection. Given the number of functioning satellites in orbit and an estimate of the average frontal area they each present to the oncoming stream, we can conservatively estimate the probability of our space *network* (the sum of all functioning satellites) taking a hit. The exact number of functioning spacecraft in orbit is not available, but estimates put the number at about 5% of the more than 7,000 cataloged Earth-orbiting objects; therefore we will assume there are ~350 operational satellites.[41]

Determining the frontal area presented to the storm is even more difficult. Satellite physical configurations vary considerably since each is generally customized to its particular mission. Also, since there is no need for streamlining, as with vehicles that operate in the atmosphere, satellites often have irregular, non-symmetric shapes. Thus, the cross-section they present will vary significantly with the angle the stream hits the vehicle.

Nearly all Earth-orbiting satellites use solar arrays for power.[42] Also, these arrays are easily damaged by meteoroids and make up a large portion of the exposed surface area. A crude estimate of an average satellite cross-section may be drawn from the power requirements of a variety of spacecraft (more readily available than physical dimensions).



Source: *Potential Danger to Space Platforms*, Beech, Brown and Jones.

Figure 6-7. Probability of Satellite Collision with a Meteoroid

If we assume body mounted cells rather than deployed arrays, we minimize the frontal area dependence on stream incidence angle and arrive at a conservative volume. A quick survey of power requirements for various satellites indicates that a reasonable average power would probably be in the 700-1,000 watt range.[43] Solar cells typically generate about 84 watts/m^2, so the required area for a 1,000 watt spacecraft is ~12 m^2.[44] Allowing 3 m^2 for thermal radiator area and appendages gives 15 m^2 as a reasonable average area.

Table 6-2. Estimated Probability of Space Network-Meteoroid Collision

Storm Enhancement (f)	Storm Duration, Seconds	Probability of Collision (%)
	500	2
10	2,000	10
	500	32
100	2,000	100
	500	100
1,000	2,000	100

Using the derived average area of 15 m^2 for each of the 350 operating satellites now in orbit, and allowing for 10% shielding from the Earth gives a space network total area of ~4,725 m^2. Using Figure 6-8, we can estimate the probability of collision between a meteoroid and a spacecraft in the network (see Figure 6-7). Admittedly, these estimates are crude, but they are accurate enough to convey the threat meteor storm activity poses to our space systems as a whole.

Another method of communicating the overall risk is to define a *meteor storm risk factor* as simply the product of the enhancement factor (f) and storm duration (T), (normalized to the typical shower level of activity shown on Figure 6-7) and plot that against various spacecraft area values. The results, which are valid for individual spacecraft or combinations, are presented in Figure 6-8.

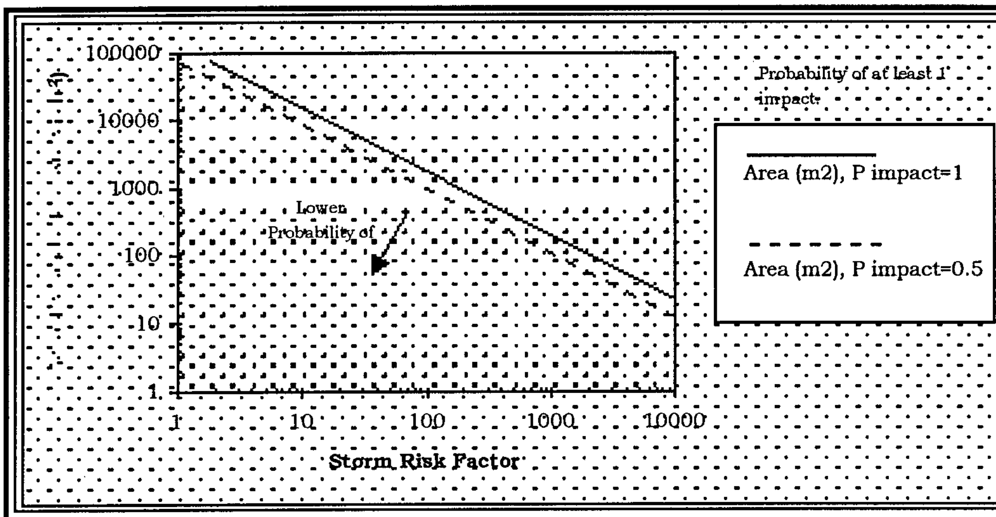


Figure 6-8. Risk of Satellite or Network of Satellites Being Struck By a Meteoroid

The bottom line is that, with all functioning satellites considered, the risk of impact is considerable even with a moderate storm. Too often, we only look at individual systems when calculating risk. As we become more dependent on global systems, and as space systems become more interdependent, we must address threats to the entire network rather than the individual pieces.

Without a greater understanding of the debris environment and the nature of the streams that intersect, or will intersect Earth's orbit in the future, we can not be confident in the safety and security of our critical space-based systems. The variability in shower intensity, combined with the potential for encountering previously unidentified streams, makes it important that we expend some effort to learn more about meteor streams.

Predicting future storms is somewhere between difficult and impossible with the data gathered so far. Still, for some streams, there is enough information to make some rough predictions. According to Beech, Brown and Jones, the stream most likely to produce a storm in the next 10 years is the Leonid stream.[45] In fact, their model predicts a moderate storm in November 1998 and a major storm on 17 November 1999.[46] If the prediction is correct we need to begin work developing risk mitigation and contingency plans and procedures as soon as possible. With the exception of the Hubble space telescope, which was maneuvered during last year's Perseid shower, satellite programs do not normally possess such plans.[47]

Summary—The NSD Threat

In this chapter we have presented the NSD risk and threat (for various elements) based on the most current information available. Unfortunately, we do not have a complete picture of the threat because the effect of impact damage on the major elements of society has not been adequately addressed.[48] Of particular concern is our inability to assess the economic consequences of a small 60 to 200 meter diameter asteroid impact. Such objects hit Earth much more frequently than the larger objects, but are being largely ignored because they do not threaten civilization, and because the projected loss of life is highly dependent on the location of the impact. In other words, unless the object hits near a population center or a coastline the loss of life will be minimal. However the economic losses from a small impactor may not be nearly as sensitive to impact location. The resources the world economy depends upon may not be as concentrated as the population.[49] Another way to look at the problem is to try to imagine a place on the world's surface where you could detonate a very large nuclear device without disrupting someone's life or livelihood. Even without the radiation, it is very hard to imagine where a 75 Megaton bomb could be detonated without anyone being effected.[50]

The meteor stream threat is a similar problem in that it continues to be ignored. Since the 1960s, we have been trapped in a paradigm wherein natural meteors are not a significant threat. As a result, the field of meteor stream research has been neglected and satellite programs are generally unprepared for a large increase in meteor activity. Fortunately, a few scientists have managed to continue studying the streams. Based on their research, we may not have much time to make up for past neglect. At least two significant storms are predicted within the next five years. A moderate storm in November of 1998 and a very intense storm around 17 November 1999.[51]

It is relatively easy to see the economic effect of losing a satellite to a meteoroid strike (i.e. the cost of replacement and loss of service until a replacement is in operation). However, the effect of losing several satellites within a short time, on critical military and civilian *systems* (especially communications) is not easily quantified. As our society becomes more dependent on space systems, and as these systems become more interdependent the loss of a satellite or two could have a cascading effect that would result in serious problems (especially for the government and military).

To wrap up the discussion, we created a notional diagram to illustrate the overall NSD threat (Figure 6-9). The lower triangle represents the traditional concept, where the greatest threat comes from the large, *planet-buster* objects, and there is essentially no threat from smaller debris (especially the meteor streams).

The larger area represents what we consider to be a more realistic view of the threat. By expanding the number of elements in the model, and by adding the meteor stream threat to spacecraft, the shape of the threat region changes significantly.

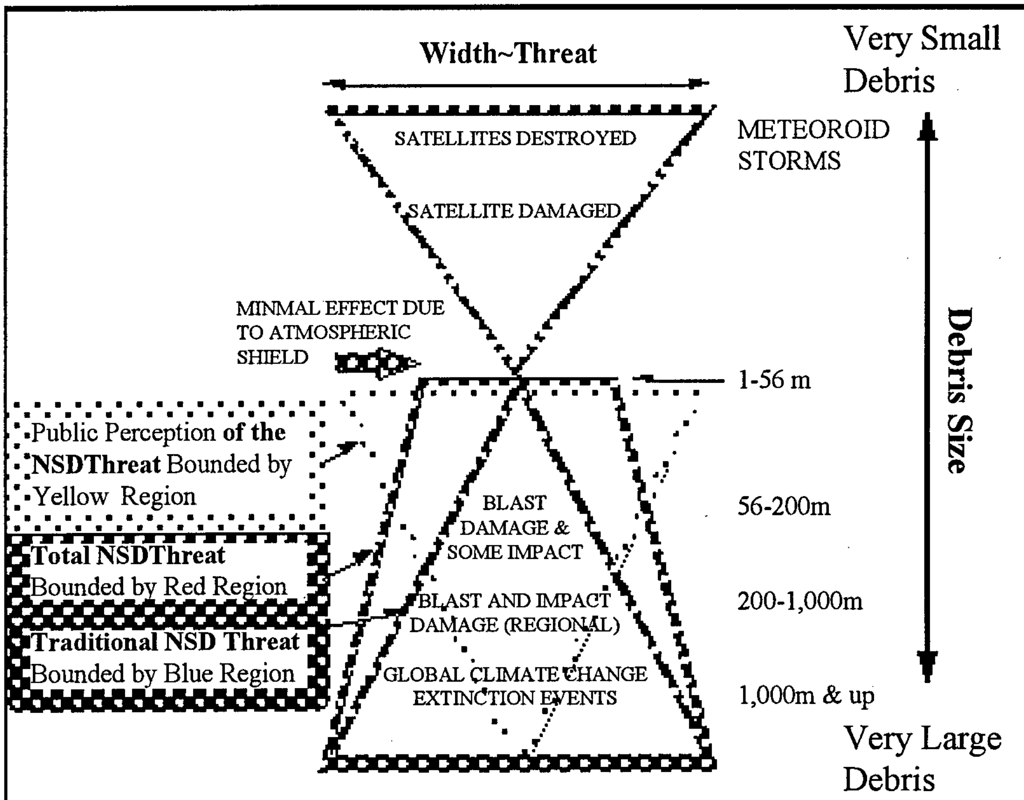


Figure 6-9. Notional NSD Threat Spectrum

Notes

[1] Note: Our reference to *defense* is used in the broad sense and does not imply we think an active missile system should already be in place. We are referring to a dedicated NSD search program and scientific research only.

[2] John K. Davies, *Cosmic Impact* (New York: St. Martin's Press, 1986), 25.

[3] Ibid., 24.

[4] Eugene M. Shoemaker, Ruth F. Wolf and Carolyn S. Shoemaker. "Asteroid and Comet Flux in the Neighborhood of Earth," *Geological Society of America Special Paper 247,* 163 (1990). and Clark R. Chapman and David Morrison, "Impacts on the Earth by asteroids and comets: assessing the hazard," *Nature* 367: 35,(January 1994) .

[5] Shoemaker and others, 168.

[6] Morrison, Chapter 3, 16.

[7] Ibid.

[8] Clark R. Chapman and David Morrison, "Impacts on the Earth by asteroids and comets: assessing the hazard." *Nature 367*: 34, (January 1994). Note: Chapman and Morrison estimate errors in debris population at a factor of 2 for objects >0.5km, 5 for smaller objects capable of causing damage and 15 for small objects.

[9] David Morrison (editor), *The Spaceguard Survey: Report of the NASA International Near-Earth-Object Detection Workshop,* NASA Office of Space Science and Applications, Solar System Exploration Division, Planetary Astronomy Program of Jet Propulsion Laboratory/California Institute of Technology, Pasadena California. 25 January 1992, 128-130 (Chapter 2, 11-13). and Clark R. Chapman and David Morrison, "Impacts on the Earth by asteroids and comets: assessing the hazard," *Nature* 367: 34, (January 1994). Note: As pointed out by Chapman and Morrison, the total average impact flux estimates derived by Shoemaker (in "Asteroid and Comet Flux in the Neighborhood of Earth," *Geological Society of America Special Paper 247*) do not take into account recent Spacewatch data suggesting an existing enhancement in the small asteroid (~50 meters) flux. Nor does it take into account possible flux rate variations due to comet showers. According to Chapman and Morrison, the impact flux may be as much as five times higher than shown in the Spaceguard report, Figure 2-4. In other words, this figure has an associated error band that is not presented.

[10] Note: From the perspective of discussing the necessity of threat mitigation measures, a conservative risk assessment is one that would accept the highest reasonable level of risk prior to taking some action.

[11] Personal interview with Mr. John Darrah, Chief Scientist, Headquarters Air Force Space Command, Peterson AFB CO, 28 November 1994. Note: In addition to this interview, we have conducted an extensive review of literature and found no indication of existing seach programs, with the exception of Spacewatch (already discussed).

[12] Note: By small debris we mean asteroids and comets between 56m and 1 km, as well as meteor streams (threat to space assets).

[13] Clark R. Chapman and David Morrison., 36.

[14] Chapman and Morrison, 33. Note: The threat to civilization is an all or nothing proposition. Either civilization is in danger of being destroyed or it isn't. Obviously, the destruction of civilization is unacceptable. As discussed in Chapter 5, the threshold for concern regarding life is about 1 in a million. This measure is normally used as the limiting case since, of all things life is held most precious. However, it seems the potential loss of civilization is more precious than an individual life (or number of lives); thus the threshold for concern will be lower than 1 in a million. The exact threshold in this case has not been determined.

[15] Keith Smith, *Environmental Hazards: Assessing Risk and Reducing Disaster*. (New York: Routledge, 1992), 38-44.

[16] Note: This statement assumes the impactor isn't large enough to create massive tidal waves. Generally objects less than 200 meters would not create a tsunami under most conditions (as discussed in Chapter 4). Tunguska is a good example of what an

impact would do in an unpopulated area. Tunguska was between 80 and 100 meters in diameter. Unfortunately, as the world population grows it will be harder to find a land mass where an object could strike without massive loss of life.

[17] Gregory H. Canavan, "Future Direction for Research: Value of Space Defenses," *The Spaceguard Survey: Near Earth Object Interception Workshop Summary* Sponsored by NASA Headquarters, Hosted by Los Alamos National Laboratory, Los Alamos, New Mexico, 14-16 January 1992, 261.

[18] Gregory Canavan "Value of Space Defenses," *The Proceedings of the Near-Earth-Object Interception Workshop* Los Alamos NM: Los Alamos National Laboratories, February 1993, 261-271. and Personal interview with Gregory H. Canavan by Major Bell. Los Alamos National Laboratory, Los Alamos, New Mexico. December 1994. Note: According to Canavan, his work analyzing the economic impact of an NSD impact as justification for detection and defense systems proposed in Spaceguard Survey is the first and only report written. An extensive literary search failed to find any other analyses.

[19] Note: Dr. Canavan's analysis was never intended for this purpose. We only mention it because as far as we can tell, it is the only substantial economic analysis that has been done.

[20] Note: The communications system may be particularly vulnerable to meteor storms if several satellites are disabled, or must be temporarily taken out of service to mitigate the risk of storm damage as a result of a storm warning (as we propose).

[21] M. Beech, P. Brown and J. Jones, "The Potential Danger to Space Platforms from Meteor Storm Activity," To be published in *Quarterly Journal of the Royal Astronomical Society*: Preliminary copy: (26 October 1994 with revised Figure 2, December 1994) 8.

[22] Ibid., 7.

[23] Ibid., 9.

[24] Ibid., 9.

[25] F. L. Whipple, *Possible Hazards to Satellite Vehicle From Meteorites,* 1 September 1946, Douglas Aircraft Company, Project RAND, Supplement to chapter 11, Rep. No. SM-11827, Appendix III, 1079.

[26] Fred L. Whipple., *The Meteoritic Risk to Space Vehicles,* 1957, Proceedings from the VIIIth International Astronautical Congress, Barcelona, 426-427.

[27] Ibid., 427.

[28] Darren S. McKnight, "Orbital Debris-A Man-made Hazard," *Space Mission Analysis and Design 2nd ed:* Eds. Wiley J. Larson and James R. Wertz, (Torrance CA and Boston: Microcosm Inc and Kluwer Academic Publishers, 1993), 758.

[29] William B. Wirin, "Law and Policy Considerations," *Space Mission Analysis and Design 2nd ed.* Eds. Wiley J. Larson and James R. Wertz, (Torrance CA and Boston: Microcosm Inc and Kluwer Academic Publishers, 1993), 756-757.

[30] McKnight, 757.

[31] Note: Some very recent discussions indicate some interest in tracking much smaller debris. At least some of this new interest is a result of the planned US space station. NASA would like to find all objects (in the space station orbit) that are bigger than a centimeter.

[32] McKnight, 759.

[33] Ibid., 759.

[34] M. Beech, P. Brown and J. Jones, 16.

[35] "Get the Drift," *Ad Astra,* 7-8, (November/December 1993).

[36] Peter Brown, International Meteor Organization, University of West Ontario, Canada. Telephone Interview, 13 October 1994.

[37] M. Beech, P. Brown and J. Jones, 2.

[38] Ibid., 3.

[39] Ibid., 3,12.

[40] Note: At least on the surface, this seems a valid assumption in that the Perseids were probably created by the same sorts of processes that created other streams. Also, the density of the Perseids is comparable to the density of most other streams, with one exception being the Draconids (which are much less dense). However, there are also some potentially important differences between the streams that may make this assumption invalid under some circumstances. The two most important being: the velocities relative to Earth and the distribution of debris within the streams. The later parameter is not well quantified for any stream. Limited debris distribution data exists on the Leonids and Perseids (see Beech Brown and Jones).

[41] McKnight, 757.

[42] Joseph K. McDermott, "Power," in *Space Mission Analysis and Design 2nd ed,* Eds. Wiley J. Larson and James R. Wertz, (Torrance CA and Boston: Microcosm Inc and Kluwer Academic Publishers, 1993), 392.

[43] Emery Reeves, "Spacecraft Design and Sizing," in *Space Mission Analysis and Design 2nd ed.* Eds. Wiley J. Larson and James R. Wertz, (Torrance CA and Boston: Microcosm Inc and Kluwer Academic Publishers, 1993), 292-295, 324-338.

[44] McDermott, 401.

[45] M. Beech, P. Brown and J. Jones, 21.

[46] M. Beech, P. Brown and J. Jones, 21. and Peter Brown. Department of Physics and International Meteor Organization, University of Western Ontario Canada.

Telephone interview regarding Leonid storm modeling status and Leonid storm dates. 29 March 1995. Note: Model predicts highest probability of storm at 23:00 universal time, 17 November 1999. Storm will be worse than the last documented storm in 1967. It will not be visible from North America. Best observation point will be in the area of Diego Garcia.

[47] McKnight, 761-766. Note: This reference addresses potential risk mitigation plans for spacecraft.

[48] Note: In addition to the impact effect, the vulnerability of the elements must be considered in the threat assessment.

[49] Note: Even temporary disruption of some resources would result in economic losses. An impact near any major land mass will affect someone's resources. An impact at sea could cause unforeseen ecological damage that would affect fishing, it could also disrupt shipping lanes, communication, deep sea oil platforms, and islands (some of which are important ports).

[50] Note: A 100 meter diameter asteroid (stone) with an impact velocity of 20 km/sec would poses kinetic energy equivalent to ~75 megatons of TNT. Refer to Chapter 4 for more info on calculating kinetic energy.

[51] M. Beech, P. Brown and J. Jones, 21. and Peter Brown. Department of Physics and International Meteor Organization, University of Western Ontario Canada. Telephone interview regarding Leonid storm modeling status and Leonid storm dates. 29 March 1995.

CHAPTER 7

The NSD Detection and Discrimination Problem

Before we discuss the various systems that could be used to find an asteroid on a collision course with Earth, we need to present some of the basic detection and discrimination methods available, and explain key problems these systems must overcome. It is our hope that an appreciation of the difficulties will provide the reader with valuable insight into the utility and limitations of various detection system components presented in Chapter 8.

The ultimate goal of any asteroid and comet detection program would be to find and catalog all near-Earth objects with the potential for causing damage on Earth. Regardless of the types of sensors used, the system will be pushed to the limits to overcome the difficulties associated with such a gargantuan task. As we discussed in Chapter 4, objects with diameters greater than ~56 meters can cause tremendous damage if they fall in or near a populated area. Therefore, we will need our system(s) to be capable of finding objects in the 50-60 meter range. According to the latest estimates, there are somewhere between 4 and 10 million Earth-crossing asteroids with diameters of 50 meters or larger, many of which come close to Earth.[1] In fact, about 6,000 asteroids larger than 100 meters in diameter pass within 0.058 AU of the Earth each year, that's almost 17 per day.[2] The near-Earth asteroid environment is fairly dense; yet, the passage of these potentially deadly rocks goes largely unnoticed. As of 1992, only 128 of them had been found.[3] Locating the remaining several million asteroids will be a big job. In addition to the problems caused by the shear number of objects, many will lie in orbits that do not favor detection from Earth-based observing systems. For those in difficult orbits or with properties that make them hard to see, one possible solution would be to build space-based sensors. Unfortunately, as we will discuss later, the cost of such systems may prove prohibitive. Therefore, we take the initial position that we will be forced to do most work from Earth-based sensors and find creative ways of coping with the inherent difficulties. To that end, we will attempt to explain the nature of the challenges ahead.

Asteroid Detection and Discrimination

There are essentially three types of systems available for finding objects out in space: visual observation, infrared sensors and active radar. All of these allow us to find and track asteroids (or comets) through two general processes we will refer to as *detection* and *discrimination*. The two step concept is illustrated in Figure 7-1 for an optical system. The detector, in this case a telescope, collects light from the sky and forms an image. The image will contain many stars as well as objects within the solar system such as planets, comets and asteroids. The discrimination step endeavors to filter out stars and known objects, leaving only the asteroids and comets.

If either the detection or discrimination processes fail to perform its function, the whole process fails. Because of the wide variety of potential impact geometry's and asteroid/comet orbits, none of the search systems are capable of doing the entire job alone. Each has difficulty in certain situations but fortunately they complement one another very well. Hence, the proper combination of systems would provide very good asteroid

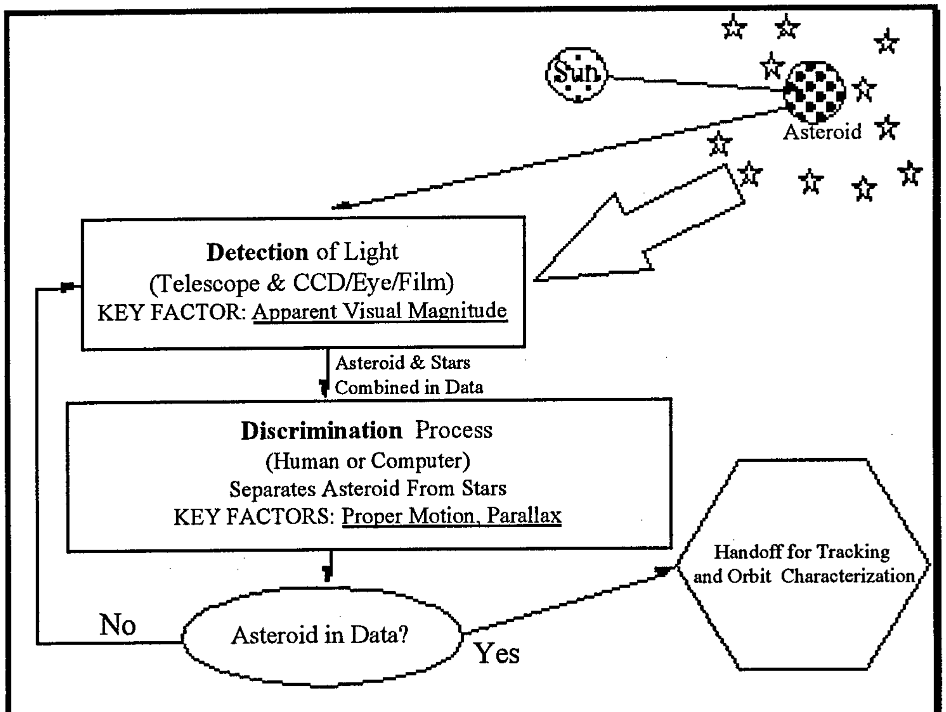


Figure 7-1. General Detection & Discrimination Process for an Optical System

detection capabilities. How do we decide what combination of systems is needed? The answer lies in developing an understanding of the capabilities and limitations of each, as applied specifically to the asteroid and comet detection problem.

Asteroid Detection Factors—Optical Telescopes

When we look through a telescope at an asteroid, we are seeing light from the Sun being reflected from its surface. The more light that's reflected, the brighter it will appear and the better we will be able to see it. The measure of brightness is known as the *apparent visual magnitude* and is determined by five parameters: distance from the Sun, distance from the Earth, diameter, albedo and reflection phase law. Many of these parameters depend on the observation geometry; that is, the relative positions of the

Earth, Sun and object being viewed. Before proceeding with a discussion of these parameters, we will review the magnitude scale to give the reader some points of reference for various values of magnitude.

Magnitude. The magnitude of an object refers to its brightness as measured from a particular location (i.e. Earth in most cases).[4] As such, magnitude does not directly relate information about an object's size. Its important to remember that the magnitude scale is a non-linear measure of brightness where the brightest objects have a lower magnitude and dimmer objects have a higher magnitude. As shown by Figure 7-2, the brightest stars in the sky are considered to have a magnitude of zero while the faintest stars that can be seen with the naked eye are 6th magnitude. A single division change in magnitude corresponds to a change in brightness of ~2 1/2 times.[5]

Orbit Geometry and Phase Angle. At present, most asteroids are found when they are within a few degrees of a point in their orbits called opposition, meaning that the Earth is between the object and the Sun; thus the object's disk, as viewed from Earth, is fully illuminated.[6] The geometry is illustrated by Figure 7-3 for an asteroid in an Earth-crossing orbit. Notice that as the angle between the Sun and Earth, called the phase angle,

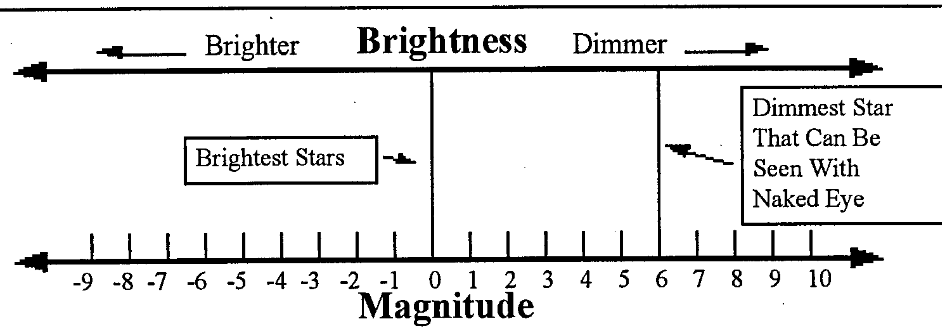


Figure 7-2. Magnitude Scale

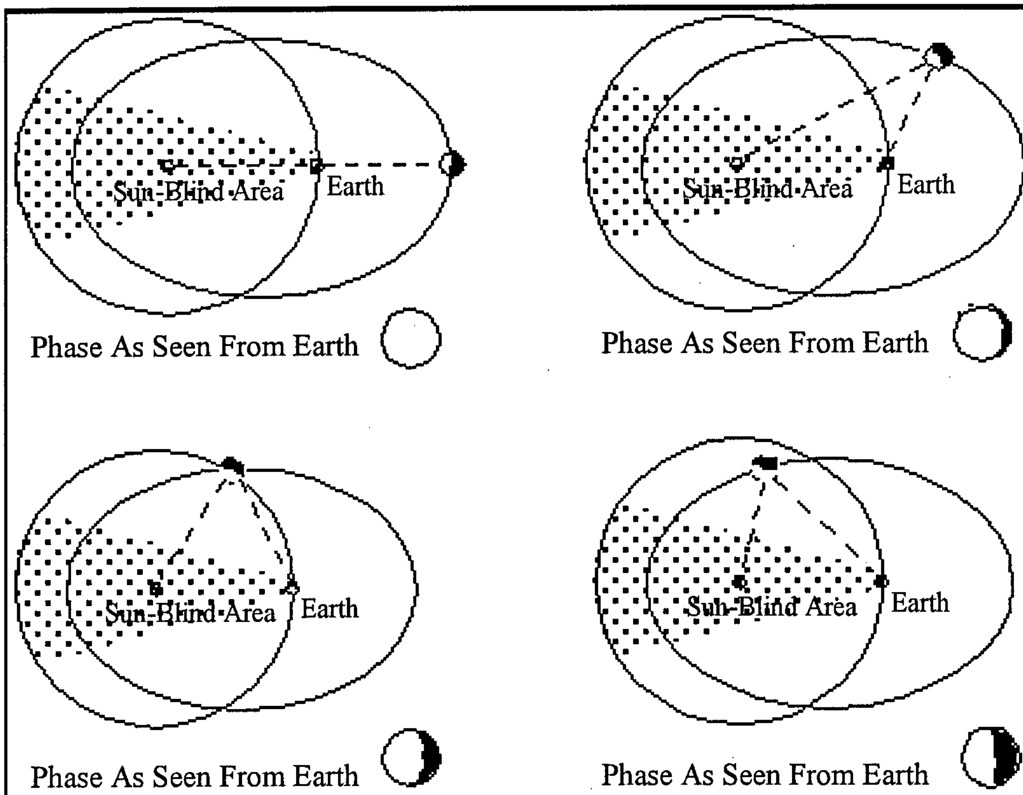


Figure 7-3. Orbit Geometry and Phase Angles for a Typical Apollo Asteroid. Opposition is in Upper Left Corner.

increases from 0° (opposition), the object will become dimmer because we are seeing a smaller portion of the lighted side. Though the geometry is different, this is the same effect that causes the moon to go through phases. A new moon corresponds to a phase angle of 180° and full moon corresponds to 0°.

Asteroids whose orbits graze or barely cross Earth's, such as those in the Atens Family, show different phase progressions. Figure 7-4 shows the geometry and phase for a typical Atens asteroid at various positions in orbit. The important difference between the Apollo/Amor asteroids and the Atens, is that the latter generally spend very little time

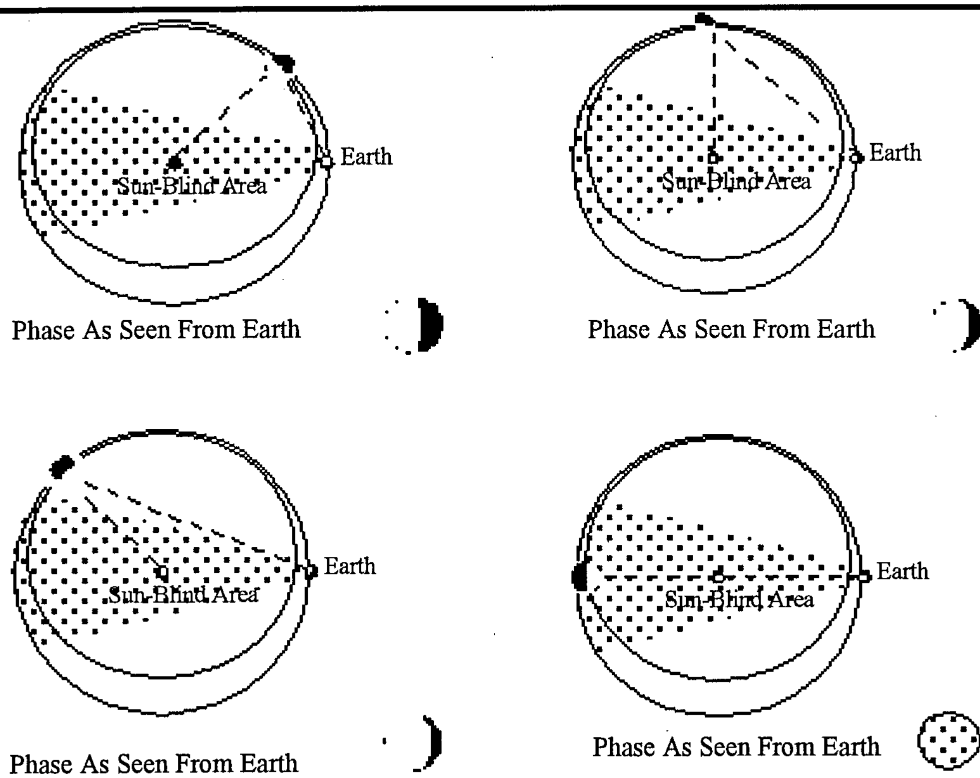


Figure 7-4. Orbit Geometry and Phase Angles for a Typical Aten Asteroid. Atens Are Rarely Seen in Opposition.

at opposition (if any). Therefore, while Apollo and Amor asteroids appear as fully illuminated or gibbous disks throughout most of their orbits, the Atens will be completely dark (when between the Earth and Sun, also called inferior conjunction) and gradually grow toward a gibbous shape until lost in the Sun. Unfortunately, optical systems are not capable of searching out objects closer than 25° or 30° of the Sun (indicated by yellow shaded region) due to the glare.[7] As a result, Atens asteroids or comets close to the Earth-Sun line will not be seen fully illuminated. The effect of phase angle on ground-based telescopes is to cause many potentially dangerous asteroids to drop below the detection threshold throughout large portions of their orbits; thus reducing our chances of finding them.

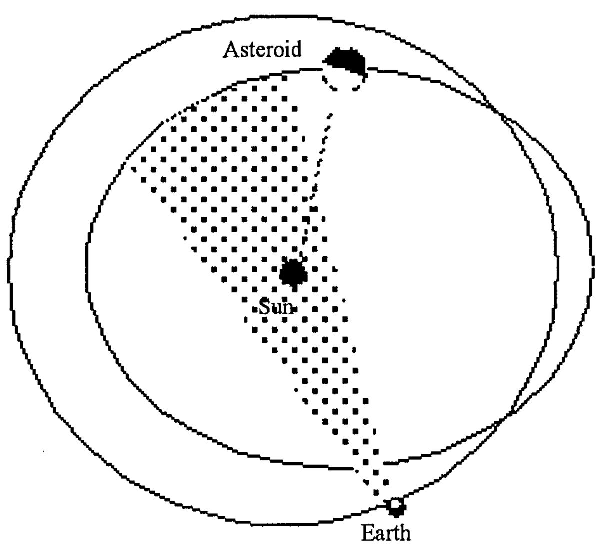
Distances. The effect of distance is relatively straight-forward. Figure 7-5 shows the path light must travel to get from the Sun to the asteroid, where it is reflected to Earth. The Sun emits light at a relatively constant level of intensity. According to the inverse square law, the intensity varies as the inverse square of the distance from the source; therefore, we can find the intensity of the sunlight at the asteroid as,[8]

$$I_{asteroid} \cong 1400 \cdot \left(\frac{r_{Earth}^2}{r_{asteroid}^2} \right) \cong \frac{1400}{r_{asteroid}^2} \qquad (19)$$

where,

$I_{asteroid}$ is in joules per square meter per second
$r_{asteroid}$ is the distance of the asteroid from the Sun in astronomical units (AU)

Thus, the farther the asteroid is from the Sun, the less light falls on its surface. Once the sunlight reaches the asteroid, only a small portion will be reflected. As we'll discuss later,



the amount of light reflected toward Earth varies greatly according to the physical surface properties of the object and phase angle; however, whatever light leaves the surface will also diminish in intensity according to the inverse square of the distance to the point of observation (Earth in this case). This means the object's distance from the Sun and Earth makes a big difference in its brightness. Therefore, an asteroid may only be visible from Earth during a small portion of its orbit.

Diameter. The influence of size on the apparent visual magnitude of an asteroid is obvious. Larger objects have a larger illuminated surface; thus the reflected light reaching Earth is greater than for small objects.

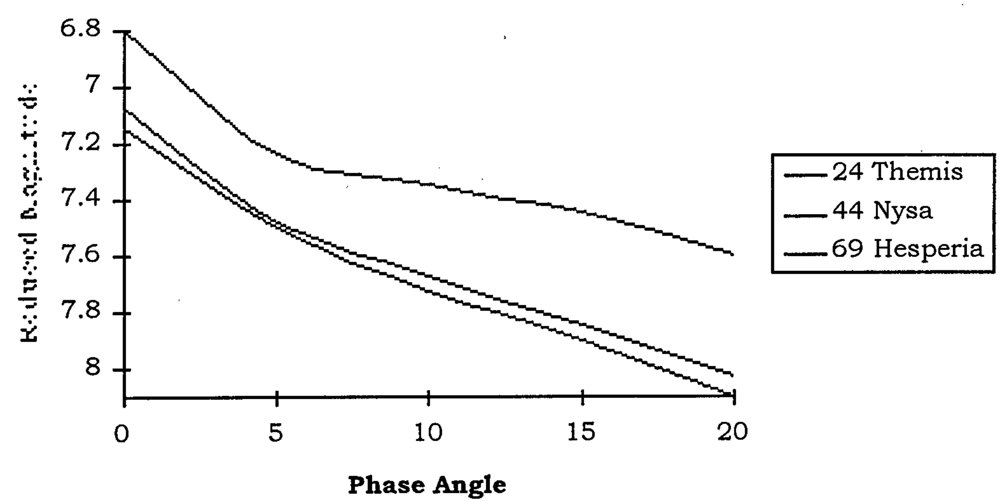
Albedo. Albedo (also called visual Bond Albedo) is defined as the ratio of light reflected to that received at the object's surface. A bright object has a high albedo. For example, Venus, the brightest planet has an albedo of about 0.65 meaning that it reflects 65% of the incident light while the Moon has an albedo of about 0.067.[9] Low albedos are typical of bodies without atmospheres. In 1986, the European Space Agency's Giotto spacecraft flew by Halley's comet. The data gathered indicates that, in spite of the bright coma and tail created by the loss of its ices, the nucleus has an albedo of only about 0.05.[10] Ground observations of other comet nuclei indicate that they too have low albedo's. The significance is that, when the comets are in deep space where no tail can form, they will be very hard to see. Halley's nucleus will only reflect 5% of the light that hits it. Its small size, low albedo and great distance from the Sun (when near aphelion) will make it practically invisible to ground based telescopes. If this is true of most comets, then there may be many more of them than we previously thought. Also, those we know about may be bigger than estimated since our size calculations are often based on brightness. Like comets, asteroids have widely varying albedos.

Reflection Phase Law. The brightness of an asteroid or comet varies significantly with changes in viewing geometry (refer to Figure 7-3). The way they vary depends on the object's optical surface properties (the way it scatters the light); unfortunately, no two surfaces are exactly alike.[11] In other words, two asteroids orbiting side-by-side with the same exact size, shape and albedo would have different apparent visual magnitudes if their phase laws were different.

Surface material composition, porosity, roughness and the object's overall shape are just some of the parameters affecting the phase law. Unfortunately, we have very little accurate data on the phase law of asteroids and comets. In addition, the data that we do have is usually gathered at low phase angles, within a few degrees of opposition.[12] As you can see from Figure 7-6, the shape of the curves change at around five degrees and all three are slightly different. These curves are typical but even larger magnitude variations have been measured.[13] Therefore, if one were to assume a phase law based on observations near opposition and try to extrapolate to large angles, the potential for error would be significant.

Because of this lack of data, Hills and Leonard developed a model based on the Moon's phase law (which is very well established), with which to size a detection system. According to their model, the change in magnitude is given by,[14]

$$\Delta V_{\text{asteroid}}(\alpha) = \frac{-0.011875448 + 0.024581561\alpha - 0.000132101 66\alpha^2}{1 - 0.0070737368\alpha + 0.000007959163\alpha^2} \qquad (20)$$



Source: Bowell et al., "Application of Photometric Models to Asteroids," in *Asteroids II.*

Figure 7-6. Phase Laws of Three Representative Asteroids

for phase angles between 0° and 160° where,

> $\Delta V_{asteroid}$ is the change in magnitude due to phase law
> α is the phase angle in degrees

The change in magnitude for angles between 160° and 180° is given by,[15]

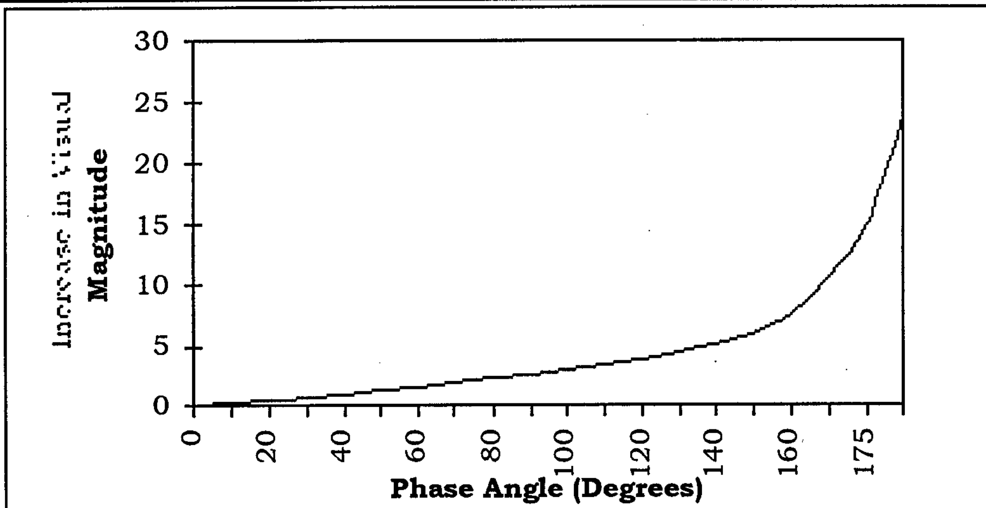
$$\Delta V_{asteroid}(\alpha) = \frac{7.5\sqrt{20}}{\sqrt{180 - \alpha}} \tag{21}$$

Plotting these equations gives us Figure 7-7. To use the plot, read the magnitude for the corresponding phase angle and add this to the object's apparent visual magnitude to compensate for phase law effects. This is a somewhat limited model as applied to asteroids and comets because it assumes the object is spherical and that surface properties obey the lunar phase law.[16] The latter assumption probably isn't too bad based on a quick comparison with a small sample of real asteroid data. Figure 7-6 shows the change in visual magnitude of three asteroids for the first 20 degrees of phase angle. The total change is only about one increment of magnitude which is consistent with Figure 7-7 over the same interval. The spherical shape assumption is probably not valid for the small 56 to 1 kilometer diameter asteroids. Its likely most of the small asteroids will be irregularly shaped. Fortunately, irregularities in shape will generally make the asteroids appear somewhat brighter at large phase angles than the equation predicts; thus the relation, while somewhat inaccurate, is conservative.[17]

Apparent Visual Magnitude. Having discussed all the parameters affecting the apparent visual magnitude of the asteroid or comet we can now tie it together. The apparent visual magnitude can be estimated by,[18]

$$\begin{aligned} V_{asteroid} = & -5.0\log_{10}\left[\left(\frac{1.0025696}{r_{asteroid-Sun}}\right)\cdot\left(\frac{10^4}{3.476\cdot 10^8}\right)\cdot\left(\frac{0.0025695}{d_{asteroid-Earth}}\right)\right] \\ & -2.5\log_{10}\left(\frac{0.2}{0.067}\right)+F(\alpha)-12.73-5.0\log_{10}\left(\frac{D}{10^4}\right)-2.5\log_{10}\left(\frac{A}{0.2}\right) \end{aligned} \quad (22)$$

where,



Source: Based on Model of Hills and Goda.

Figure 7-7. Lunar Phase Law

$r_{asteroid\text{-}Sun}$ is the distance from the Sun to the asteroid in AU
$d_{asteroid\text{-}Earth}$ is the distance from the asteroid to the Earth in AU
D is the diameter of the asteroid in *centimeters*
A is the visual Bond albedo (dimensionless)
$F(\alpha)$ is the change in magnitude for the appropriate phase angle, α from Figure 7-7

Given the magnitude, as we'll see in the next chapter, we can determine the requirements for the optical detection system (telescope and CCD) for various geometry's and object sizes. Conversely, we can also estimate the capabilities of existing systems and compare them to the performance required to find an object near the minimum (56 meter) size of interest. We will tackle systems and system performance in the next chapter using these relations.

Asteroid Detection Factors—IR Telescopes

Optical (visible) wavelengths are not the only frequencies that can be exploited to detect asteroids and comets. All objects with sunlight falling on them will convert some of that light into heat by absorption. As we discussed above, much of the light falling on an asteroid's surface is not reflected. The measure of reflectance is albedo. So, an object with an albedo of 0.1 will reflect 10% of the light that hits its surface. The other 90% is converted to infrared or black body radiation, otherwise known as heat. The parameters affecting an object's IR brightness are nearly the same set of parameters we used for the optical systems. The asteroid's distance from the Sun and Earth, its diameter and its albedo are all important. However, phase law is not a significant factor.

If we assume a spherical object that is tumbling just fast enough to evenly heat its surface, the phase law effect discussed above for optical systems does not apply. An IR detector *sees* the object by detecting the heat that is radiating from it. Thus, temperature becomes a measure of IR brightness (and emission frequency). For a solid object with reasonably good thermal conductivity, no matter where the heat (sunlight) is applied, the entire object will appear to be at very nearly the same temperature regardless of the viewing angle. Even an asteroid almost directly between the Earth and the Sun would appear bright in IR even though the lighted side is turned completely away from Earth. An object will appear as a fully illuminated disk at all phase angles in IR.

The apparent IR magnitude of an object as viewed from Earth is given by the following series of Equations,[19]

$$T_{eff} = 263\sqrt{1/r_{asteroid-Sun}} \cdot \left[\frac{(1-A)}{0.8}\right]^{1/4} \quad (23)$$

$$f_N = 1.51 \cdot 10^{-19}\left(\frac{1}{d_{asteroid-Earth}}\right)^2 \cdot \left\{\exp\left[5.36 \cdot \left(r_{asteroid-Sun}\right)^{1/2}\right] - 1\right\}^{-1} \cdot \left(\frac{D}{10^4}\right)^2 \quad (24)$$

$$N = -2.5\log_{10}\left(\frac{f_N}{1.23 \cdot 10^{-16}}\right) \quad (25)$$

where,

$r_{asteroid\text{-}Sun}$ is the distance from the Sun to the asteroid in AU
$d_{asteroid\text{-}Earth}$ is the distance from the asteroid to the Earth in AU
D is the diameter of the asteroid in *centimeters*
A is the visual Bond albedo (dimensionless)
T_{eff} is the object's effective temperature in °K
f_N is IR (N-Band, 10.2 μm) flux in W cm^{-2} μm^{-1}
N is the apparent magnitude in infrared

As with the optical systems, we will use these relations in the next chapter to help evaluate detection system options where IR systems would be useful.

Optical and IR System Comparison. Optical detection systems have two major disadvantages as applied to the Earth crossing asteroid detection problem: strong dependence on phase law and the low albedos of most natural space debris.

Dependence on phase law means that objects will not be visible throughout much of their orbits because of the phase geometry we discussed earlier. This is going to make finding objects in the Aten and Apollo families difficult since many of these are seldom seen at opposition.

Low albedo refers to the fact that most of the light is not reflected; rather, its absorbed by the object and re-radiated as heat. A quick survey of albedo data on 3318 asteroids indicates typical values range from 0.03 to 0.25.[20] So, we can expect only 3% to 25% of the incident light to be reflected. Obviously, the combined effect of low albedo and a large phase angle would make optical detection of a small asteroid very difficult if not impossible. On the other hand, IR systems are relatively independent of phase effects. Objects radiate heat in all directions regardless of the orientation of the illuminated side with respect to the observer. Further, while a low albedo makes optical brightness lower, it makes IR brightness higher.

It would seem from our discussion that IR systems are far superior to optical systems, so why use optical at all? The answer is that optical detectors are more sensitive, especially when applied to objects outside of Earth's orbit and near opposition. Optical systems are also generally less expensive than IR detectors; however, technology and demand may change this in the near future.

RADAR Systems (Detection & Discrimination)

Radar systems can and have been used to study asteroids but not nearly as extensively as optical and IR systems. The biggest problem with using radar is the high power required. Unlike optical and IR systems that use the Sun as the source of illumination, radar must provide its own. Therefore, the amount of energy arriving at the antenna after reflection from the asteroid will be diminished by the distance to the asteroid raised to the fourth power. In essence, that means you'll need a high power transmitter and a high gain antenna to get an echo from a small asteroid if the distance to the asteroid is great. A general relation for the smallest detectable object is given by,[21]

$$\sigma = \frac{4\pi R^4 \lambda^2 L(S/N)kT_s}{P_{avg} A_e^2 t_{ot}} \tag{26}$$

where,

σ is the minimum detectable radar cross-section (m^2)
R is the distance to the asteroid in meters
λ is the wavelength of the radar in meters
L is a miscellaneous loss factor
S/N is the required signal to noise ratio for detection
k is the Boltzmann constant (J/K)
T_s is the system noise temperature in °K
P_{avg} is the average transmitter power in watts
A_e is the equivalent area of the antenna in m^2
t_{ot} is the time on target (asteroid) in seconds

As you can see, the primary considerations for radar detection of an asteroid is distance to the target, transmitter power, antenna gain and the operating frequency. In spite of radar's disadvantage for long range targets, it does offer some capabilities not offered by optical and IR systems.

Radar has an advantage over optical systems in that, like the IR systems, phase angle does not apply. The transmitter illuminates the asteroid from Earth and the radio wave returns, having been reflected from the asteroid surface; so, the effective phase angle will always be zero. Thus, radar can be used to search any segment of the sky without regard for the position of the Sun. Obviously, the Sun can be a source of interference; however, with proper design a radar can search the area very near (from our line of sight) the Sun without difficulty. Furthermore, when a signal (echo) is received, you know immediately that the object is not a star or other distant object. You don't need to worry about distinguishing the object from the stars by proper motion or parallax. The strength, polarization and time between signal transmission and receipt tells much about the object's size and position.

This discussion makes it seem radar is easier to use than it really is. False echoes, interference, definition of search patterns, unknown surface properties of the asteroids and high cost are just a few of the problems that a deep space surveillance radar system would have to deal with. By itself, radar can not do the job, but it does complement the other systems in key areas, such as those near the Earth or near the Earth-Sun line. As we will see in the next section, several existing space surveillance radars could contribute to the asteroid detection problem as well as help characterize the major meteor streams.

Distinguishing Asteroids and Comets from Background Stars (Discrimination)

Having discussed the basic mechanisms governing the visibility or detection of an asteroid, we need to go a step further to discuss how we might go about identifying a small asteroid from among the many thousands of other specks of light within the detector's field of view. There are three available methods to distinguish an asteroid from the background stars: positional, proper motion, and parallax. The positional method is of little use in asteroid hunting because it requires knowledge of the object's position and ephemeris. In other words, you need to know where it is before you point your instrument. While this is useful for tracking known objects, (a necessary activity since orbits can change dramatically due to perturbations of planets), it will not help with the larger problem of finding the bulk of the undiscovered objects. Therefore, we will only discuss the last two methods.

Proper Motion. Proper motion of an object refers to its apparent motion, as seen from Earth, against the star background. The procedure for detecting asteroids using their proper motion was developed over a century ago and remains largely unchanged today[22] It involves taking a time exposed picture of a segment of sky with a wide field of view telescope designed to compensate for Earth's rotation (track a fixed point in space). When the film is developed, stars in the field look like small dots of light, while the objects closer to Earth (which are moving) such as asteroids and comets will create a smeared image. A similar method involves taking two photographs of the same segment of sky about 45 minutes apart. These photos, when viewed under a stereoscopic microscope, will show any moving object within the field in three dimensions. In other words, they will appear to float in front of the star field.[23] Eugene and Carolyn Shoemaker used this method to find comet Shoemaker-Levy 9.[24]

Photographic methods work, but are expensive, labor intensive and slow.[25] The Spacewatch telescope system represents one of the first technological improvements in asteroid and comet detection. Spacewatch, a telescope run by the University of Arizona, uses a charge-coupled detector (CCD) instead of film to capture the images. As the images are captured, they are stored and processed by a computer in near real time to seek out possible new comets and asteroids[26] The automation saves a lot of time and labor but a significant amount of data must still be worked by hand.[27]

Regardless of which of the above methods we choose, we are still relying the object's proper motion. It is important to remember throughout our discussion on detection systems that asteroids and some comets (those with minimal coma and tail) will look like just a dim point of light when viewed through even the best of telescopes. Proper motion is an effective method of distinguishing an object from the background when the geometry is such that we are able to see it moving. Unfortunately, the objects we are most concerned with, those on a collision course with Earth, will have very small proper motions (less than 0.2 arcsec per minute).[28] From our perspective, they will be coming straight toward us. Therefore, they will not seem to be moving with respect to the stars; so they would escape detection by methods dependent on proper motion.

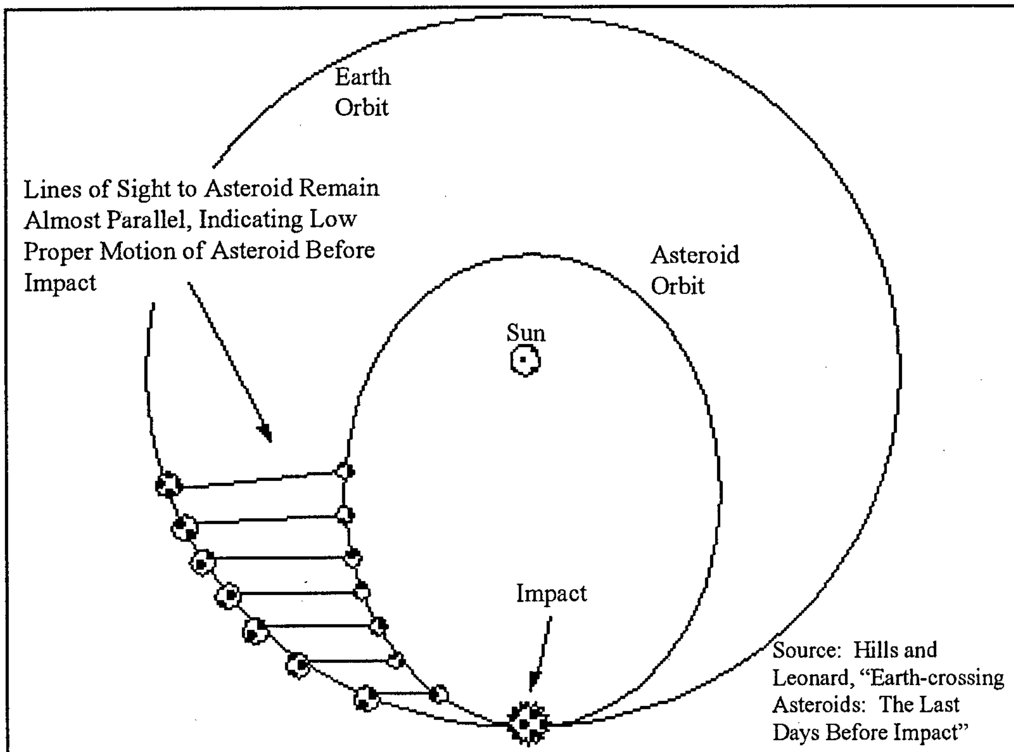


Figure 7-8. Collision With a Typical Aten Asteroid, Showing Small Proper Motion

Fortunately, we have another method at our disposal.

Parallax. Parallax refers to the apparent change in position of an object (against the star background) when viewed over a baseline of one Earth radius. For very distant objects, such as stars, the parallax angle is too small to measure. However, closer objects, will have a measurable parallax. So, for objects on a collision course with Earth, we can use their parallax to distinguish them from the stars. In the last one or two weeks from impact, an asteroid or comet will have a small proper motion but a large parallax.[29] It will also be getting brighter. Therefore, a system built to look at the near Earth environment, looking specifically for objects with a large parallax would be able to find objects bearing

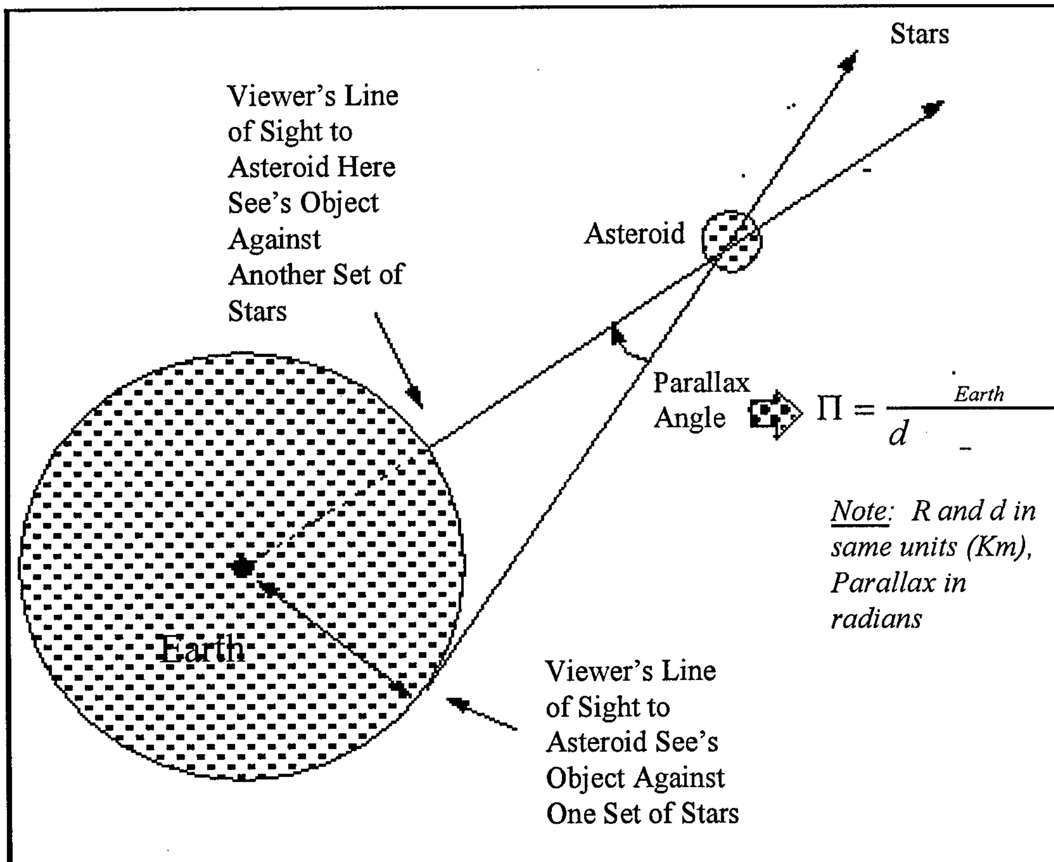


Figure 7-9. Geocentric Parallax of an Asteroid Seen From Earth

directly down on Earth.

Effects of Atmosphere on Ground-based Systems

Since we are focusing on the use of ground based systems to find asteroids and comets, we need to address another important factor that will influence the design and location of an asteroid warning network: the atmosphere. No matter what type of system we use, optical, IR or radar, the detection path must pass through the Earth's atmosphere. As environmentalists frequently point out, our air is not transparent. Smog and light pollution combined with natural conditions such as fog, clouds, and air turbulence will decrease our ability to detect objects whose apparent visual magnitudes, proper motions and/or parallax are near the limits of our instrument's capabilities. To a large degree atmospheric effects can be minimized by putting the instruments in locations that have good observing conditions. This is a common practice and is the reason we find so many observatories on mountain tops and in the deserts of the US southwest. But even in the best of locations, the atmosphere will have a measurable effect.

Atmosphere Effect On Apparent Visual Magnitude. For optical systems, the change in apparent visual magnitude can be estimated by,[30]

$$\Delta m = \frac{0.2}{\cos(z)} \qquad (27)$$

where,

Δm is the increase in magnitude due to the atmosphere.
z is the zenith angle, 0° is straight up and 90° is on the horizon. Equation is only valid over the range $0° \leq z \leq 85°$.

This relation is shown by Figure 7-10. As you can see, objects directly overhead are only slightly dimmed, whereas, objects near the horizon will appear nearly two an a half magnitudes dimmer. Remember, this is only an estimate and it is only valid for relatively clear skies. Viewing conditions will vary significantly between locations and over a range of weather conditions. Even a good location will have times where the seeing is bad. The effect of atmosphere on optical systems is a significant factor when we begin discussing various systems in the next chapter. At least one system (using a liquid mirror) must always point straight up. While this is a disadvantage in some respects, it is also an advantage in that the system is always working at the point of least atmospheric effect. More on this in Chapter 8.

Atmosphere Effects on Resolving Power. In addition to dimming the light from

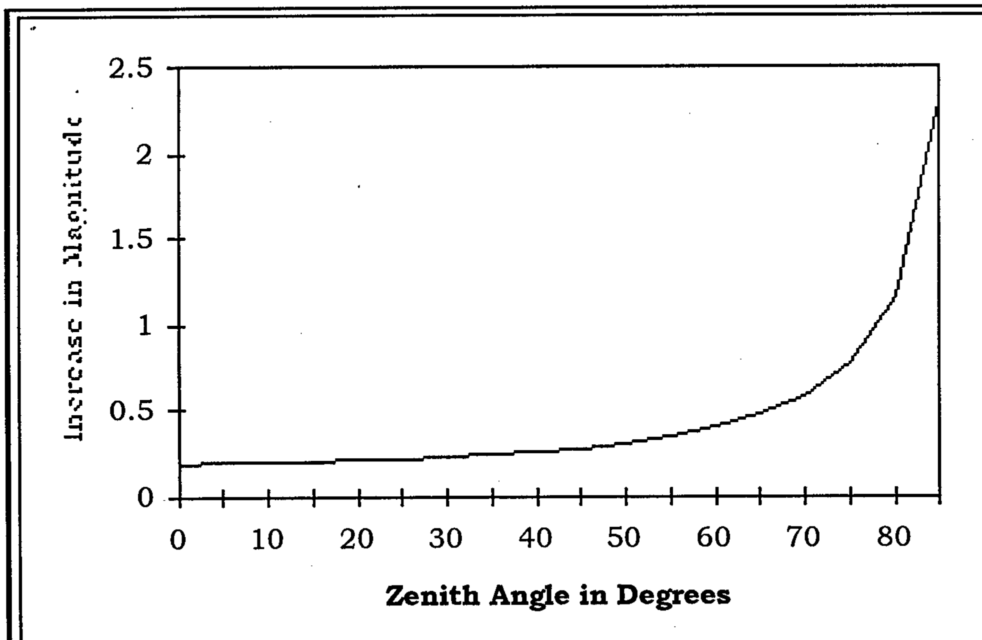


Figure 7-10. Change In Asteroid's Apparent Visual Magnitude Due to Atmospheric Extinction

an asteroid, turbulence and temperature gradients in the atmosphere will distort the light before it gets to the telescope. It is this effect that causes the stars to twinkle. Unfortunately, the distortion makes it difficult to perceive small proper motions or parallax angles of objects in the field of view. As a result, even a system that is designed to resolve very small angles will often not be able to realize its full capability. For example, the Spacewatch telescope has a theoretical resolving power of ~ 0.15 arc seconds; yet even the best seeing conditions would permit no better than 1 arc second.[31] More often than not, *seeing* would limit the instrument to around 2 arc seconds of resolution.

We will address how we determine an instrument's resolving power later in this chapter. For now, just be aware that the ability of an instrument to resolve small angles is directly related to its resolving power and will be limited by the atmosphere. The best way to minimize atmospheric distortion is to select a site that has good seeing. However, as long as the system is Earth based, you can not expect to get much better than 1 arc second of resolution; so if the optical system can't do the job with that limitation you have to turn to other systems. Possible solutions include fitting the telescope with adaptive optics or moving the system outside of the atmosphere.

Atmospheric Effects on IR and Radar Systems. The atmospheric effects discussed so far were tailored to optical systems. While, similar, the effects of atmosphere on IR and radar systems are a good bit more complicated and will not be presented. The important thing to remember is that these systems will also have diminished performance due to the atmosphere, especially near the horizon.

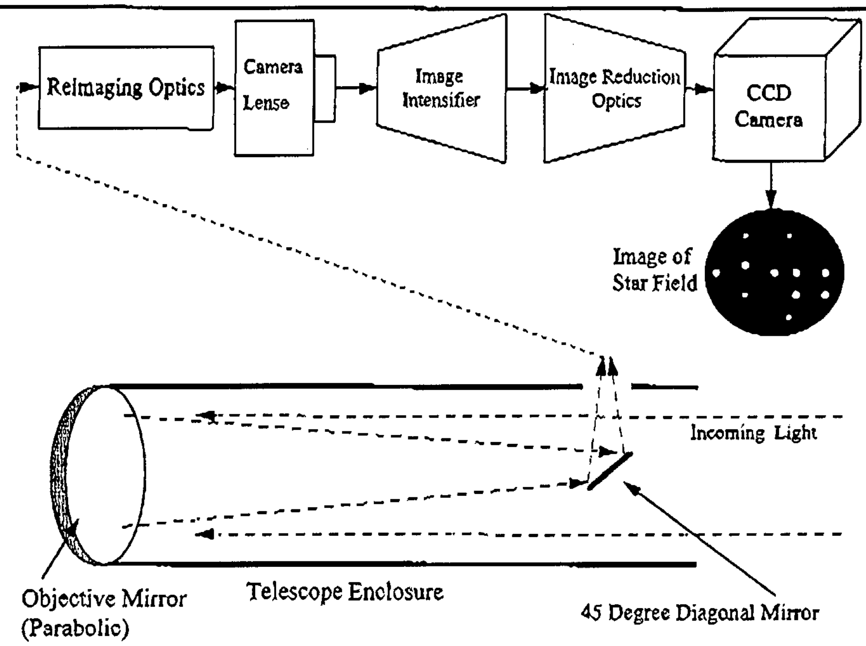


Figure 7-1. Basic Functional Layout of a Typical Newtonian Telescope System

Key Instrument Design/Performance Factors (Optical and IR Systems)

In the next chapter we will be looking at both new (i.e. proposed) and existing systems to determine how they might be used to search out Earth-crossing asteroids and comets. In order to conduct a meaningful assessment we need to get a handle on the key design factors affecting system performance. As before, we will discuss the detection and discrimination issues separately.

Detection. The limiting magnitude of the telescope system defines its capability to find asteroids and is determined by the focal ratio, the diameter of the objective and the sensitivity of the device capturing the image. Hills and Leonard showed that the limiting magnitude of a modern CCD based system can be approximated by,[32]

$$M_{\lim it} \cong 22 + 5\log_{10}\left(\frac{f \cdot D}{457.2}\right) \qquad (28)$$

where,

> f is the focal ratio of the objective, only valid for $f \leq 5$
> D is the diameter of the objective in centimeters

Further, the dwell time, that is, the amount of time the telescope must stare at the object before sufficient light has been collected to produce a satisfactory image (i.e. time exposure equivalent) is given by,[33]

$$t_{\exp osure} = 2\left(\frac{f}{5}\right)^2 \text{ minutes} \qquad (29)$$

Therefore, given the diameter and focal ratio of the optics, we can estimate the limiting magnitude various instruments can reach, as well as the amount of time required to cover a given area of sky.

The general detection criteria is summarized in Figure 7-12. While the figure is describing an optical system, the IR criteria are very similar. The major difference being that the factors influencing the apparent visual magnitude of the asteroid in the IR band (discussed earlier) would replace those of the optical system. In essence, Figure 7-12 just says the asteroid must be brighter than the minimum capability of the instrument in order to be detected.

Discrimination. In order to tell the difference between an asteroid (or comet) and the background stars we use proper motion or parallax. The actual process of discrimination is done by a software algorithm, or alternately, by a very dedicated, experienced person. However, the performance of the optics and camera also play a critical role. The ability of these components, as a system, to detect either proper motion or parallax is related to the system's *resolving power* which is defined as,[34]

$$\vartheta_{\min imum} = 1.22 \cdot \frac{\lambda}{D} \tag{30}$$

where,

> λ is the light-wavelength of interest, $5.6\text{x}10^{-5}$cm for white light and $1.02\text{x}10^{-3}$cm for IR[35]
> D is the diameter of the telescope objective in centimeters
> $\theta_{minimum}$ is the minimum angular displacement that the instrument can detect in radians (multiply by 206264.81 to get arc seconds)

Equation 30 defines the theoretical limit of resolution for the telescope optics in a vacuum. Unfortunately, minor defects in the optics combined with the atmospheric effects already covered, will prevent the instrument from achieving such a high level of performance. For example, the GEODSS telescopes have a 40 inch (101.6 cm) objective.[36] Thus for white

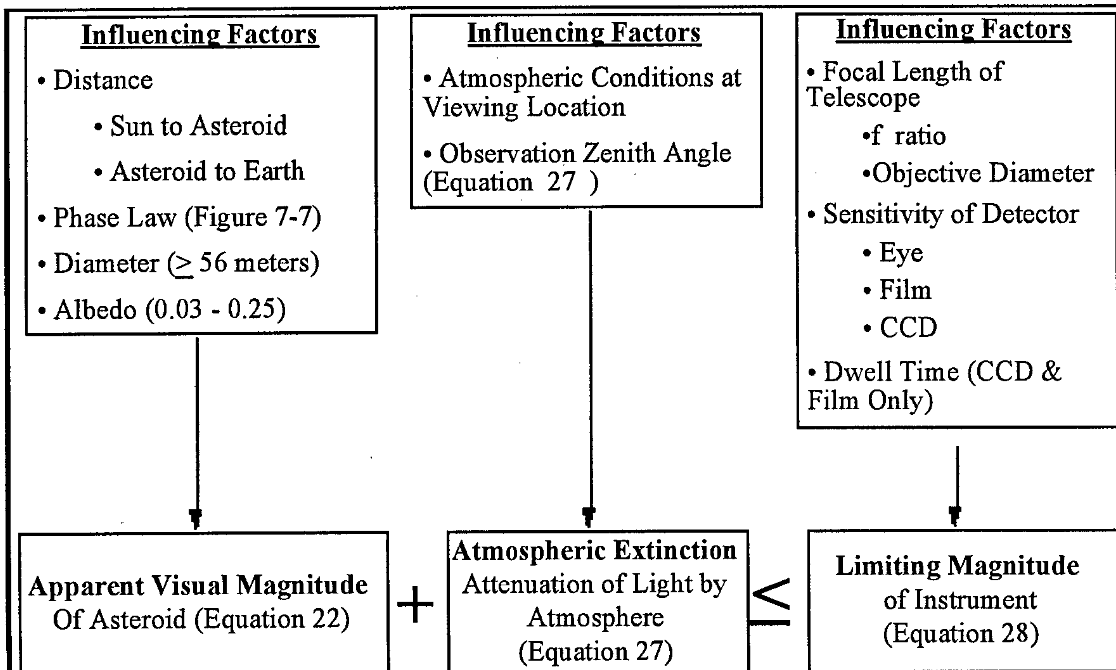


Figure 7-12. Factors Governing Detection

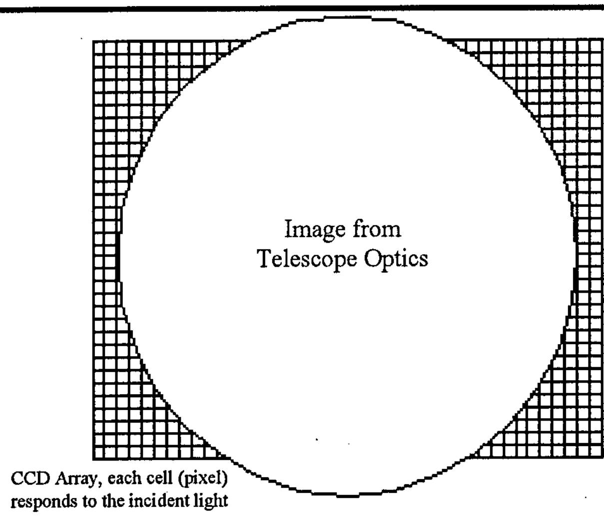


Figure 7-13. Image Placement on CCD

light, one could expect a minimum angular resolution around 0.14 arc seconds. The atmosphere will seldom allow better than 1 arc second; so as we said before, the atmosphere is the limiting factor (unless adaptive optics are used).

Another factor is the resolution of the camera CCD or film. Since we hope to work toward an automated system, we will focus on the CCD. The idea is to choose a sensitive CCD (to minimize $t_{exposure}$) with sufficient number and density of cells, such that the resolution of each cell is about equal to the minimum angle of resolution (with atmospheric effects included), then select optics to project the image on the CCD as shown in Figure 7-13. In most cases, the CCD will be the limiting factor in the system design because it will determine the limiting magnitude of the telescope, as well as its resolution. As we will discuss in the next chapter, these are two of the key system performance factors; so the selection of the CCD will be critical.

Summary

In this chapter we have discussed how NSD is found and some of the problems a search system will have to overcome. The next step is to look at systems, both new and existing, that could be used in a search program and assess their utility and cost.

Notes

[1] David Morrison (editor), *The Spaceguard Survey: Report of the NASA International Near-Earth-Object Detection Workshop* NASA Office of Space Science and Applications, Solar System Exploration Division, Planetary Astronomy Program of Jet Propulsion Laboratory/California Institute of Technology, Pasadena California. Chapter 3, 16, (25 January 1992).

[2] J.G. Hills and Peter J.T. Leonard, "Earth-crossing Asteroids: The Last Days Before Earth Impact," to be published in *Astronomical Journal* (January 1995), Draft Document dated 18 August 1994, 21.

[3] Morrison, Chapter 3, 15.

[4] James Muirden, *The Amateur Astronomer s Handbook 3rd Edition* (New York: Harper & Row Publishers, 1983), 4-5.

[5] Ibid., 5.

[6] Hills and Leonard, 15.

[7] Hills and Leonard, 27.

[8] Francis A. Jenkins and Harvey E. White, *Fundamentals of Optics, 4th Edition*, (New York: McGraw-Hill Book Company, 1976), 230-231.

[9] Paul Weissman, Michael F. A'Hearn, L.A. McFadden and H. Rickman., "Evolution of Comets into Asteroids," *Asteroids II:* Eds. Richard P. Binzel, Tom Gehrels and Mildred Shapley Matthews (Tucson, AZ: University of Arizona Press, 1989), 900-901 and Hills and Leonard, 15.

[10] Weissman and others, 900-901.

[11] Edward Bowell, Bruce Hapke, Deborah Domingue, Kari Lumme, Jouni Peltoniemi and Alan W. Harris, "Application of Photometric Models to Asteroids," *Asteroids II:* Eds. Richard P. Binzel, Tom Gehrels and Mildred Shapley Matthews (Tucson, AZ: University of Arizona Press, 1989), 524.

[12] Hills and Leonard, 15.

[13] Bowell and others, 542-546.

[14] Hills and Leonard, 15.

[15] Ibid.,15.

[16] Ibid.,17.

[17] Ibid.,17.

[18] Ibid.,16.

[19] Ibid.,19-20.

[20] Edward F. Tedesco, "Asteroid Magnitudes, UBV Colors, and IRAS Albedos and Diameters," *Asteroids II:* Eds. Richard P. Binzel, Tom Gehrels and Mildred Shapley Matthews (Tucson, AZ: University of Arizona Press, 1989), 1093-1138.

[21] Ross T. McNutt, Phillips Laboratory, Air Force Systems Command, Hanscom Air Force Base, MA, *Orbiting Space Debris: Dangers, Measurement and Mitigation* Research paper, No. PL-TR-92-2146 1102, 92, (1 June 1992).

[22] W. Bowell, N.S. Chernykh and B.G. Marsden, "Discovery and Follow Up of Asteroids," *Asteroids II:* Eds. Richard P. Binzel, Tom Gehrels and Mildred Shapley Matthews (Tucson, AZ: University of Arizona Press, 1989), 24 & 33.

[23] Eugene M. Shoemaker, Scientist Emeritus, US Geological Survey, "Discovering the Beauties and Dangers of Comets," Lecture at the USGS, Menlo Park, CA. 6 December 1994.

[24] Ibid.

[25] Ibid.

[26] Jim Scotti, Director Space Watch Program, University of Arizona, Tucson Arizona. Telephone Interview. 13 October 1994.

[27] Jim Scotti. Director, Spacewatch Program, University of Arizona, Tucson AZ. Telephone Interview. 13 October 1994.

[28] Hills and Leonard, 22.

[29] Ibid., 21.

[30] Peter Duffett-Smith, *Practical Astronomy With Your Calculator 3rd Edition*, (Cambridge: Cambridge University Press, 1988), 82.

[31] Don Kessler and Drew Potter, NASA JSC, Telephone Interview. 9 February 1995.

[32] Hills and Leonard, 26.

[33] Ibid.

[34] Jenkins and White, 330-331.

[35] Peter J. Brancazio, *The Nature of Physics* (New York: Macmillan Publishing Co., 1975), 353. and Hills and Leonard, 18. Note: N-Band magnitude equations are for 10.2 μm = 1.02 x 10^{-3} cm.

[36] McNutt, 91.

CHAPTER 8

Search Systems

In previous chapters we defined the nature of NSD and explained the nature of the threat. The next step is to investigate what can be done to find the myriad of asteroids and comets in Earth-crossing or Earth-approaching orbits. In Chapter 7, we presented the key factors associated with an instrument's ability to find an asteroid. Our focus now will be to use that information as the basis for assessing the capability of existing Air Force assets to carry out an asteroid/comet search mission. We recognize that existing systems may not have excess capacity; thus may not be able to absorb another mission. It's beyond the scope of this paper to conduct usage surveys in an effort to determine whether various resources are being fully utilized. Our goal is to show what these systems *could do* if tasked. If Air Force or government leaders decide the Air Force should assume responsibility for asteroid/comet search and defense, then the following assessment will serve as a starting point from which to establish a program.

In keeping with our initial premise, that we can not afford to devote a lot of resources to the task, we stress the use of existing systems and equipment designs instead of new systems designed specifically for the task. In other words, we want to see how much of the search can be done with what we have on hand (again, assuming the system is available for use). Only in areas where clear deficiencies exist will we present suggestions for new systems to fill the gap. Even in these cases, emphasis will be placed on low cost solutions.

General System Objectives and Requirements

Ultimately, we would like to outline a viable and cost effective search program. Unfortunately, to do this right, we need something we don't have: a clear set of objectives and related requirements for system performance. In other words, how do we know what the system must do to be considered successful? What are our objectives? Without that information, we can not define the system, and without a system definition we can't develop a cost estimate. It is true that Spaceguard made progress on this issue. However, that report primarily defines requirements in terms of "specialized ground-based" equipment rather than in general terms applicable to any system, existing or otherwise.[1] To fill the void, we offer the following objectives for an NSD search system. An effective Natural Space Debris Search System must:

> **Asteroids & Comets:** Detect, discriminate, determine orbit parameters, determine size and composition, and catalog natural space debris that crosses or approaches Earth orbit in order to provide adequate warning of Earth impact. Provide follow up observation of cataloged objects in order to update orbit parameters.

> **Meteor Streams:** Identify and characterize meteor streams capable of generating storms such that these storms can be predicted far enough in advance to permit orbiting assets to implement their threat mitigation plans.

Note that the *system* is defined as the sum-total of all assets allocated to the search task, not just individual instruments. Optical, Infrared (IR) and radar must be used in concert if we are to have an effective program. Figure 8-1 shows the way these systems will be used to compliment one another.

Optical instruments (telescopes) will be the primary search tools. They provide the simplest means to cover large volumes of space. However, as our search areas approach the Earth-Sun line, optical systems become less effective. Glare from the Sun and the

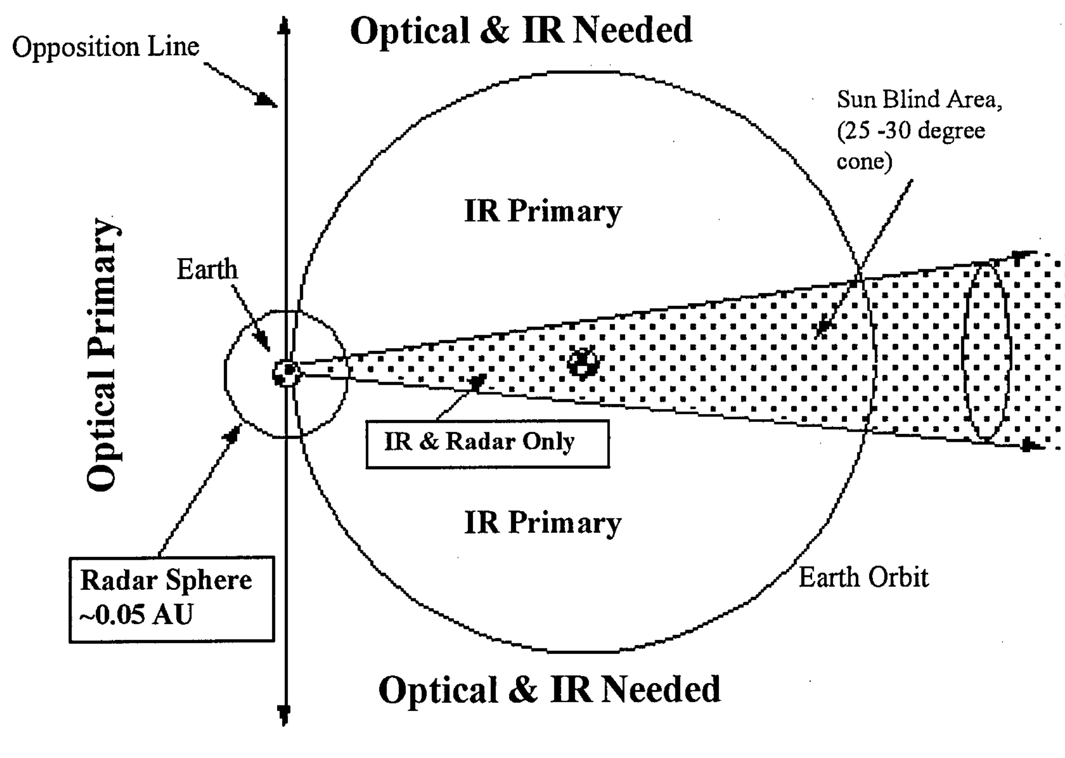


Figure 8-1. Contributions of Optical, IR and Radar Systems to Search Mission in Terms of General Search Areas

effect of phase angle on the magnitude of the targets (as discussed in Chapter 7) will severely degrade optical performance. It is in this area that the IR systems are most useful. They do not suffer from the phase angle effect on magnitude, so they will have very good performance where the optical systems fail. Finally, radar is the only instrument capable of searching very close to the Earth-Sun line. But because of the huge power requirements, it is limited to objects fairly close to Earth.[2] The real utility of radar is its ability to quickly gather the data necessary to accurately determine an object's orbit. Given time, optical and IR systems, can do the job by determining the object's position at several (three or more) points in its orbit. By adding radar measurements (range and range rate) we can do the job faster and with greater accuracy.

Obviously, the stated objectives are very broad and lack the substance necessary to perform an assessment of a system's capability to do the job. Therefore, the next step is to break the objectives down into requirements which, if met, would lead to a successful search program. Without a doubt, the rigorous definition of system requirements is worthy of a study in itself and is therefore beyond the scope of our paper. Still, we need something to work with, so we pulled together the requirements shown in Table 8-1. We believe the key system performance factors shown are valid (for reasons we will address below), and that together they provide a set of requirements we can use for system evaluation and comparison. However, there may be other key factors that we have not identified. These would be brought out in a rigorous systems analysis.

The requirements are divided into two groups: *preferred* and *acceptable*. The *preferred* column reflects the performance we would like the system to have in an idealized sense, and the *acceptable* column represents a lower limit on acceptable system performance. Taken together, they define a performance range that we can use as a rough measure of merit for the search systems we will discuss later. The following paragraphs explain why these factors were chosen and how we arrived at the suggested requirements.

Table 8-1. Asteroid and Comet Search System Key Requirements

	Key Factor	Suggested General System Requirement	
		Preferred Capability	Acceptable Capability
General	*Minimum Object Diameter of Interest* Assuming Worst Case Albedo (0.03) at Opposition	56+ meters	200 meters
	Survey Duration: Time Required to Find 90% or More of Asteroids and Short-period Comets	≤ 5 years	≤ 25 years
Optical	*Maximum Warning Time (Indicator Only)* for 1 km Diameter Asteroid (Albedo = 0.03 at opposition)	10 years	1 year
	Coverage (Coverage Rate of twice per month adequate for both dark and standard sky search areas)	Dark Sky Region: centered on opposition, ± 120° celestial long. by + 90° celestial lat. (~34,000 sq deg)	Standard Region: centered on opposition, ± 30° celestial long. by + 60° celestial lat. (~6,000 sq deg)
	Resolution: Minimum Detectable Proper Motion or Parallax	0.2 arcsec	1-2 arcsec
IR	*Limiting Magnitude*	16	8
Radar	*Resolution*	3 arcsec	15 arcsec
	Coverage	14,000 sq deg	3,000 sq deg
	Minimum Number of Objects That Can be Observed by Radar (Total System)	100 per year	50 per year
Archit.	*Maximum Radar Tasking Response Time*	1 day	7 days
	General System Architecture	Centralized Control and Coordination, Distributed Instrument Sites	Centralized Control and Coordination, Distributed Instrument Sites
Data	*Data Storage*	Full Image Storage	Partially Processed

General System Requirements

Minimum Object Diameter of Interest. We base our minimum detectable object diameters on our discussions in Chapter 4 (see Figure 4-8). As you'll recall, the largest asteroid the atmosphere can effectively stop is around 56 meters in diameter. Anything larger (or more dense than stone) will penetrate far enough to cause damage at the surface. Therefore, we would like our system to be able to find asteroids and comets 56 meters and larger.

Some reviewers have suggested that going after such small objects is overly ambitious, and even unnecessary. This is hardly surprising when we consider the heated debate that took place between members of the Near Earth Object Detection Workshop and the Near Earth Object Interception Workshop. On one side of the debate we have those who are convinced that objects on the small end of the spectrum present the greatest threat (*Tunguska class*), and on the other side we have those who adamantly insist that only those greater than ~2 km in diameter are a threat.[3] After considering both sides of the argument, we conclude that it would be unwise to ignore the smaller objects.

Small asteroids (50 to 80 meter range) impact Earth about once every one hundred years.[4] Larger objects, (200 meters in diameter) only hit once every five to ten thousand years, and planet busters every million years or so.[5] While it's true that statistically, the threat from larger objects is much greater than that of the Tunguska sized objects, it is also true that we are much more likely to see a Tunguska event in our lifetimes. The question is: which is more important in the eyes of the public? As we discussed in Chapters 5 and 6, the public's perception of risk or hazard is not always governed by logic alone: emotions are always involved to some degree. Further, it appears from the highly personal nature of the debate (as documented in the Intercept Workshop record), that scientists are not exempt from this rule.

What is of greatest concern to the public: a small (but still energetic) impact that may occur in their lifetime or a large planetbuster that may happen sometime in the next million years? Since the public will ultimately be asked to pay for the effort, it seems reasonable to weigh their expectations along with the statistics before we decide to ignore the smaller objects. We are concerned that, once a program is funded, the public will expect to be informed of all impending impacts, (if not completely protected from them). In addition, from the public's perspective any impact damage, no matter how slight, will be deemed unacceptable, especially if they believe it could have been prevented. Therefore, we really can not afford to ignore the very objects that are most likely to hit us, no matter how localized we expect the resulting damage to be. Finally, we should not get too caught up in the probability of impact data. Statistically, we should expect only one Tunguska per one or two centuries; however, we could easily get the next ten impacts all within the same ten year period, instead of over a millennium.

We submit that, assuming an NSD search program is to be undertaken, there is only one acceptable reason for not going after Tunguska sized objects: a clear lack of technology to support the task. If cost is to be the overriding determinant (as is more likely) we need to perform a careful cost/benefit trade study to ensure the decision is well thought out and that the public clearly understands, not only what they are buying but more importantly, what they are not. We realize this sounds like an exercise designed to *cover your six.* While it might serve that purpose, the intent is to ensure such an important decision is not made in a cavalier fashion.

If finding the smaller objects isn't cost effective or technically possible, the next logical cutoff would be at around 200 meters. At this size, stony asteroids are capable of completely penetrating the atmosphere, resulting in damage from direct, as well as indirect, effects such as tsunamis and earthquakes.[6] From all we have seen, existing technology is adequate to find this size of object; however, if cost becomes an issue and a larger minimum size must be selected, our comments regarding a careful trade study still apply.

Survey Duration. This factor gives us a measure of how long we expect the survey to take. Because of the dynamic nature of the NSD system, we will never be completely finished. We will always have to be on the lookout for new objects and continue updating our databases to reflect the current status of the ever changing NSD orbits. However, there will come a time when we will have found and cataloged most objects. Our primary task will change from search, to the tracking and updating of orbit parameters for known objects. How long it takes to reach that point depends on the performance of the search system.

In general, we would like to minimize the amount of time it takes to complete the survey. In so doing, we decrease our costs as well as the risk of getting hit by an asteroid before we have had a chance to see it coming. Like warning time, the time required to complete the search will depend on the limiting magnitude of the search system, and additionally, the amount of sky it can survey in a particular period of time. These two parameters, in effect, define the system's search volume. Sensitivity to greater magnitudes allows an instrument to see *further* out for each square degree of sky searched; thus the survey can be completed faster.

The general concept is shown in Figure 8-2. Objects outside of the detection sphere (centered on Earth as it orbits the Sun) will not be found until their orbits carry them inside the sphere. Greater instrument sensitivity serves to enlarge the detection sphere, thus shortening the time required to complete the survey.

The Spaceguard team modeled the fraction of near-Earth objects that would be discovered in a hypothetical whole-sky survey as a function of object diameter, the limiting magnitude of the telescopes and the duration of the search program.[7] The results are shown in Figure 8-3 for all objects 1 km and larger. Notice the dramatic effect of limiting magnitude on the time it takes to complete the survey. At magnitude 22, it can be done (to 90%) within about 5 years, whereas at magnitude 20 it would take well over 25 years.

Based on the Spaceguard model, our suggested survey duration requirement of

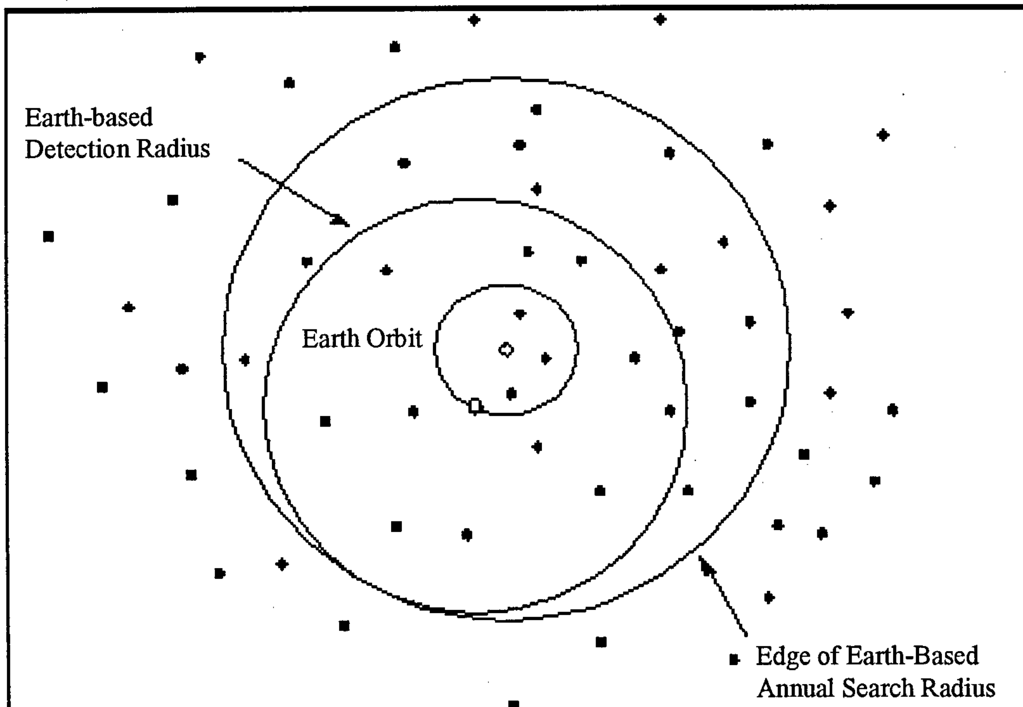
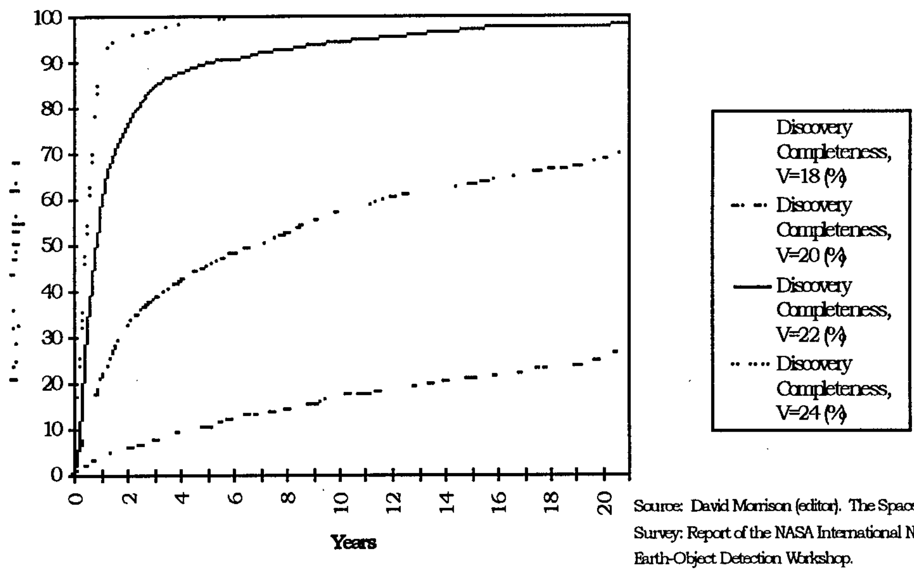


Figure 8-2. Objects Outside of Our Detection Sphere Will Not Be Found Until Their Orbits Carry Them Within Range of the Instruments



Source: David Morrison (editor). The Spaceguard Survey: Report of the NASA International Near-Earth-Object Detection Workshop.

Figure 8-3. Discovery Completeness For 1 km and Larger Earth-crossing Objects (Hypothetical Whole Sky Survey)

less than ten years (preferred) and 25 years (acceptable) seems well within reason. Current technology will easily permit instruments to reach magnitudes of 22 or even a bit higher. Of course, the times given assume the system conducts a complete survey of the sky twice per month (which is the minimum required for discrimination). A true whole-sky survey is not possible due to interference from the Sun and Moon, so the completion times given can not be taken literally. Depending on the actual coverage rate, some additional time would be needed. We will discuss coverage in more detail later.

Before we proceed, the reader should note that our requirements for minimum object diameter and survey duration apply to all instruments since they are all to be part of the same, integrated search program.

Optical System Requirements

Warning Time Indicator. The warning time requirement provides a way to compare the ability of various systems to detect incoming objects. As such it is directly related to the limiting magnitude capability of a system. However, unlike a magnitude specification, the warning time indicator gives the reader a feel for the effect that an instrument's limiting magnitude can have on the time we have to respond to a threat.

The purpose of an NSD search system is to identify threats so that we can take action to prevent impact or otherwise minimize damage. The nature of our response will depend on the size of the object and the time we have to respond. For objects in the 50 to 100 meter diameter range, it is not clear whether we should attempt to prevent impact or simply activate a disaster network and prepare to respond after impact (more on mitigation measures in Chapter 10). However, very large objects (1 km and up) determined to be on a collision course with Earth would almost certainly need to be deflected or destroyed since they present a threat to Earth's ecosystem and civilization itself (see Chapter 4). Deflection of such large objects is most easily (and reliably) accomplished many years before impact.[8] If we have warning on the order of decades, there are a great number of options open to us. Nuclear and/or conventional means could be used to alter the object's path enough to prevent impact.[9] As the warning decreases toward a year, we will have very few options left. There will be no time to perform reconnaissance missions and no margin for error. Further, nuclear devices will almost certainly be required since no other method can deliver the required energy. Table 8-2 shows the effects of warning time on interception for a 1 km diameter object. The bottom line is that greater warning time gives us more freedom of action (nukes vs. conventional means), increased safety margin (in case of error or failures) and an overall improved probability of successfully preventing a catastrophic impact. Therefore, warning time is a key system performance factor.

Table 8-2. Warning Time Effect on Interception

Category	**Warning Time**	**Action**	**Objects**
Well defined orbits. —Precursor missions are strongly advisable for detailed evaluation.	Decades	Long-term missions	Earth-crossing asteroids only
More Uncertain Orbit. —Luxury of precursor mission may be absent —Intermediate warning time (but still urgent) —Objects motion is affected by nongravitational forces (cometary bodies)	Years	Urgent response without much room for error	Newly discovered Earth-crossing asteroids and short-period comets
Immediate Threat —Best scenario: discovery at 10 AU. Discovery initiates emergency	12 Months to 1 Month	Every available engineering measure. Continue to refine orbit.	Long-period comets and small, newly discovered Earth-crossing asteroids
No Warning	0-30 Days	Evacuate Impact Area	Long-period comets and unknown Earth-crossing asteroids

Source: Derived from Table 2-1, Spaceguard Survey, Report of the Near-Earth-Object Interception Workshop.

The amount of warning we actually get will depend on a tremendous number of variables, not the least of which is random chance. Natural debris of all sizes is scattered throughout the solar system and is constantly in motion. When we finally establish an NSD search system we may well find a *planetbuster* on a collision course and only a short time from impact (bad luck), but more likely, we will find objects with the potential for hitting Earth many years in the future.

Whatever search system we choose, the survey will take time. We will not be able to survey the entire volume of space in the vicinity of Earth all at once; thus, even though our system may be capable of detecting the object several years from impact, it does not mean that it will do so. Given the complexity associated with finding NSD, we need to develop a simplified model by which we can compare the performance of various systems in terms of warning time and do so in a way that maintains a tie between instrument performance (limiting magnitude) and its effect on our ability to react to the threat, (warning time).

Simplified Warning Time Model. The warning time an instrument can provide is related to its ability to detect very faint (high magnitude) objects. Given a worst case albedo of 3% and phase angle of zero, we can determine the maximum distance a particular instrument can detect various sizes of objects using Equation 22. The problem

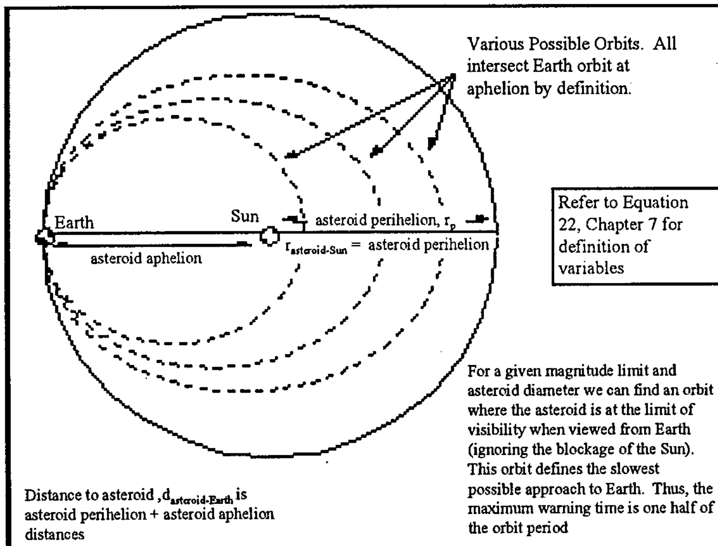
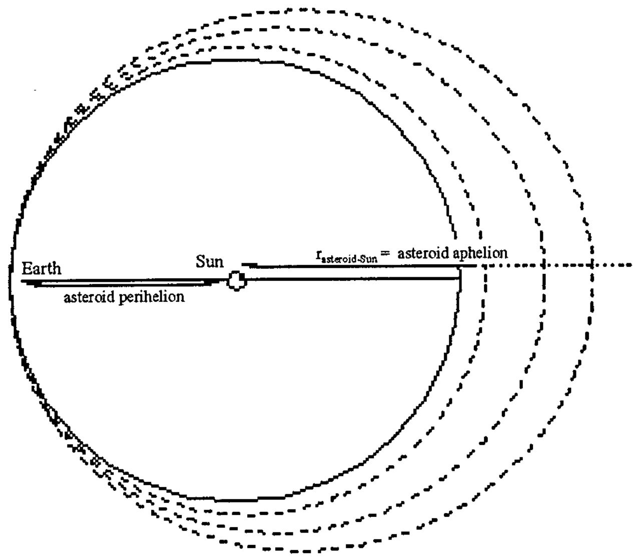


Figure 8-4. Geometry of Orbits Used to Determine Warning Time Indicator, Asteroid Orbit Intersects Earth Orbit at Aphelion



then becomes how to translate the distances into a measure of time to impact. Since both the NSD and the Earth are in orbit, the time to impact will depend on the path the object *flies* between its position when detected and the impact point. There are an infinite number of possible orbits that can connect two points in space; however, only one will define the maximum time to impact (assuming impact on first Earth-orbit crossing). The geometry associated with this maximum time to impact is shown in Figure 8-4. and Figure 8-5.

For an asteroid or comet to hit Earth, its orbit must at some point intersect Earth's orbit. Therefore, the model defines elliptical orbits with intersections at either aphelion (Figure 8-4) or perihelion (Figure 8-5). Ignoring the fact that the Sun blocks our line of site, we define the detection point to be at opposition (far side of Sun). Thus, assuming an impact is going to take place, the maximum time to impact for an object detected on the Earth-Sun line is half the orbital period of this orbit.

Using this geometry, we can find the orbit parameters and period as follows.

Setting,

$$r_{asteroid-Sun} = r$$
$$d_{asteroid-Earth} = r + 1.0167$$
$$A = 0.03$$
$$F(\alpha) = 0$$
$$\mathrm{V}_{asteroid} = \mathrm{V}_{\lim it}$$

we can solve Equation 22 (using the same variable definitions and units) for r,

$$r = \frac{-1.0167 + \sqrt{1.0167^2 + 4 \cdot c}}{2} \tag{31}$$

where,

$$c = \frac{-7.41111216 \cdot 10^{-8}}{10^y} \tag{32}$$

and

$$y = \frac{\left\{-V_{\lim it} - 11.86 - 5\log\left(\frac{D}{10^4}\right)\right\}}{5} \tag{33}$$

Therefore, using Equations 31 through 33, we can find the orbit associated with the maximum warning time for any combination of object diameter and instrument limiting magnitude. Once the distances are known we can find the orbital period by,

$$P = 2\pi \sqrt{a^3 / \mu_{Sun}} \tag{34}$$

where,

$$a = \frac{(r + 1.0167)}{2} \tag{35}$$

and,

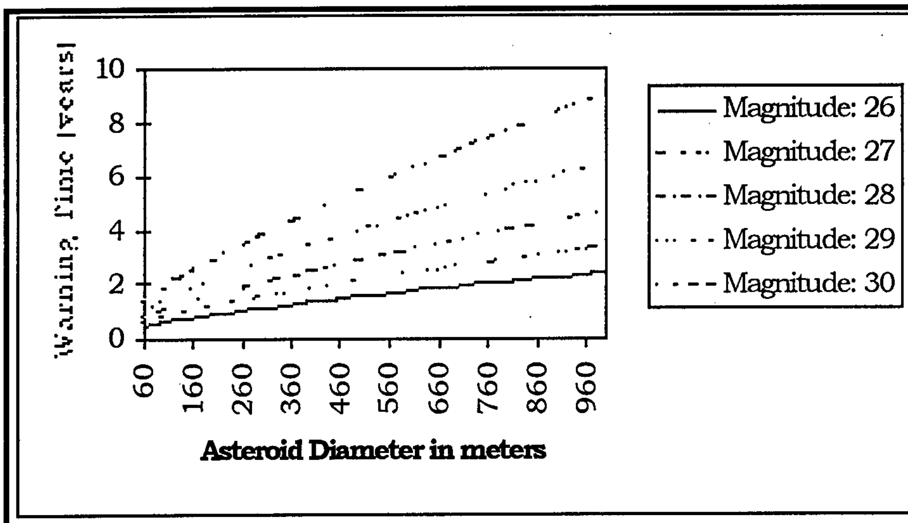


Figure 8-6. The Maximum Warning Time an Instrument Can Provide Depends On Its Limiting Magnitude and Object Diameter

μ_{Sun} is 1.32712438 x 10^{20} m^3/sec^2 (Sun's gravitational constant)
a is the semi-major axis of the object's orbit in AU
P is the orbital period in seconds, (1 year = 3.1557 x 10^7 seconds)

The warning time is then (by our definition) simply one half of the orbital period.

Figure 8-6 shows the results of the model for objects ranging from 60 meters to 1 km in diameter. As you can see, it will be very difficult to design a system that can give us the 10 years warning we said we would like to have (Table 8-1). Based on the model, we would need an instrument capable of reaching magnitude 30.3. A look at Equation 28 shows how impractical that is with today's technology. It would require a tremendous telescope with a mirror nearly 42 meters in diameter (assuming a focal ratio of 5). Even if we were to build such an instrument, the atmosphere would make it nearly impossible to achieve the limiting magnitude most of the time, leaving us with few alternatives. We could get improved performance by moving to a space-based system but that's probably too expensive. Barring major improvements in CCD sensitivity (quantum efficiencies) our only other choice is to do the best we can with existing technology and design our risk mitigation measures accordingly. In other words, we need to plan ahead and prepare ourselves to respond to the threat in a short time.

Using more realistic limiting magnitudes we see that warning times will most likely be on the order of only a few years for large objects. For example, the Spacewatch telescope is capable of reaching magnitudes somewhere between 20.5 and 22, so from Figure 8-7 we can see that we could only expect between six and nine months warning.[10]

Before we move on to the next factor, we want to reemphasize that the warning times predicted by the model are intended as a means to relate the performance of an instrument to its effect on our ability to react to a potential threat. The model reflects the maximum time we would have to respond to an unknown object that *drops in out of the black*. Thus, it gives a good indication of how a system would do against long-period comets. However, for known objects or those with periods less than a few hundred years, we could easily have much more warning than the model predicts. We have assumed that impact occurs on the first pass by Earth orbit (after detection). If the object does not hit,

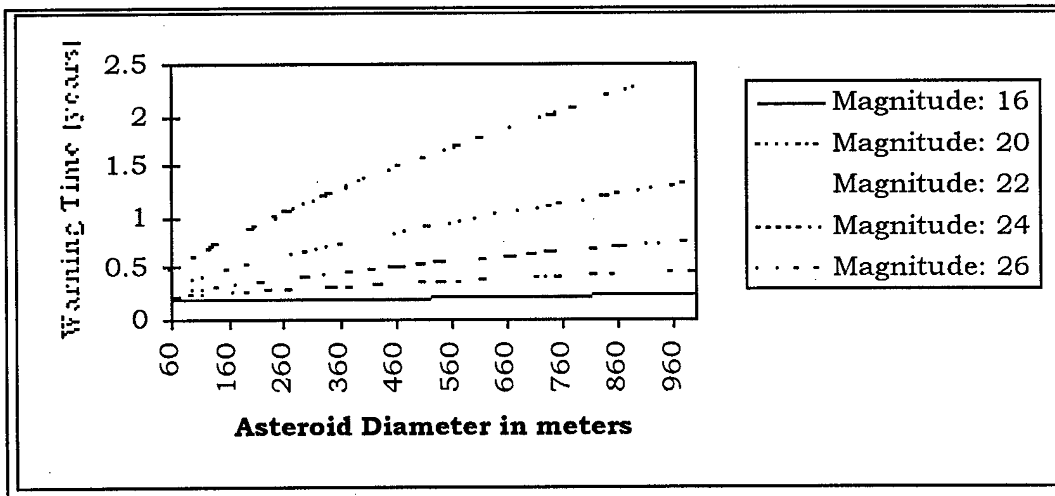


Figure 8-7. Realistic Maximum Warning Times

we will have more time.

Coverage. The maximum area of sky that can be covered by a ground-based optical system is an area centered on opposition, + 120° celestial longitude and +90° celestial latitude.[11] Called the *dark sky region,* it is an area free from solar (light) interference, where faint objects are most easily detected. Unfortunately, it would take a lot of instruments to cover 34,000 square degrees to magnitude 22. While a very large survey area is desirable from the standpoint that it allows us to finish the survey faster, it may not prove cost effective because it may drive us to operating an inordinate number of telescopes.

As a result, the Spaceguard team came up with what they believed to be a more reasonable search area called the *standard region.*[12] The standard region is an area centered on opposition, extending + 30° celestial longitude by +60° celestial latitude, for a total of about 6,000 square degrees. As you can see, the standard search area is only

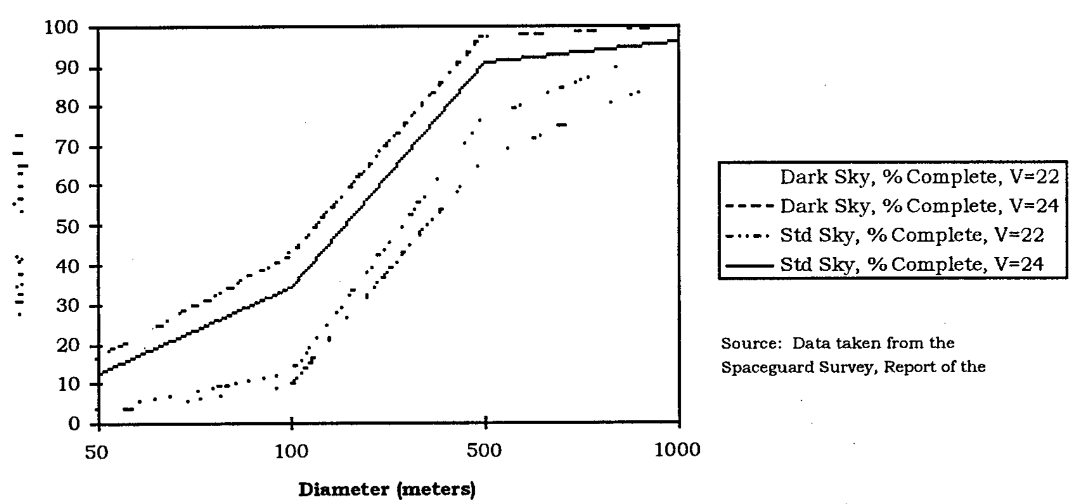


Figure 8-8. Percent of Objects Found in a 25 Year, Monthly Survey Using Dark Sky and Standard Search Areas

around one sixth the size of the dark sky area; thus if we choose to conduct the survey with the smaller area we should expect it to take significantly longer to complete. Figure 8-8 shows the effect of search area size on effectiveness (percent of all objects found) for a hypothetical 25 year survey. Assuming we wish to find at least 90% of all objects greater than 1 km in diameter, and that our instruments have a limiting magnitude of 22, we see that the standard area would only find 85% of the 1 km objects, whereas using the dark sky criteria we would find 95%. The bottom line is that we would not be able to meet the survey duration requirement (minimum acceptable) with the standard sky search area. If we are to use that area, we would need to extend the survey duration, increase the frequency of the search or use instruments with a higher limiting magnitude. Given that the survey duration will probably be driven by programmatics (i.e. money and budgetary constraints), we have to perform trades between coverage area, frequency of coverage and limiting magnitude to get the job done in a reasonable amount of time.

The Spaceguard team found that increasing the search frequency is not a very effective way to enhance system performance. As an example, they cite a case where searching the standard sky area once per month at a limiting magnitude of 22 for 25 years, yields a completeness (for objects 500 meters in diameter and up) of 66%.[13] Scanning twice per month would increase the completeness to only 69%.[14] Doing twice the work only yields a 3% improvement in performance. The only way to have a significant effect on performance is to increase the volume of space being searched. Thus, the solution is to play search area size against the limiting magnitude of our instruments to get the percent completion we need, in the time available.

As an example of the effectiveness of increasing search volume, refer to Figure 8-3. Limiting magnitude is proportional to what could be called *seeing distance*, in other words, how far out in space we can see an object. Hence, increasing the limiting magnitude effectively increases the search volume. Unfortunately, current CCD technology will not permit us to reach limiting magnitudes much beyond the 22 to 24 range. So we do not have much flexibility in this regard.

So what does all this mean? If we need to achieve a certain level of completion within a defined period of time (survey duration) we will only have three parameters to work with: observing frequency, limiting magnitude and search area. Observing frequency has a very small influence on completeness; so it is not an effective tool to increase system performance. Limiting magnitude will probably be set by the technology. Even very advanced equipment will be hard pressed to make a limit of 24. That leaves an increase in search area as the only viable solution to a deficiency. Larger search areas can be had by adding to the number of available instruments and/or increasing the field of view of existing telescopes. Therefore, the cost trade becomes one of choosing between up-front non-recurring costs to increase the search area capability, or maintaining the existing capability and extending the survey duration with the resulting increase in recurring operating costs. While the latter choice is viable, it is not recommended. Extending the survey duration is only slightly more effective than increasing the observing frequency. For example, a 10 year survey to magnitude 22 would find 71% of all objects 500 meters in diameter and larger.[15] The same survey extended to 20 years would find only 81%.[16] Twice the effort (and operational cost) would yield only a 10% increase in performance.

One final note regarding system coverage. In order to perform the discrimination function, we must cover the same area of sky at least twice each period. More frequent revisits may be necessary to increase the chances of discriminating very faint or slow moving objects, and to take the measurements necessary for orbit determination. In fact, the Spaceguard team recommended nine revisits per month.[17] Therefore, whatever area of sky we decide our system should cover, we must size the system to ensure we can cover the area several times per month.

For example, if we wish to cover 6,000 square degrees per month, we will need to design our system to cover nine times that area, or 54,000 square degrees per month. Given that most good sites have between 60 and 80 hours of good, dark sky observing time each month; and that the time required to collect each image (given by Equation 29) is around 100 seconds, we can estimate how many telescopes are needed by,

$$Obs.Time \geq \mathrm{Re}visits \cdot Sys.Coverage \cdot \frac{1}{A.O.V.} \cdot \frac{t_{\exp}}{3600} \cdot \frac{1}{NumberofInstruments} \quad (36)$$

where,

Obs. Time is the average maximum dark sky observing time for the site in hours per month. Between 60 and 80 hours per month for most good sites.
Revisits are the number of times the area must be surveyed each month. Generally, 2-3 times for discrimination plus another 3-6 times for orbit determination.
Sys. Coverage is the area of sky we need the system to cover in square degrees per month.
A.O.V. is the average field of view of the instruments used, in square degrees per image. Equals CCD field of view (deg) squared, times 3.14159.
t_{exp} is the required exposure time to reach limiting magnitude in seconds per image, (Equation 29).
Number of Instruments is the number of instruments needed for the survey.

Impact Trip Wire—Implications for Coverage. Previous discussions addressed coverage for the bulk of the search mission. There is another way of looking at the amount of coverage needed that deserves consideration. Spaceguard defines any sizable object that passes within 0.05 AU of Earth as being "potentially hazardous" and therefore worthy of our attention.[18] Based on this, one could reason that our search system should be able to find all objects within a 0.05 AU sphere around the Earth; thus providing a trip wire of sorts to ensure some minimal warning of impact for any object that slips by the larger search effort. A secondary benefit would be to highlight objects that come close to Earth so they can be observed for a time to determine the new orbit parameters, since such a close encounter will likely change their orbits significantly.

For a typical relative velocity of 10 km/sec, a 0.05 AU trip wire would give us only about 8.5 days of warning before impact.[19] What this means to our search system is that it must cover the entire sphere at least twice every 8.5 days. Referring back to Figure 8-1, its obvious that both optical and IR instruments would be needed. Each would need to cover one hemisphere of the sphere: optical, the hemisphere toward opposition and IR, the one toward the Sun. The total required search area would be about 25,500 square degrees for each hemisphere, and it would have to be completely covered about twice a week to a magnitude of 22 (optical) and 12 (IR) to find objects 56 meters and larger.

We have decided not to include support for the trip wire in Table 8-1 because the trip wire is not required in order to conduct a successful search program. However, that does not mean it would not be useful. It would complement the main effort as described above, especially in the early years of the program when the number of unidentified objects is still large.

Minimum Detectable Proper Motion and Parallax. As discussed in Chapter 7, the minimum detectable proper motion and parallax depend on the resolution of the search system, and affects its ability to distinguish asteroids and comets from the star background. Most of the systems we will be considering have resolutions (including normal atmospheric effects) between 1 and 2 arc seconds, which is more than adequate under most circumstances. However, objects on a collision course with Earth will generally have a proper motion less than 0.2 arc seconds per minute; thus they would be essentially invisible until they are only a few days from impact where changes in brightness, or radar, could be used to identify them.[20] An effective search system must be designed to overcome this problem.

One possible solution is to assemble a system that makes use of the fact that the parallax of objects several weeks from impact will be large. If measured over the Earth's radius (see Figure 7-9), most asteroids will have a parallax greater than 10 arc seconds, while still three months from impact.[21] Though three months warning isn't as much as we would like, it is better than the alternative: zero. The only other means available to us for finding such objects would be to use adaptive optics or space-based sensors to improve our resolution and therefore our ability to detect smaller amounts of proper motion.

Adaptive optics could be used to eliminate some portion of the atmospheric effects, thus allowing our instruments to operate at their full capability. With proper CCD design, we could achieve less than 1 arc second resolution, perhaps doing better than 0.2 arc seconds. However, this small improvement hardly seems worth the likely cost and increased complexity associated with adaptive optics.

As mentioned before, space-based systems offer a way to solve several tough problems. Not the least of which, is their ability to find objects that have small proper motions when viewed from Earth. Placement of a spacecraft in orbit about Venus, in

Earth orbit or at the L2 (Earth-Sun) libration point have all been suggested and would certainly solve much or all of the problem.[22] The issue is whether the cost of such a system would be justified. It may be the only solution to the problem. However, before deciding to build a space-based sensor, a thorough study of the class of objects likely to display very low proper motion (defined by Hills and Leonard), and available ground-based options should be done. It seems likely that an integrated system of telescopes (IR and visual), capable of finding objects by parallax would be just as effective and much cheaper.

The suggested requirements shown in Table 8-1 are based more on reality than the capability demanded by the task. Obviously, we would like to have very good resolution but the reality of atmospheric effects, the cost of space-based systems and adaptive optics all lead us to accept performance that is less than ideal.

The *preferred* requirement reflects the *absolute best* that a ground based system could do using adaptive optics. We have found no comprehensive studies on this; but it seems a reasonable value to bound the performance range. We base this on the fact that the maximum theoretical resolution of the GEODSS system (as an example) is about 0.14 arc seconds (see Equation 30). Even if the adaptive optics could remove 100% of the atmospheric effects, the system could not do better. Making some allowance for the inefficiency of the adaptive optics leads us to believe that we would never do better than 0.2 arc seconds with a ground based system. The *acceptable* value of 1 arc second is simply based on the capability of current instruments.

IR System Requirements

As shown in Figure 8-1, IR will be used primarily as a means to find objects with a large phase angle or within ~30° of the Earth-Sun line. We have specified only three IR-specific factors: Limiting N-band magnitude, IR resolution and coverage. We resisted specifying limiting magnitude for the optical instruments, favoring instead a model to measure performance in terms of our real interests: warning time and survey duration. Unfortunately, warning time is not as good an indicator for the IR system because many of the objects approaching Earth from the direction of the Sun are members of the Atens family, whose orbital periods are around a year or less.[23] So, using the model (remember, it assumes impact on the first orbit), the maximum warning time would be around 6 months or less.

IR Limiting Magnitude. We had a difficult time relating our objectives to a defensible range of limiting magnitudes. Obviously, it is beneficial to have a highly

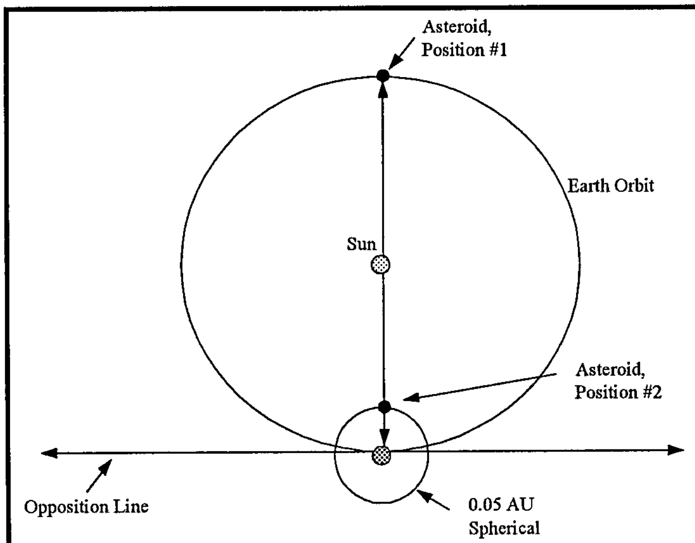


Figure 8-9. Orbit Geometry Used to Bound IR Limiting Magnitude Requirements

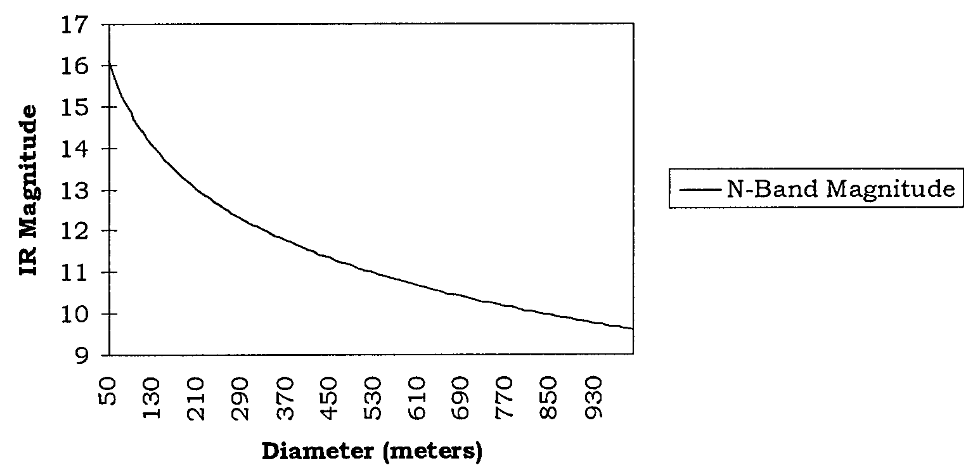


Figure 8-10. IR Magnitude of Object in Position #1

sensitive instrument. The question we ponder is: how much is enough? Figure 8-9 shows the orbit geometry we chose to bound the limiting magnitude. Position 1 represents the worst case condition where we are viewing an Aten (ignoring the Sun's blockage).

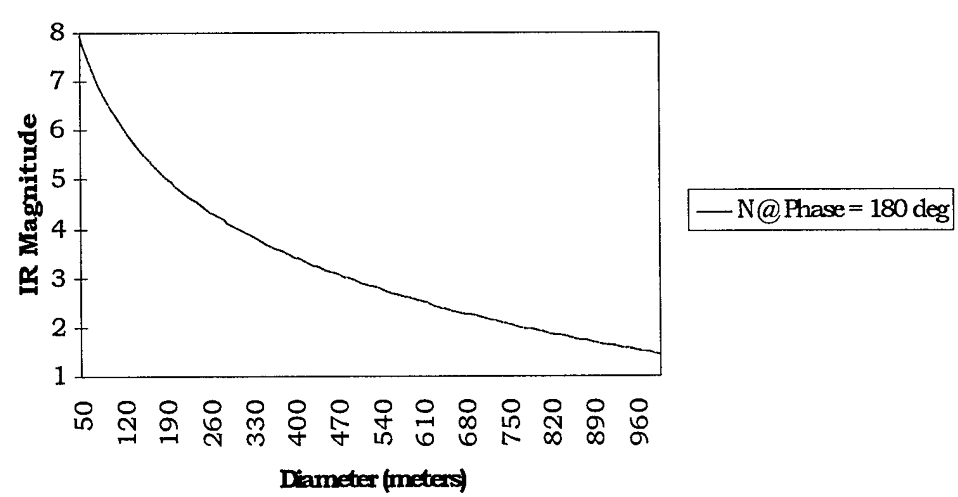


Figure 8-11. IR Magnitude of Object in Position #2

Position 2, defines minimum acceptable limiting magnitude as that of an object on the edge of the 0.05 AU sphere we discussed earlier.

Figure 8-10 shows the IR magnitude of the asteroid in position 1. In order to find a 56 meter object, the instrument would need a limiting magnitude of at least 16. The same object in position 2 would be much brighter, requiring a limiting magnitude of about 8 for detection.

Here's where we run into a problem. A ground based instrument will be hard pressed to make magnitude 8, with a more likely limit being around 6 for an affordable, wide field of view instrument.[24] Yet, it would seem we need at least magnitude 8 just to find the small objects a few days from Earth (position 2). Figure 8-12 shows the minimum detectable object size as a function of its distance from the Earth and the limiting magnitude of the IR telescope. The asteroid's distance from the Sun is always 1 AU (by definition); so this should bound the performance of the instrument for the Atens family of asteroids since they generally stay within 1 AU of the Sun. Notice that with a limiting

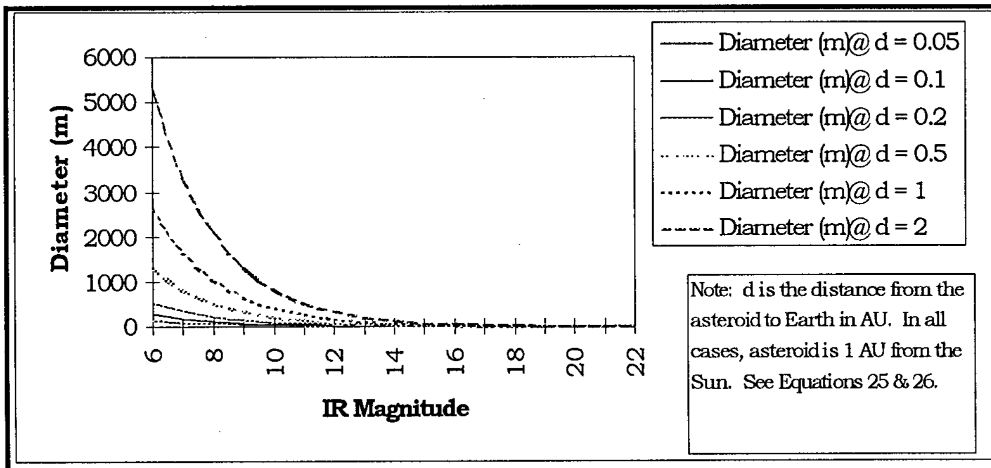


Figure 8-12. Smallest Visible Object for a Given Instrument Limiting Magnitude

magnitude of 6, only the largest objects are visible beyond a fraction of one AU.

The conclusion we draw from this is that there may be a valid argument for investing in a space-based IR sensor. Space-based sensors should be capable of reaching magnitude 20 or more with existing technology, thereby solving the limiting magnitude problem.[25] An orbiting spacecraft would also make greater coverage possible because there would be no interference from weather, and the area scan rate can be higher because the dwell time to reach limiting magnitude will be much shorter. The cost of a space-based sensor could conceivably compete with a sophisticated Earth-based system.

An example of a spacecraft having approximately the right capabilities is the Wide-Field-of-view IR Explorer, called WIRE. Sponsored by NASA as an Explorer class spacecraft, its mission is to detect the extremely faint IR signatures of distant galaxies.[26] It would require modification in order to perform the asteroid detection mission, but the complexity of the bus and sensor are comparable to what we expect would be needed. Also, WIRE is designed to fly in a sun-synchronous orbit. It is not clear what the optimum asteroid mission orbit would be, but it seems a sun-synchronous (noon) orbit could do the job. The total cost of the WIRE mission, including the Pegasus launch vehicle is reported to be around $37 million.[27] At this price, it may be cheaper than a set of Earth-based IR instruments and it could do a much better job.

An alternative to a modified WIRE mission would be to mount an IR telescope on the upcoming space station. The IR sensor will need a cryogen coolant for the detector, and this coolant must be replenished periodically. If the sensor is put on a satellite, when the cryogen runs out the mission will end (about 1 year, assuming nitrogen can be used in place of the helium used by WIRE), whereas on the space station, the coolant could be re-supplied as needed. Hence, the useful life of the sensor would be much longer.

IR Resolution. The effect of resolution on our ability to discriminate between background stars and asteroids is the same for IR as it was for optical instruments. Many objects on a collision course with Earth with have very small proper motion until a few days before impact.

Because of the longer wave lengths involved, the resolution of IR system will be somewhat less than those at visual wavelengths. Using Equation 30, we find that the best theoretical resolution for an N-band instrument would be about 2.5 arcsec (assuming a 100 cm aperture). Thus, the best resolution we can hope for in operation will be about 2.5 to 3 arcsec or higher. The minimum acceptable resolution, by our definition, corresponds to the parallax of an object near the 0.05 AU sphere. At this distance, objects will have a large parallax when viewed over one Earth radius. According to Hills and Leonard, an object with a relative speed of 10 km/sec 10 days from impact will be around 0.058 AU from Earth and have a parallax of about 150 arcsec.[28] Thus, allowing for margin and the current state of technology, we adopt 15 arcsec as the minimum acceptable IR resolution.

IR Coverage. The area of sky to be covered can be bounded on the low end by the 30° cone extending from Earth toward the Sun (see Figure 8-1) where optical telescopes become ineffective. This gives a total area of 2,800 square degrees.

The high end of the coverage range is a bit harder to quantify. As a first cut, we assume a 67.5° cone centered on Earth, extending toward the Sun for a total of ~14,000 square degrees. This covers most of the area inside Earth's orbit (where the Atens reside) and provides IR coverage for most objects with large phase angles (hard to see optically).

IR Coverage Rate. As a minimum, the IR system would need to cover the area at least twice per month (for detection and discrimination). More frequent coverage may be required, depending on the sensitivity of the instruments used. For example, if the instrument can only reach magnitude 13, it would only be seeing small objects (56 meters) about 0.05 AU from Earth. As we discussed earlier, that's about 1 week from impact (assuming an impact will take place). At that magnitude, it would be wise to scan the area three or four times each week.

Radar System Requirements

Wide Area Search. Because of the limitations discussed in Chapter 7, radar can not do the wide area, long range search mission. According to Canavan, the Ballistic Missile Early Warning System (BMEWS) radars only have *search range* of about 60,000 km, (less than 0.0004 AU), for a 100 meter diameter object.[29] Other radars have similar performance against deep space targets. Therefore, the search mission must be left to the optical (visual and IR) instruments.

Tracking and Orbit Characterization. Radar's big contribution will be in the tracking and orbit characterization effort. Once found by the optical systems, the object's coordinates will be handed off to the radar for tracking.

In order to determine an object's orbit, we need at least six independent variables. One way to get them is by observing the object's position at three different times. To be accurate, you would like those measurements to be made far apart (in time). Thus, this method takes a while to pin down an accurate orbit. Radar helps tremendously because it can measure something the optical systems can't: range and range rate. Using a combination of radar (range and range rate) and optical (position) observations we can quickly and accurately determine the object's orbit. However, to be of use the radar must be capable of tracking at long ranges. Something on the order of 1 or 2 AU would be preferred. Unfortunately, that's not possible with existing systems.

The tracking range of a radar is much better than its search range because the energy is spread over a smaller area. The BMEWS radars are capable of tracking asteroids or comets out to about three million kilometers (~0.02 AU).[30] This is useful but still far short of what we would like to have. The Arecibo and Goldstone radars operate at a more favorable frequency (~5 cm) and have a range of around 0.1 AU making them more useful than the BMEWS, but the demand for these systems is very high.[31] It is unlikely that anything short of an emergency would allow us to use them for extensive asteroid tracking and orbit determination.

Currently, only five to fifteen near-Earth object observations per year can be accommodated from Arecibo.[32] With nearly 6,000 sizable asteroids passing within 0.058 AU of Earth each year, it seems likely existing radars will not be able to do the job.[33] Both range and capacity are inadequate.

Radar systems capable of meeting our needs could be designed and built but would be very expensive. In our judgment, they would not be worth the money. Given time and enough optical resources, we can do most of the search job without radar support. For those objects that get within range of the BMEWS, Arecibo or Goldstone radars we will have to compete with other users for time. We should set up a mechanism, in advance, for the search team to request time on these critical instruments in time of emergency. Given optically derived orbit parameters that indicate a close approach, the team would seemingly have a strong argument for preempting other users. Though admittedly, by the time we get the radars on the target we will have very little time remaining to respond.

The bottom line is that radar isn't going to be able to do a lot for us (except in the study of meteor streams). Only objects coming very close to Earth (0.01 to 0.05 AU) will be in range of the BMEWS radars and only those deemed likely to hit Earth (from optical data) will be observed by Arecibo or Goldstone (15 or so per year). To track several hundred to a thousand objects would probably require a dedicated radar. The benefit of a dedicated, special purpose, NEO tracking radar would be too low to justify the tremendous cost.

The requirements noted in Table 8-1 assume Arecibo or Goldstone will be used for objects 0.01 to 0.05 AU from Earth and that BMEWS radars will be used for closer objects or very large (1 km and up) objects out to 0.05 AU. Further, they assume that radar observations will only be used to refine the orbits of objects passing very near Earth (based on optical measurements). The numbers used for the preferred and acceptable capabilities reflect an order of magnitude increase in observation (over present case), and are probably the best that can be done.[34]

System Architecture

Beyond simply choosing the right mix of instruments, we must find a suitable architecture to coordinate the efforts of the various instrument sites, as well as handle the potentially massive amount of data must be collected and processed. Figure 8-13 shows, in general terms, an effective way to organize the system. The heart of the search program is the Centralized Control and Coordination Center. This group is responsible for getting the job done.

Reporting to the CCCC are a myriad of supporting sites. These supporting sites would fall into two categories. First, we would have those sites that are dedicated to the NSD search mission. They would be *owned* by the CCCC and would perform only work directed by the CCCC. The second type of site would be those who voluntarily contribute to the greater effort by periodically feeding data into the main system. They would be expected to follow the standards and procedures developed by the CCCC for this task. In return, they would get: access to the data; fair credit for discoveries made by their instruments (and efforts); and finally, some small level of assistance in meeting the

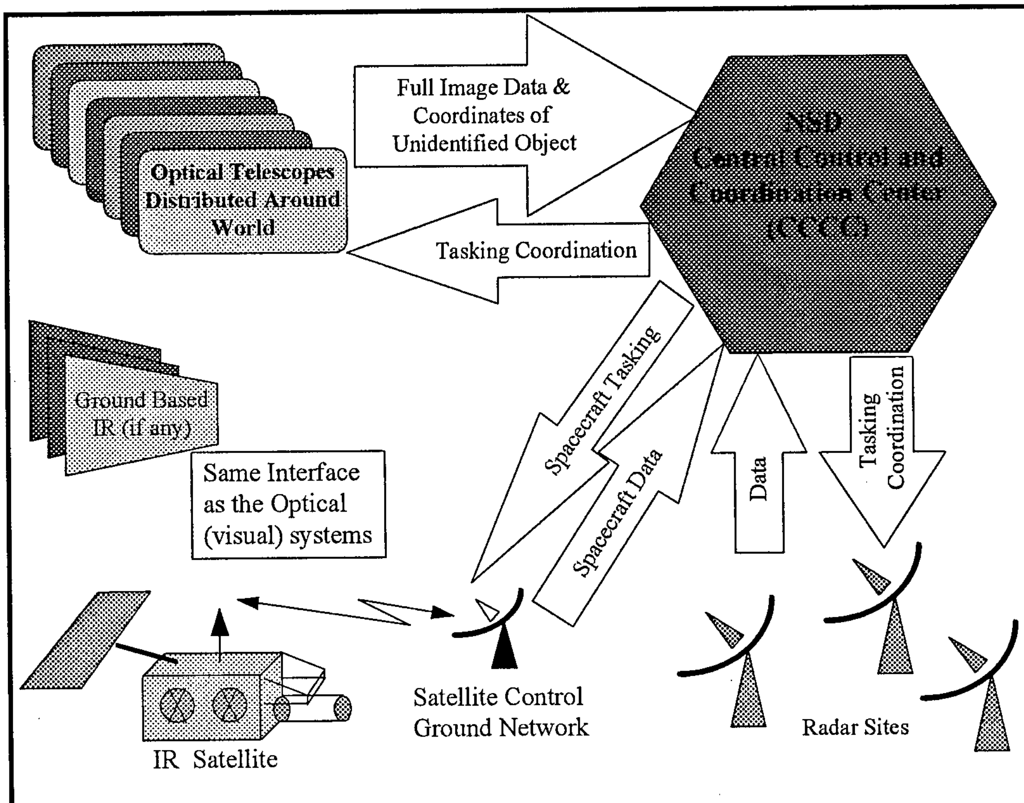


Figure 8-13. Efficient Search System Architecture With Centralized Control & Coordination Center

standards and procedures for participation (both financial and technical). The benefit to the overall search program would be the use of many more instruments than we could otherwise afford; thus increasing the potential coverage area and rate, as well as increased tasking flexibility (less dependence on weather, more overlap in required areas).

The Centralized Control and Coordination Center (CCCC). The purpose of the CCCC is to coordinate the efforts of all fielded instruments to ensure their capabilities are used in the most efficient manner possible to accomplish the NSD search mission objectives. In this role, it acts as a single point of contact for all instrument sites regarding the conduct of the NSD search mission. Second, it is the repository for all collected data and will perform detailed, long-term analysis of the data to identify, catalog, and track objects to determine whether impact is possible.

While similar to the Survey Clearinghouse and Coordination Center proposed by the Spaceguard team, the Centralized Control and Coordination Center (CCCC) we propose would have administrative and funding control over the supporting sites (insofar as the NSD search mission is concerned).[35] Spaceguard calls for their *clearinghouse* to develop standards and procedures for all sites to follow, in order to ensure smooth and efficient operation; yet it is not clear that it will have control of funds, or the authority to direct operations at the sites. To be effective, the control center must have the ability and authority to commit resources to the solution of problems within the search system. Without it, the more significant problems will not get resolved.

What we need is a control center with a small but adequate budget, experience with the systems used in the NSD search, familiarity with the space debris search mission, and finally, an organizational structure capable of performing the technical function (orbit analysis, object cataloging, follow-up tracking and orbit updates etc.), as well as the huge, potentially international, coordination effort.

Responsibility For NSD Search. The responsibility for the successful accomplishment of the NSD search mission lies with the Centralized Control and Coordination Center. It seems there are only three organizations in existence that are capable of fulfilling a significant number of the CCCC requirements: the International Astronomical Union's Central Bureau for Astronomical Telegrams and Minor Planet Center, operating at the Smithsonian Astrophysical Observatory in Cambridge MA; the NASA Clearinghouse at JPL and US Space Command in Colorado Springs.

The Minor Planet Center is capable of coordinating and cataloging asteroids at the rate of about 1,000 per year.[36] They do not control the sites that feed them information; however, they do coordinate at the international level and have more experience than any other US organization with finding asteroids and comets, calculating their orbits and cataloging them. They do not have the capability to take on the task without significant investment in computing power as well as expansion of their organization structure to accommodate the 2,000 to 3,000 new near-Earth objects that will be identified by the search system each year.[37]

The second option, the NASA Clearinghouse is a fledgling organization with little experience (as an organization). It was apparently established sometime around 1992 to do some of the clearinghouse tasks identified in the Spaceguard survey.[38] As a new organization, it will have to be built from the ground up in order to do the whole job. Because it does not have any existing organizational structure to draw upon, the NASA

Clearinghouse would probably take more time and money to get up to speed than simply enhancing an existing organization.

The final organization, US Space Command, already operates a space debris identification and tracking system designed to find, catalog and track Earth-orbiting debris. They have a lot of experience with the types of systems that would be used in a deep space NSD search. They also have equipment that could be used for both missions, and an existing organizational structure well suited to the administration of a large search and cataloging effort. Finally, they have experience working in the international arena. Extending US Space Command's debris mission to include asteroids, comets and meteor streams seems logical. We believe this would be the most cost effective way to establish the CCCC function.

Data Handling and Storage

There are three levels of data collection and storage that could be implemented: storage of image-parameter data of moving objects only, storage of all visible objects (mostly stars), or storage of the full image.[39]

In the first two options, the image is pre-processed by computers at the observing site to identify potential asteroids and/or comets within the field of view. Once done, only this data is sent to the CCCC for storage and analysis. While this cuts down significantly on the data storage space requirements for the system, and limits the data transmission requirements from the sites to the CCCC, it also dramatically reduces the utility of the data. Once the original data is disposed of, we will have lost the capability to re-process the data in order to identify difficult objects through the use of more sophisticated analysis tools at the CCCC. Most of the search system cost will go to the collection of data. It would be foolish to throw it away unless we were absolutely sure it would be of no further use.

From this we conclude that the only sensible option is the last one. We should preserve 100% of the raw data for later re-processing. However, this isn't to say we don't need to pre-process data at the site. This would still be a useful function and would help limit the communications requirements between the site and CCCC. On a routine basis, pre-processed data on new objects could be sent to the CCCC in near real time. The raw data could be stored, on tape if necessary, and sent via mail to the CCCC for analysis and storage. This would be critical for remote sites where modern communications are not readily available. Modern sites could be connected to the CCCC via fiber optics to enable direct transmission of the raw data.

Unfortunately, storing all of the raw data (in a useful format) will be difficult. For example, looking back at Table 8-1, we see that the minimum acceptable coverage is defined to be about 6,000 square degrees per month. If we use the predicted Spaceguard telescope performance as a guide, we can determine roughly how much data storage will be needed. Spaceguard (as proposed) has a 2° field of view and will probably use four 2 kilobyte by 2 kilo-byte CCD's to capture the image. To cover 6,000 square degrees with a 12.6 square degree field, requires about 476 images per month. One image takes 1.6×10^7 bytes (16 megabytes). Therefore, 476 images would take about 7.6×10^9 bytes per month (7.6 giga-bytes per month). But this is just the beginning. If we were to use the preferred coverage requirement (34,000 square degrees) we would need nearly 43 giga-bytes per month; and this still doesn't include the IR and radar data! What's more, we need to cover this area up to nine times a month, not just once. So these numbers must be multiplied by nine.

Over a 25 year period, we would need somewhere upwards of 90,000 giga-bytes of data storage just for the optical (visual) data. As bad as this sounds, it is possible. With modern optical data storage media (CD) technology, data compression techniques and likely data storage improvements that will become available during the 25 year survey, it should be possible to store this much data in an affordable manner.

Meteor Storm Characterization System Requirements

The characterization of meteor streams is primarily a job for radar, though the use of optical telescopes to record the trails of incoming meteors during a storm could be useful. Spacecraft sampling missions could also be used to gain more detailed knowledge. Regardless of the instruments used, there are some specific parameters we would like to determine. To meet the objective outlined earlier in the chapter, we need to characterize meteor streams such that we can predict meteor storms far enough in advance to allow those who control the orbiting spacecraft to implement their impact mitigation plans. The key factors governing a storm warning system are presented in Table 8-3. In addition to these factors, we assume that the meteor stream orbit parameters are well defined; and therefore, the direction of meteor approach is known.

Table 8-3. Meteor Stream Characterization and Storm Warning Factors

Key Factor	Requirement
Predicted Zenithal Hourly Rate (ZHR)	Prediction of ZHR > 1,000 to trigger storm warning[40]
Storm Risk Factor	Indicates severity of predicted storm for a spacecraft as a function of its cross-sectional area (see Chapter 6)
Minimum Warning Time	4-10 days

Predicted Zenithal Hourly Rate and Storm Risk Factor. These are discussed at length in Chapter 6. In general, the ZHR is used as a trigger to indicate when we have crossed from a meteor shower (or outburst) to a storm. The storm risk factor serves as an indicator of how bad the storm is expected to be. It takes into account both the storm duration and meteor impact flux. Knowing the storm risk factor allows us to determine the probability of impact for a satellite of a given cross-sectional area.

Minimum Meteor Storm Warning Time. Based on typical satellite tasking cycles, we would probably need four to ten days warning to safely implement a mitigation plan. Of course, this assumes the mitigation plans have already been developed and tested. It also does not allow time for changing spacecraft orbits (orbit changes probably wouldn't help).

Survey of Optical Systems

Now that we have a set of requirements with which to assess the capability of various instruments, we can begin to quantify existing capabilities, identify deficiencies that may need to be corrected; and ultimately, pin down the expected costs. We surveyed the NEO community for systems or instruments (both exiting and proposed), that are capable of fulfilling a significant portion of the requirements in Table 8-1. The following text discusses the results of our survey.

The results of our survey are presented in Table 8-4 for the optical (visual) requirements. The highlighted entries correspond to the search system requirements developed in the first part of this chapter. A quick comparison with Table 8-1 shows that none of the systems can meet our requirements by themselves, but Spaceguard, GEODSS and the NASA Liquid Mirror systems come close. By combining these systems in the right way we can no doubt meet the requirements; however, cost may force us to make some additional performance trades. Before we begin our cost discussion, we will briefly review all six systems.

Spaceguard Survey Network. Conceived by the Spaceguard team, it consists of six specialized telescopes distributed around the world such that both northern and southern hemispheres are covered. It is primarily designed to find objects 1 km in diameter and larger. The telescopes are to be manned by an international team, and linked together at the Survey Clearinghouse and Coordination Center by a moderate speed communications system.[41] Data from the telescopes is pre-processed at the individual sites with a high-end work station computer to identify any unknown objects, then the full image data is transferred to the clearinghouse for storage and more detailed processing. The cataloging, orbit determination and impact prediction task will be done by a team at the clearinghouse.

The Spaceguard network does not yet exist. The concept was finalized in ~1992, and at that time they estimated the system could be built and in operation within five years (if funded). This includes the time required to establish the clearinghouse; however, it apparently assumes the international facilities are made available quickly and at no charge.[42]

Spacewatch. Spacewatch is run by the University of Arizona at Tucson. Though primarily dedicated to asteroid and comet studies, it is not intended to be an all-encompassing NSD survey tool. It is, however, one of the very few programs specializing in NEO studies; so it is considered a good example of what an NSD search system should do, albeit on a small scale.

Spacewatch has a single telescope with a single CCD array at the focal plane. The image data is pre-processed by a Sanborn computer with three CPU's (similar to a SPARC 2 work station) running custom-built software for NEO discrimination.[43] The software separates objects in the field into three categories: slow moving (~1/2°/day); large and bright; and fast moving, but faint objects. The software then examines the first two categories to identify new asteroids and comets. The latter category must be worked by hand.

GEODSS. The Ground-based Electro-Optical Deep Space Surveillance System is operated by US Space Command for the purpose of identifying Earth-orbiting man-made debris that could be a hazard to our space assets. As of November 1994, there were three operating sites world wide: Socorro, New Mexico; Maui, Hawaii and Diego Garcia in the Indian ocean.[44]

The Socorro site has two large telescopes (40 inch aperture), and one auxiliary scope (15 inch aperture).[45] There are two more large telescopes and an auxiliary at Maui, and three large telescopes at Diego Garcia for a total of seven large and two small telescopes in the GEODSS system.[46] Presently, these instruments do not have the sensitivity required to successfully participate in an NSD search program.[47] However, once the Ebsicon imaging tubes are replaced by the large CCD's as demonstrated by the GEODSS Upgrade Prototype System (GUPS), the telescopes should be capable of reaching magnitudes in the 20-22 range, making them suitable for participating in an NSD search program. The CCD upgrades could be completed within about two years from the go-ahead date.[48]

TOS. Space Command's Transportable Optical System (TOS), is a "modern-technology, single telescope, real time, ground based, deep space satellite tracking, transportable optical system" designed for tracking man-made, Earth orbiting debris in a manner similar to the GEODSS telescopes.[49] Though less capable than the GEODSS, they are "relatively inexpensive," simple to use and require only a small 30 by 60 foot plot of land for operation.[50] In addition, they have built-in computer pointing and tracking

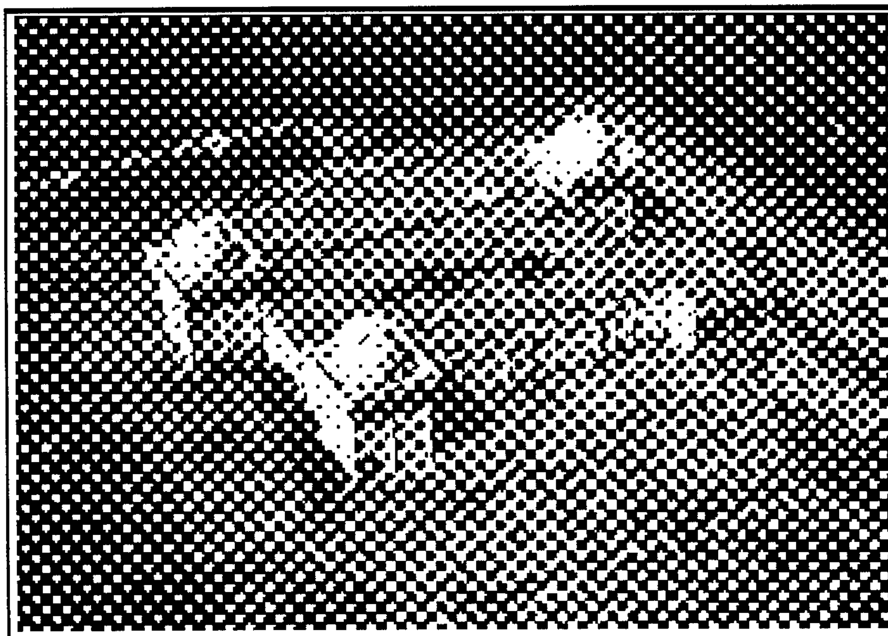


Figure 8-14. GEODSS Site

control and some data processing. While they are designed for finding and tracking Earth-orbiting debris, they should be capable of participating in a deep space NSD search program with relatively minor modification of software, and perhaps some added computing power. As you can see from Table 8-4, TOS has performance capabilities close to those of the Spacewatch telescope, but in general it would not be our first choice for the bulk search mission. Because, its limiting magnitude (~19) is too low.

TOS instruments would be best suited to a *gap filler* mission. Its mobility and self-contained design makes it well suited for filling coverage gaps in remote areas of the world and to temporarily fill in for inoperative mainstream instruments. They could also be used to track known objects and help maintain the currency of the catalog to relieve mainstream telescopes of this task.

Table 8-4. Optical Search System Specifications

	Space Guard Proposal Note: 51	Space Watch Note: 52	GEODSS Note: 53	TOS Note: 54	NASA Liquid Mirror Note: 55	LLNL Wide Field of View Note: 56
Limiting Magnitude	22-24	20.5	20-22 22 w/filters	19.3 (Eqn 28)	22 (Eqn 28)	16
CCD Field of View	2°	0.7°	2.1°	2° Estimate	0.35° (CCD ltd)	5.3°
Objective Diameter focal ratio	2.5 m 5.2	0.91 m 5	1.02 m 2.15	0.56 m 2.4	3 m 1.49	0.10 m 3.3
Number of Optical Telescopes	6	1	2	1	~10[57]	9
Coverage (Sky Region)	1000°^{2}/mo per telescope	~2700°^{2} per month	2958°^{2}/mo per telescope	Similar to GEODSS 2958°^{2} per mo per telescope	10.5°^{2} per hour per scope	2500°^{2} per night per scope

Table 8-5. (Continued)

Number of Scans per Sky Region	9	1	9	2 or more per scope	2 with 10 scopes	More than 9
Resolution	1 arcsec	1 arcsec	2.27 arcsec	Assume GEODSS 2.27 arcsec	1 arcsec	9.3 Arcsec (Loral Unit)
Total System Coverage[58]	6000^{o2}/mo.	~2700^{o2} per month	5917^{o2}/mo	2958^{o2} per mo	6300^{o2} per mo.	22,800^{o2}/ night.
Time Required to Find 90% of Asteroids & Short-period Comets, 1 km & larger	25 yrs	~50+ yrs	~25 yrs	~50+ yrs.	~25 yrs	Only 28% at 25yrs[59]
Maximum Warning Time for 1km asteroid Albedo= 0.03 F(α)=0	9 months at Mag 22, 1.3 years at Mag 24	6 months	9 months	6 months	9 months	3 months

NASA Liquid-Mirror Telescopes. Scientists at the Johnson Space Center have developed a large aperture telescope with an objective mirror made from a rotating pool of liquid mercury. Spinning the pool of mercury forces the surface into a parabolic figure, making an essentially perfect mirrored surface for a reflecting telescope. The advantage of the liquid mirror is that it costs much less than its glass equivalent.[60] There are also several disadvantages, among the more significant are: the hazards associated with mercury vapors and the fact that the telescope can not be steered.[61]

Liquid Mercury vapors are hazardous. When inhaled, the mercury moves directly into the blood stream where it can seriously damage the central nervous system.[62]

Unfortunately, the vapor problem becomes somewhat worse at high altitudes (precisely where most observatories are located), due to lower atmospheric pressure. In addition, liquid mercury would endanger the environment if an uncontained spill were to occur. NASA has developed safety precautions, procedures and equipment that will prevent spills (spill containment area) and ensure personnel are not exposed to the vapors.[63] The safety provisions are quite extensive and should be adequate, but they do complicate the system and may make it difficult to find acceptable sites.

In order for the mercury to maintain its figure, the telescope must point directly at the zenith point at all times. It can not be steered in the normal sense. However, as the Earth rotates, the instrument will sweep out an area of sky 0.7° wide (small, 3 cm CCD), at the rate of about 15° per hour.[64] By placing a series of these telescopes at different latitudes we can cover a very large portion of the sky with minimal fuss. Obviously, since they cannot be pointed we would need additional telescopes to perform precision tracking, orbit characterization and to fill coverage gaps. The strength of the liquid mirror concept is its ability to provide a very large aperture instrument at low cost, so that we can cover large parts of the sky quickly and to a very high magnitude. In other words, they seem ideal for the bulk search function.

A prototype unit has been built and is undergoing tests. The first series of tests were completed in the Houston, Texas area. Problems with the mirror's air bearing were identified and corrected during those tests. The instrument is in the process of being moved to a site with better seeing conditions and less light pollution, near Cloudcroft, New Mexico.[65] When reassembled, testing will continue.

LLNL Wide-Field-of-View Telescope System. This system was developed by the Lawrence Livermore National Laboratory (LLNL) with the assistance of scientists at the University of Michigan and Lowell Observatory to search for new Earth-crossing asteroids and comets.[66] The proposed system would consist of nine wide-field-of-view CCD cameras, mounted on three computer controlled, precision tracking mounts.[67]

The system's strength is the tremendous coverage rate. It is capable of covering the entire night sky (over 22,800 square degrees each night), weather permitting.[68] Another major advantage is the fact that the telescopes are computer controlled and do their own real-time data processing using a SPARC 10 computer (main host) and one SPARC 2 CPU for each of the nine cameras.[69] As a result, operating costs will probably be lower than that of a normal telescope system.

The most significant disadvantage is its limiting magnitude: only 16.[70] Therefore, even though the area scanned is very large, the volume scanned is relatively small when compared to a magnitude 22 system. For example, a magnitude 22 limited instrument can see a 1 km diameter asteroid about twice as far away as a magnitude 16 instrument.

Overall, this system could be useful for performing the bulk search mission in conjunction with more capable instruments. In particular, this system could be useful in detecting objects crossing the 0.05 AU *tripwire* discussed earlier.

Infrared (IR) Systems Survey

A brief search of literature was performed in an effort to find information on existing ground based or space-based instruments capable of meeting our needs. In the arena of ground-based instruments we came up empty handed. Though there must certainly be some research instruments out there, we were unable to track them down in the time available. As for space-based sensors, we identified two: IRAS and WIRE.

IRAS. In 1983, IRAS (Infrared Astronomical Satellite), performed the most complete and least biased asteroid survey to date.[71] All totaled, 1811 asteroids and 25 comets with known orbits were examined, but more importantly, there is evidence within the data for a very large population of unknown asteroids.[72] Rough analysis of the data indicates as many as 10,000 unidentified asteroids may have been seen by IRAS during its brief life.[73] Unfortunately, the data has not yet been studied to derive the fullest possible benefit.

If new asteroids are discovered by a search system and can be correlated to IRAS data, then diameters and albedos can be calculated. In addition, the IRAS data could be used to gather additional statistical data about the distribution of asteroids and comets in the solar system.

We were unable to locate cost and detailed design specifications for IRAS; however, the little information we do have indicates it would be more than adequate to fulfill the IR search requirements presented in Table 8-1. With more persistence, one might be able to dredge up the cost information as well as the technical data. Rough estimates by some of those familiar with the program put the cost somewhere in the $400 million range. If accurate, this probably means that another IRAS-class satellite would be out of the question for an NSD search program. Fortunately, a new IR program is underway that may be better suited to our needs and more in line with available funding.

WIRE. The Wide-field-of-view IR Explorer was discussed earlier in the chapter (IR System Requirements section) so we will not cover it again here. As a part of the growing *cheap-sat* class of vehicles, WIRE could put a space-based IR capability within financial reach.

Radar Systems Survey

A brief survey of US military radars that could be used for tracking asteroids and comets, as well as studying meteor streams is presented in Table 8-6. In addition to these, the Arecibo and Goldstone radars discussed earlier would be most useful. Unfortunately, existing military radars will not do a very good job against deep space objects without modification (frequency, power etc.), since they are only useful out to 0.05 AU or less.

Search System Costs

With the requirements defined, we can begin to estimate the cost of an NSD search system. GEODSS/GUPS **Based System.** The first system uses only GEODSS/GUPS instruments for the optical portion of the mission. As you can see from Table 8-4, only two telescopes are required to meet our minimum requirements. However, our requirements do not account for the necessary dispersion of telescopes between northern and southern latitudes. Also, according to Equation 31, two GEODSS telescopes would give us little margin. More than 54 hours would be required to cover the required area nine times in a month. With only 60 hours of good observing conditions available each month (on average) at most sites, we have little room to compensate for mechanical or weather problems.

Table 8-7 shows the estimated costs of several potential elements of a search system. Understand that the costs shown do not represent the total cost of a *system*. They are simply the costs of various pieces. To determine the total cost, we must determine the proper combination, and number of instruments.

Several combinations are capable of meeting our requirements, so we need to define what pieces we will be using in our system. Thus, for the purpose of cost estimation, we will define, then compare, two variations on a GEODSS based asteroid/comet search system.

General System Architecture. Both variations described assume the system is designed around a Centralized Control and Coordination Center (CCCC) as described earlier in this chapter. Further, we assume that this organization is operated by, and co-located with US Space Command's existing space surveillance operations. As a result, we can take full advantage of shared expertise, equipment, communications and organizational structure to minimize the costs associated with this critical function.

Table 8-6. Military Radars

Radar Name	Number of Sites	Primary Mission	Range (km)
NAVSPASUR (Naval Space Surveillance System)	3 Transmit 7 Receive	Satellite Tracking	8,100
PACBAR (Pacific Barrier Radar)	2	Satellite Tracking	2,500
AN/FPS-85	1	SLBM Early Warning	3,500
BMEWS (Ballistic Missile Early Warning System)	3	Missile Warning	4,000-5,500
Cobra Dane	1	Missile Test Monitoring	5,500
PARCS (Perimeter Attack Radar Characterization System)	1	Missile Warning	3,200
Pave Paws	4	Missile Warning	5,555
Eastern Test Range	2	Launch Support	1,600-2,300
Western Test Range	4	Launch Support	5,555-40,000
Millstone	1	Satellite Tracking	35,000
Haystack	1	Satellite Tracking	35,000

Source: Ross T. McNutt, *Orbiting Space Debris: Dangers, Measurements and Mitigation.* Phillips Laboratory, PL-TR-92-2146.

GEODSS/GUPS Based System. The first system uses only GEODSS/GUPS instruments for the optical portion of the mission. As you can see from Table 8-4, only two telescopes are required to meet our minimum requirements. However, our requirements do not account for the necessary dispersion of telescopes between northern and southern latitudes. Also, according to Equation 31, two GEODSS telescopes would give us little margin. More than 54 hours would be required to cover the required area nine times in a month. With only 60 hours of good observing conditions available each month (on average) at most sites, we have little room to compensate for mechanical or weather problems.

Table 8-7. Detection Instrument Cost Estimates

	GEODSS/GUPS[74]	Liquid Mirror[75]	TOS[76]	LLNL[77]
Non-recurring Costs				
Instrument Costs: Includes telescope, CCD camera, computers, S/W, site prep and facility	$8450K 1 scope per site $1400K for 2nd scope at same site.	$500K per scope. Note: Only 1 scope per site needed	$1,000K per system, with one telescope and processing equipment	$329K total, $31K per telescope & $50K for SPARC 10 Host Computer (need one for 1 to 9 telescopes)
Large (8cm) CCD upgrade for 0.6° F.O.V.	n/a	$300K per scope	n/a	n/a
Spares (~5% of initial non-recurring)	$400K per site	$25K per site	$50K per system	$16K per 9 scopes
Recurring Costs				
Staff (per Site, up to 3 scopes) Using $173K per person as loaded cost[78]	$1900K/yr (11 people per site)	$691K/yr (4 people per site)	$115K/yr (2 people, technician grade)	$691K/yr (4 people per site)
Misc Parts (per site up 3 scopes)	$50K/yr	$25K/yr	$25K/yr	$25K/yr
Communication costs per site[79] US-US site US-Overseas Utilities for new site	$10K/yr $20K/yr $50K per year	$10K/yr $20K/yr $50K per year	$10K/yr $20K/yr $50K per year	$10K/yr $20K/yr $50K per year
Utilities, additional for existing site (assumes some shared overhead)	$10K per year	$10K per year	$10K per year	$10K per year

In order to ensure a robust system, and to properly distribute the telescopes in latitude, we believe four GEODSS/GUPS instruments are required. For the sake of discussion, we assume two asteroid dedicated telescopes at Socorro, New Mexico (an existing GEODSS site) and two asteroid dedicated telescopes at a single new site in Australia.

Combined NASA Liquid Mirror-GEODSS/GUPS System. The second architecture uses ten liquid mirror telescopes with the large CCD option (giving 0.6° field of view per instrument) to find new objects. While the optimum distribution of these instruments has not been determined, we assume the telescopes are distributed 10° apart (in latitude), with five in the northern hemisphere and five in the southern. This distribution allows for overlapping fields of view and covers the most critical area of sky.[80]

Once the objects are located, a GEODSS/GUPS based steerable telescope will be used to track and determine the orbits of the new objects. Since the liquid mirror scopes are doing the wide area search mission, we will not need as many GEODSS instruments to do the job. As a minimum, one dedicated telescope per hemisphere (north and south) should be able to do the job.

Using the information in Table 8-6, we compiled the costs of these two *systems* in Table 8-7. However, this is not the entire system. We still need to address the IR, radar and CCCC costs. These are summarized in Table 8-9. Finally, the total cost of an NSD detection system is shown in Table 8-10.

Table 8-8. Estimated Optical Search System Costs

	GEODSS/GUPS	NASA Liquid Mirror & GEODSS/GUPS
Nonrecurring Costs		
Nonrecurring Investment in Equipment and Sites. Assumes land available at no cost and utilities are readily available.	$9850K (2 scopes to Australia, new site) $2800K (2 new scopes@ Socorro)	$8000K (10 Liquid Mirror Scopes w/CCD upgrade) $3700K single-scope new GEODSS site in Australia. Share site with 1 liquid mirror scope. $1400 1 new GEODSS scope to Socorro site
Spares	$800K	$250K (liquid mirror scopes) $400 for one new GEODSS site
Recurring Costs		
Staff	$1900K/yr in Australia $1900K/yr added to Socorro site	$3460K/yr for 10 liquid mirror sites $1557K/yr (9 people at Australia site, note they are co-located with 2 people from liquid mirror) $865K/yr (5 additional people at Socorro site)
Misc Parts	$100K/yr	$250K/yr (liquid mirror) $50K (New GEODSS site)
Comm	$30K/yr	$160K (assume 8 of 10 sites not Conus) $20K Conus sites
Utilities	$50K/yr (1 new site) $10K/yr(1 existing site)	$400K/yr (assume 8 new sites) $20K/yr (2 existing sites)
Total Nonrecurring	$13.45 million	$13.75 million
Total Recurring	$4 million/yr	$6.8 million/yr

Table 8-9. IR, Radar and CCCC Costs

System Component	Estimated Cost
IR Satellite (similar to WIRE or SPIRIT III)	$37 million nonrecurring (includes spacecraft, sensor and Pegasus launch)[81] $2 million/yr operating costs (assumes free use of AFSCN. Data processing and vehicle health and status monitoring by 10 people).
Radar system support by BMEWS	$1 million/ year (crude estimate based on tracking 1,000 objects per year).
Arecibo and Goldstone support	$2 million/ year (based on tracking 100 high-interest objects per year)[82]
Centralized Control and Coordination Center (takes advantage of existing Space Command organization and sharing of some assets)	$5 million (workstation computers for orbit computation, cataloging, tasking and general workload management). $1 million for data storage and communications equipment. $3.6 million/yr (Staff and basic organization. Takes advantage of existing infrastructure of space surveillance network.)[83]
Total Nonrecurring	$43 million
Total Recurring	$8.6 million/yr

Table 8-10. Estimated Cost of Complete Search System

	GEODSS/GUPS	Liquid Mirror and GEODSS	Spaceguard Proposal[84]
Nonrecurring			
Total optical costs	$13.45 million	$13.75 million	
IR Sensor	$37 million	$37 million	
Centralized Control and Coordination Center	$6 million	$6 million	
TOTAL SYSTEM NONRECURRING COSTS	**$56.45 million**	**$56.75 million**	**$50 million No IR Capability!**
Recurring			
Total optical operating	$4 million/yr	$6.8 million/yr	
IR Sat. Ops	$2 million/yr	$2 million/yr	
BMEWS Support	$1 million/yr	$1 million/yr	
Arecibo/Goldstone Support	$2 million/yr	$2 million/yr	
Centralized Control and Coordination Center	$3.6 million/yr	$3.6 million/yr	
TOTAL SYSTEM RECURRING COSTS	**$12.6 million/yr**	**$15.4 million/yr**	**$10-15 million/yr**

This table shows approximately what it will cost to do the search mission. Both of the optical architectures will do a good job; however, the combination liquid mirror and GEODSS/GUPS architecture offers superior performance because the liquid mirror instruments have three meter objectives; thus they will have much greater limiting magnitudes. A quick comparison with the estimated costs of the proposed Spaceguard system shows that both of the options we selected are far less expensive and (except for IR) offer comparable performance. As for IR, remember the Spaceguard proposal did not include IR capabilities; thus for the Spaceguard system to have this capability we would have to add $37 million for the IR satellite and $2 million/yr for operations to the Spaceguard budget (making their recurring $87 million and nonrecurring $12-17 million).

One note of caution is appropriate at this point. The cost numbers given are extremely crude in some respects. Our team was unable to consult with qualified contractors to obtain current and detailed pricing for various components; therefore, we used what data we had at hand. We believe the total cost figures are close to the minimum expected cost of the system, but in general, a +25% margin of error should be applied.[85]

Meteor Stream Characterization Costs

The costs associated with meteor stream characterization were provided to NASA by Professor J. Jones of the University of Western Ontario (UWO) in July 1994.[86] The proposal involved assessing the meteoroid storm hazard to Earth-orbiting space platforms from three active streams: the Perseids, Leonids and Draconids. It also proposed the funding of a new radar at UWO for studying the fine structure of these streams, as well as the enhancement of specialized computational software with which to improve our understanding of meteor streams.

The total funding requested was $122,390 for the first year and $107,390 for the second through fifth years.[87] However, this proposal only addressed three of the eleven currently active meteor streams.[88] Given that our dependence on space is growing and will continue to grow in the foreseeable future, we need to address all streams. Therefore, we estimate the cost of a study of all eleven active streams by simply scaling from the proposed three-stream figures. The resulting estimate is approximately $400K/yr for all eleven streams.

The effect of adding streams to the study task upon the time required isn't as clear. More than the original five years would probably be required since there is relatively little data on some of these additional streams. Somewhere around eight years total should be sufficient. Thus, we estimate the total cost of the meteor stream characterization effort would be about $3.2 million over eight years.

During the study, individual programs would be periodically briefed on our understanding of the meteor storm threat. Each program would be responsible for studying the vulnerability of their system to meteor strikes for various storm levels, and for developing appropriate risk mitigation procedures. The costs above do not include costs that might be incurred by various programs to mitigate the meteor storm threat.

Conclusions

By taking advantage of the existing space surveillance network within US Space Command (the organization, equipment designs and sites), as well as radars and the Satellite Control Network (if an IR satellite is to be a part of the system), it appears that the US Air Force can do the search mission significantly cheaper than the system proposed by Spaceguard.

The key questions that must be answered before a search program can begin are:

(1) Is an IR capability needed, and if so, how can we best accomplish our objectives? Could an IR sensor mounted on the future space station do the job cheaper than the WIRE-type of vehicle? Could the sensor be mounted on the Defense Meteorological Satellites?

(2) Do existing GEODSS sites have sufficient excess capability to contribute to an asteroid search mission without building new instruments, or do they have excess capability that would allow us to do the job with fewer additional instruments? Our study assumes no contribution from the existing instruments.

(3) Is the NASA proposed liquid bearing telescope concept practical for a large, multi-instrument program? Are they safe and reliable? If so, they allow us to have many large aperture telescopes at very low cost.

(4) Do we want or need a tripwire? If so, by using the LLNL cameras we could do the job (visual spectrum portion) for a relatively low cost.

(5) What do we do about the lack of radar capability beyond a few tenths of an AU? Is the value of a system capable of reaching ~1 AU worth the expense? If not, do we need more optical instruments to handle the orbit definition mission?

(6) How do we manage the huge amount of data that will converge on the CCCC? How will it be stored, retrieved, and processed?

If the Air Force decides to tackle the NSD search mission, as we believe they should, these question must be answered before a true system definition and cost estimate can be assembled.

As for the meteor stream problem, knowing what we do about the potential for major meteor storms in the near future, and the susceptibility of our space assets to serious damage by these storms we believe it is imperative that we begin to characterize the eleven active streams as soon as possible. The cost of the research is insignificant when compared to the cost of losing even one satellite. While its true that the knowledge will not guarantee the safety of our spacecraft, it will allow us to better understand the risks we face and what might be done to lower those risks.

Notes

[1] David Morrison (editor), *The Spaceguard Survey: Report of the NASA International Near-Earth-Object Detection Workshop.* NASA Office of Space Science and Applications, Solar System Exploration Division, Planetary Astronomy Program of Jet Propulsion Laboratory/California Institute of Technology, Pasadena California. (Executive Summary) page v, 25 June 1992.

[2] Ross T. McNutt, *Orbiting Space Debris: Dangers, Measurement and Mitigation.* Phillips Laboratory, Air Force Systems Command, Hanscom Air Force Base, MA, Research paper, No. PL-TR-92-2146 1102, 92 & 97-99, 1 June 1992.

[3] Clark R. Chapman, Planetary Science Inst./SAIC. Memorandum to Gregory Canavan on Updated Comments on the Interception Workshop Reports, 3 December 1992. (Published as part of Appendix C to the Near-Earth Object Interception Workshop Reports).

[4] Clark R. Chapman and David Morrison, "Impacts on the Earth by Asteroids and Comets: Assessing the Hazard," *Nature 367:* Figure 1. 35, 6 January 1994.

[5] Ibid.

[6] J.G. Hills and M. Patrick Goda, "The Fragmentation of Small Asteroids in the Atmosphere," *Astronomical Journal 105:* 1140-1142, (March 1993).

[7] Morrison, Chapter 5, 29-30.

[8] John D.G. Rather, Jurgen H. Rahe and Gregory Canavan, *The Spaceguard Survey: Report of the International Near-Earth-Object Interception Workshop* Sponsored by NASA Headquarters, Hosted by Los Alamos National Laboratory. Los Alamos, New Mexico, 14-16 January 1992,Chapter 2, 17 & 18.

[9] Gregory Canavan and Johndale Solem, *The Spaceguard Survey: Near-Earth-Object Interception Workshop Summary* Sponsored by NASA Headquarters, Hosted by Los Alamos National Laboratory, Los Alamos NM, 14-16 January 1992.

[10] J.G. Hills and Peter J.T. Leonard, Theoretical Division, Los Alamos National Laboratory, "Earth-crossing Asteroids: The Last Days Before Earth Impact," to be published in *Astronomical Journal* (January 1995), Draft Document dated 18 August 1994, 27. Note: Based on a 1km object.

[11] Ibid, 30.

[12] Ibid, 31.

[13] Ibid.

[14] Ibid. Note: Spaceguard considers one survey to consist of two scans per area of sky which is the minimum required for discrimination.

[15] Ibid, 31.

[16] Ibid.

[17] Morrison, Chapter 7, 42. Note: two to three scans are needed for asteroid discrimination and an average of another four are required for orbit determination.

[18] Morrison, Chapter 5, 27.

[19] Hills and Leonard, 10 Note: Relative velocity for Atens.

[20] Ibid, 22 and 50.

[21] Ibid, 21,48-49.

[22] Ibid, 29.

[23] Ibid, 9,11 & 20.

[24] John Hackwell, Space Environmental Technology Center, Aerospace Corporation, El Segundo CA. Telephone interview. 2 Mar 95.

[25] Ibid.

[26] John Kemp, WIRE Program Manager and Chief Systems Engineer, Utah State University. Telephone Interview, 3 Mar 95.

[27] Ibid.

[28] Ibid, 21.

[29] Gregory H. Canavan, "Acquisition and Track of Near-Earth Objects," in the Reports of the Near-Earth Object Intercept Working Group, Los Alamos NM, 1992, 212 & 219.

[30] Ibid, 214.

[31] Ibid.

[32] S.J. Ostro and D.K. Yeomans, JPL, "NEO Survey: Ten-Year Plan for Radar Reconnaissance of Potentially Hazardous NEOs," Meeting at Flagstaff Arizona, 18 November 1994.

[33] Hills and Leonard, 21.

[34] Ostro and Yeomans.

[35] Morrison, Chapter 6, 39-40.

[36] Ibid.

[37] Ibid.

[38] Ibid.

[39] Morrison, Chapter 7, 43-44.

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[41] Morrison, Chapter 7, 43-44.

[42] Morrison, Chapter 8, 45-46 and Chapter 9, 50-52.

[43] Jim Scotti, Director, Spacewatch Program, University of Arizona, Tucson AZ. Telephone Interview. 13 October 1994.

[44] ESC/TNG, "GEODSS Upgrades for Asteroid Detection." Briefing Charts, Presented at second NEO Meeting, 3 November 1994. Package Dated 18 November 1994.

[45] Ibid.

[46] Ibid.

[47] Robert Weber, MIT Lincoln Laboratory, "TOS to ATDS to GUPS to GMP to Asteroids," Briefing Handout, Presented to First NEO Meeting, 16 September 1994.

[48] ESC/TNG, "GEODSS Upgrades for Asteroid Detection."

[49] Weber, "TOS to ATDS to GUPS to GMP to Asteroids."

[50] Ibid.

[51] Morrison, Chapter 9, 50.

[52] Morrison, Chapters 4, 5 and 7. and Hills and Leonard, 26.

[53] Gene Rork, "Lincoln CCD Imager/GEODSS Telescope for Asteroid Detection," Lincoln Laboratory, Massachusetts Institute of Technology, Briefing Charts, Briefing at Lincoln Labs, 22 September 1994.

[54] Weber, "TOS to ATDS to GUPS to GMP to Asteroids."

[55] Drew Potter, Principal Investigator, Liquid-Mirror Program, Johnson Space Center, NASA, Houston TX. Personal Correspondence, 15 February 1995.

[56] Richard M. Bionta, Carl Akerlof, Eugene Shoemaker and Edward Bowell, "Fast Detection of New Comets and Asteroids with Lawrence Livermore National Laboratory Wide-Field-of-View Telescope System," Briefing Charts, Near Earth Object Survey Committee Meeting, Hye-Sook Park, 18 November 1994.

[57] Don Kessler, JSC Liquid Metal Mirror Program, NASA JSC, Houston TX. Telephone Interview. 17 November 1994. Note: Assumes no other coverage from other optical instruments. Optimization study has not been done. Number of instruments required is a rough estimate.

[58] Morrison, Chapter 7, 4. Note: All coverage's assume 700 hours per year of clear sky observing time at a site. For simplicity, all instruments assumed at same site.

[59] Morrison, Chapter 5, 30. Figure 5-4.

[60] Kessler, Telephone Interview.

[61] Potter, Personal Correspondence.

[62] Ibid.

[63] Ibid.

[64] Potter, Personal Correspondence, 14 March 1995.

[65] Potter, Personal Correspondence, 15 February and 14 March 1995.

[66] Bionta and others, "Fast Detection of New Comets and Asteroids with Lawrence Livermore National Laboratory Wide-Field-of-View Telescope System."

[67] Ibid.

[68] Ibid.

[69] Ibid.

[70] Ibid.

[71] Dennis L. Matson, Glenn J. Veeder, Edward F. Tedesco and Larry A. Lebofsky, "The IRAS Asteroid and Comet Survey," *Asteroids II:* Eds. Binzel, Richard P., Tom

Gehrels and Mildred Shapley Matthews. (Tucson Az: The University of Arizona Press, 1989), 269.

[72] Ibid., 276.

[73] Ibid.

[74] ESC/TNG, "GEODSS Upgrades for Asteroid Detection."

[75] Don Kessler and Drew Potter, JSC Liquid Metal Mirror Program, NASA JSC, Houston TX. Telephone Interview. 17 November 1994 and 14 March 1995, and Drew Potter, Principal Investigator, Liquid-Mirror Program, Johnson Space Center, NASA, Houston TX. Personal Correspondence. 15 February 1995.

[76] John Darrah, Chief Scientist, Air Force Space Command, Colorado Springs CO. Telephone Interview.

20 March 1995.

[77] Richard M. Bionta and others, "Fast Detection of New Comets and Asteroids."

[78] ESC/TNG, "GEODSS Upgrades for Asteroid Detection," Loaded cost of personnel (salary, benefits, etc) based upon contractor estimates given to GEODSS program. Cost or personnel applied uniformly to all systems; however, the number of people required to operate the systems is based upon estimates given in documents related to those systems. See endnotes in table column headings.

[79] AT&T cost estimate based on 12 hr/day digital communications line to site where lines physically exist. Actual costs vary significantly according to sites chosen. Estimates dated 14 March 1985.

[80] Morrison, Chapter 5, 28-30.

[81] John Kemp, WIRE Program Manager and Chief Systems Engineer, Utah State University. Telephone Interview, 3 Mar 95 and Personal Correspondence dated 3 March 1995.

[82] Ostro and Yeomans.

[83] Working Group on Near-Earth Objects. Flagstaff AZ. Meeting Charts 18 November 1994. Note: Contains budget of Minor Planet Center (only organization doing a CCCC type effort). Their budget for 1998 is ~$300L per year. They normally handle 1000 new object's year. Spaceguard predicted 1000 new objects per month with search program. We scaled CCCC costs by factor of 12 to account for increased workload.

[84] Morrison, Chapter 9, 51.

[85] Note: 25% is based on accuracy of sited data. In all cases where an accuracy was sited, the value used was 25%.

[86] J. Jones and others, University of Western Ontario, SEE Proposal,NRA 94-LaRC-1, "Meteoroid Storm Hazard Assessment," Delivered to NASA on 8 July 1994.

[87] Ibid, 15.

[88] M. Beech, P. Brown and J. Jones, "The Potential Danger to Space," 9.

CHAPTER 9

The Military's Response to the Natural Space Debris Threat as a Natural Disaster

There is a great deal of information available concerning natural disasters. Volumes have been written by sociologists, psychologists, public administrators, emergency managers, and others concerning planning for, preparing for, responding to, and learning from natural disasters. The most common natural disasters we read of are those that happen most often and/or those that wreak the most havoc and destruction when they occur. An interesting phenomena, is that the preponderance of what is written, as well as actions taken in response to what is discussed, comes in the wake of a catastrophic disaster; when the death and destruction caused by the disaster is freshest on everyone's mind. As a result of the recent *Kobe* earthquake in Japan, for example, research will be completed and suggestions made concerning what is necessary to avoid similar results if and when the *Big One* strikes in California. For this reason, it is not at all surprising to find that little if any has been written to date on the topic of natural disasters resulting from an impact of Earth by an asteroid or comet. Modern society has not experienced this type of disaster and has little idea of the possible consequences of an NSD induced natural disaster. Previous chapters of this paper have discussed those consequences and the risk associated with the NSD threat. This chapter will briefly discuss the NSD threat as a natural disaster. It goes without saying that the benefit of this discussion is in realizing the need to plan ahead for this possibility so that we don't rely, as we have in the past, on an *ad hoc* reaction in the wake of a such a disaster.

Military Involvement in Disaster Response

As mentioned in the introduction to this paper, the Department of Defense's role in disaster preparedness and response is not a new mission. Historically, the federal government's active participation in providing disaster assistance, of any type, began with the passage of the 1950 Federal Disaster Relief Act.[1] Since that time, disaster relief planning and relief authority has rested with the President. The President has always delegated authority for planning federal disaster programs and for providing assistance to various federal organizations. Table 9-1 summarizes the changes in federal disaster relief organizations from 1950 to today's current system.[2] In July 1979, President Carter assigned federal leadership responsibility for planning and coordinating federal disaster relief activities as well as operational responsibilities in the aftermath of major disasters to the Federal Emergency Management Agency (FEMA).[3] This reorganization served to centralize federal efforts to plan for, and respond to, natural and man-made disasters. Many organizations, with functional responsibility across a broad spectrum of civil defense, planning, and disaster assistance, were combined into this one agency. Of interest to this paper is the fact that the Defense Civil Preparedness Agency within the Department of Defense was one of the organizations dissolved into FEMA; hence there is a direct pre-existing link between the DOD and federal disaster response. The role today's military has in planning for and responding to natural disasters has been shaped by numerous recent events in the world arena. The end of the Cold War and reduced military threats

Table 9-1. Disaster Relief Organizations

Period	Lead Federal Agency	Organizational Status
Pre-1950s	No lead Federal Agency	
1951-53	Housing and Home Finance Administration	Independent agency; disaster activities limited to provision of the 1950 act
1953-58	Federal Civil Defense Administration (FCDA)	Independent agency; responsible for civil defense and disaster relief provisions
1958-61	Office of Civil Defense Mobilization (OCDM)	White House agency; responsible for disaster relief, civil defense, and defense mobilization
1961-73	Office of Emergency Planning (OEP)	White House agency; responsible for disaster relief and planning civil defense; operations of latter shifted to Defense Dept.
1973-79	Federal Disaster Assistance Administration (FDAA)	HUD agency; responsible only for disaster relief; civil defense and preparedness shifted to other agencies
1979-present	Federal Emergency Management Agency (FEMA)	Independent agency; responsible for disaster relief, civil defense and preparedness

Source: May, *Recovering From Catastrophes: Disaster Relief Policy and Politics.*

abroad has resulted in a shift in focus to what we now call *operations other than war*. In President Clinton's National Security Strategy of Engagement and Enlargement the President recognizes that

> U.S. military forces and assets are frequently called upon to provide assistance to victims of floods, storms, drought and other disasters. Both at home and abroad, U.S. forces provide emergency food, shelter, medical care and security to those in need.[4]

That the military is well suited to the tasks associated with response to a natural disaster is not seriously debated. Rather there has been consideration in the aftermath of recent disasters, to increase the military's role in disaster preparedness and response, and even a suggestion by Senator Bob Graham of Florida that "the military should be thought of as the principal response agency in the crisis period to major disasters."[5] Congressman Stark presented H.R. 867 in February 1993, subsequently withdrawn in September 1993, to the Committees on Armed Services and Public Works and Transportation which sought to transfer the functions of the Director of FEMA to the Secretary of Defense.[6] This discussion took place in the days following Hurricane Andrew (in 1992), because the federal disaster assistance provided to the victims of that catastrophe was largely considered inadequate. As a result of congressional scrutiny and public criticism, FEMA and the nation's disaster management system were reexamined by the Clinton Administration.

Two reports generated as a result of this examination, by the National Academy of Public Administration (NAPA) and by the U.S. General Accounting Office (GAO), specifically addressed the proper role of the military in disasters. Both made similar recommendations that "strongly oppose moving FEMA into the military."[7] According to the GAO report, military leadership espouses a similar opinion as to the proper level of military involvement:

> DOD officials strongly believe that assuming overall management responsibility could create the impression that the military is attempting to make or direct domestic policy, which runs contrary to principles that have guided the military's roles in the United States.[8]

The NAPA and GAO reports, however, were clear on the point that there is a definite role for the military in disaster response. Another of the GAO reports that the Sylves article cites, contained the following statement which delineates a military role that is both short-term and under civilian disaster agency direction:

> Increasing reliance on DOD to provide mass care would strengthen the federal role following a catastrophic disaster when there is a gap between what the private sector can provide and what disaster victims need.[9]

The discussion to this point has attempted to ascertain whether the military has an acknowledged role (not so much by choice but by necessity) in the federal emergency management strategy. Before we specifically consider the problem of natural space debris induced disasters, one additional lesson should be drawn from the perceived inadequacy of our federal government's response to past catastrophes. The current federal emergency management organization will be stretched well beyond it's capacity to effectively respond to the scope and magnitude of disaster that would result from a comet or asteroid impact. The problem with rare or massive events, is that emergency managers and response agencies will most likely be facing an event for which they have not adequately planned, since historically, such an event has not been experienced.[10] For this reason, planning for an NSD event is extremely difficult. How can planners make precise recommendations on what to do to deal with such situations when they don't know what to expect? The emphasis, therefore, must be on continued research and public education concerning the NSD threat. At this time, it is simply not wise to expect that the response to a natural disaster caused by natural space debris will be adequate if the plan is to handle such an emergency just like any other natural disaster. Unequivocally, the military should plan to be thrust into a primary, rather than a supplemental, disaster relief role if such a disaster occurs. Put simply, no other agency is capable of providing the organizational base, materiel resources, medical teams and supplies, air and road transportation groups, communication specialists, and the myriad of other things necessary for a rapid response to such a disaster, either at home or abroad.

Doctrine Governing Military Support of Civil Authorities

The framework under which the military provides disaster assistance is outlined in a number of directives. Understanding the doctrine and legislation the DOD follows in providing such assistance is helpful in determining the necessary changes to be considered should the military be faced with a natural disaster of the scope that we think possible.

The Robert T. Stafford Disaster Relief and Emergency Assistance Act provides Presidential authority to exercise federal agencies in support of state and local governments in responding to any disaster for which the President has declared either an *Emergency* or a *Major Disaster*. The support provided is to be the essential assistance needed to meet immediate threats to life and property, and should only be carried out for a period not to exceed 10 days.[11] Although intended to be general in nature, so that the President can be flexible in his response to an emergency, the Stafford Act guidance is lacking in at least two respects. First, as the law is currently written, it pertains only to disasters occurring in the United States. A disaster resulting from NSD, could very possibly take place outside of the U.S., but would be of such magnitude and consequence to require immediate federal support for the international relief effort. Secondly, the proposed 10 day restriction for the use of federally supplied support is grossly restrictive when one considers the cataclysmic proportions of such an event.

The Stafford Act is supported by *The Federal Response Plan (FRP)*. This Plan establishes the basis for the provision of Federal assistance to a State and its affected local governments impacted by a catastrophic or significant disaster or emergency which results in a requirement for Federal response assistance.[12] The plan groups the most likely requirements for assistance by functional area (Emergency Support Functions (ESF's)) and then assigns primary or support responsibility to the federal agencies and/or departments based on resources and capabilities to support that functional area. Table 9-2 is a matrix that shows the twelve ESF's and the primary and support agencies for each. The DOD is listed as primary agency for the *Public Works and Engineering* and the *Urban Search and Rescue* functional areas, and is a supporting agency for all of the remaining ESF's. It is our opinion that the Federal Response Plan, as written, is well organized and appropriate for the purposes intended. Although disasters as a result of NSD are not specifically mentioned, it is critically important that the FRP allows for the possibility of disasters of any scope; even providing that some situations may result that require the use of national security authorities and procedures.[13] As a result of this provision, the FRP created and reserves a position for the Defense Coordinating Officer (DCO), who directly supports the Federal Coordinating Officer appointed by FEMA, should the military's services be required. The DCO is critically important to an effective military response to an NSD disaster spanning all functional areas. After all, military success will hinge on effective management and apportionment of limited military resources and the DCO is instrumental to this process.

The military's response to previous natural disasters, though successful in most aspects, had been done in an *ad hoc* manner. A lack of dedicated planning and an unclear definition of the mission to be accomplished required a *seat of the pants* methodology when faced with disaster situations. It is a credit to the leadership and discipline inherent in military organizations that such success was met. However, as previously mentioned, the focus has changed, and *Humanitarian Assistance* has become much more than an additional duty. Rather, success in this arena is integral to establishing forward presence and credibility for our military forces. Realizing this, DOD issued Department of Defense Directive (DODD) 3025.1 in early 1993 in the hope of formalizing the business of providing military assistance to civil authorities. This directive gives a high level perspective of the regulatory requirements governing military actions in a disaster, but it can hardly be relied on to ensure those actions are appropriate.

The responsibility for planning and coordinating effective and appropriate DOD assistance to civil authorities rests with the Secretary of the Army, who has been appointed by the SECDEF to be the executive agent for providing military domestic support. The Secretary of the Army has authority to task DOD components to plan for, and to commit DOD resources in response to, requests for military support. As such, there is a provision for seeking to commit the military forces of the unified or specified commands, once coordinated with the Chairman of the Joint Chiefs of Staff (CJCS). There is a definite need for doctrinal guidance beyond the broad scope provided by DODD 3025.1. In that light, the U.S. Army and the U.S. Marine Corps have jointly published FM 100-19, *Domestic Support Operations,* which provides more specific guidance to Army and Marine Corps commanders and staff tasked with planning, preparing for, and conducting domestic support operations[14]. More specific guidance for the CINC, should they be called upon, is identified in appropriate DOD directives, guidelines and operational plans.

It is beyond the scope of this paper to determine the adequacy of these plans and directives in response to natural disasters; however, such a review is critically important considering the implications of failing to do so. If there are indeed shortcomings in DOD directives relating to natural disasters, they likely will surface as a result of attempting to use the guidance provided in response to an actual emergency. Recent past disasters generally point to doctrinal weaknesses concerning the *tactics, techniques, and procedures* used by military personnel in responding to emergencies, rather than to problems with the general descriptive doctrine, discussed previously, of planning for and conducting domestic disaster relief operations.[15]

Table 9-2. Emergency Support Function Assignment Matrix

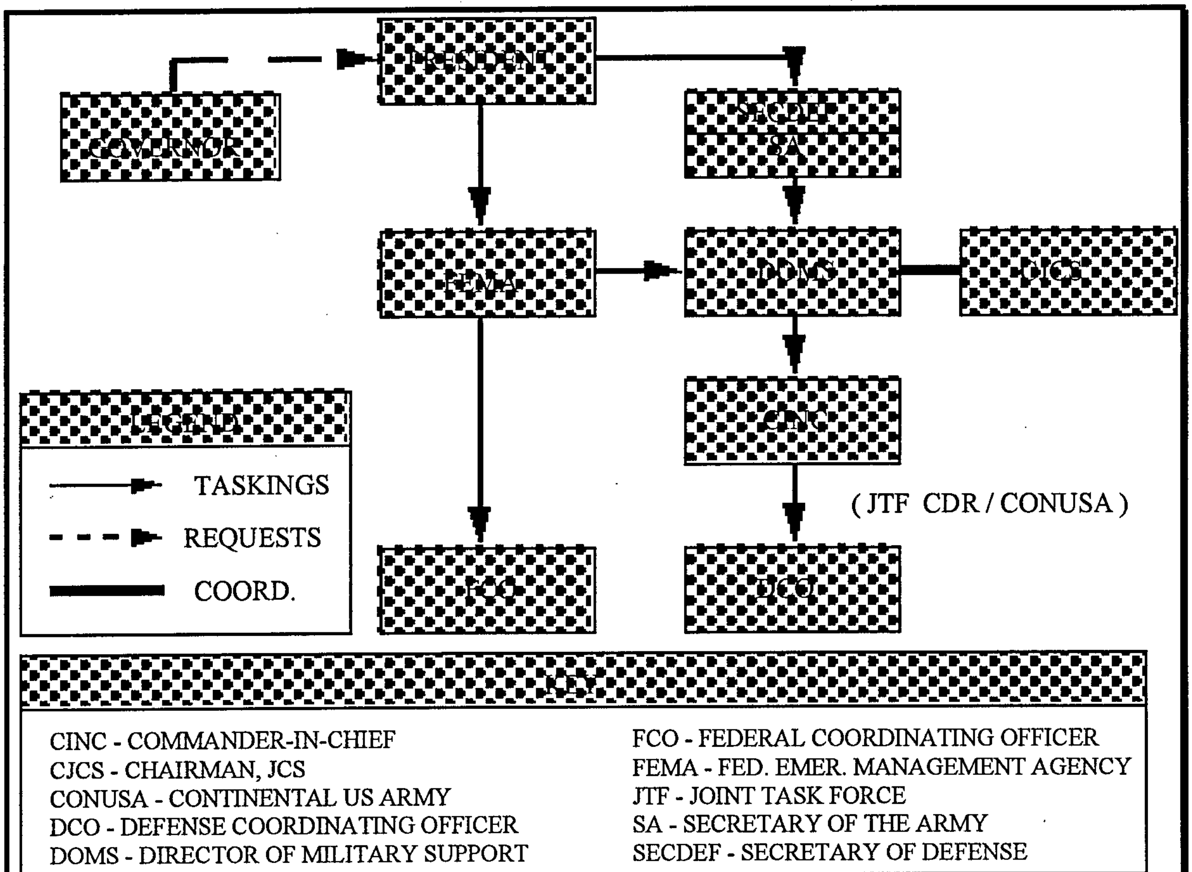
ESF / ORG	Transportation	Communications	[illegible]	Firefighting	Information and Planning	Mass Care	Resource Support	[illegible]	Urban Search and Rescue	Hazardous Materials	Food	Energy
USDA	S	S	S	P	S	S	S	S	S	S	P	S
DOC		S	S	S	S	S	S			S		
DOD	S	S	P	S	S	S	S	S	P	S	S	S
DOEd					S							
DOE	S		S		S		S			S		P
DHHS			S		S	S	S	P	S	S	S	
DHUD						S						
DOI		S	S	S	S					S		
DOJ					S			S		S		
DOL			S				S		S	S		
DOS	S									S		S
DOT	P	S	S		S	S	S	S	S	S	S	S
TREAS					S							
VA			S			S	S	S				
AID								S	S			
ARC					S	P		S			S	
EPA			S	S	S			S	S	P	S	
FCC		S										
FEMA		S		S	P	S	S	S	S	S	S	
GSA	S	S	S		S	S	P	S	S	S		S
ICC	S											
NASA					S							
NCS		P			S		S	S				S
NRC					S					S		S
OPM							S					
TVA	S		S									S
USPS	S					S		S				

P - Primary Agency: Responsible for Management of the ESF
S - Support Agency: Responsible for Supporting the Primary Agency
Source: *The Federal Response Plan,* April 1992.

Employment of Military Forces in Domestic Disaster Relief

National policy guidance and Federal Response Plan requirements are the impetus for the military providing assistance to civil authorities in response to natural disasters. The doctrinal guidance discussed above addresses the responsibilities and requirements given to military commanders who are tasked with providing assistance in a natural disaster. It is necessary to understand the strategic and operational level requirements of employing military forces in disaster relief, to better understand the scope of the problem that we face in responding to the NSD threat.

Strategic Requirements. The use of military forces is at the discretion of the President, if he determines that such action will save lives and protect property. Prior to an emergency declaration being made, local active duty commanders have the authority to commit resources during an emergency under the *immediate response* provisions of DODD 3025.1.[16] If and when state and local governments are overwhelmed by the situation, state governors will be authorized the use of National Guard forces, who have primary federal responsibility for providing military assistance. As currently written, the Stafford Act only permits the use of federal forces after state resources have been exhausted and the President has declared a national *major disaster* or *emergency.* At this point, FEMA, who has been delegated Presidential authority to do so, will appoint a Federal Coordinating Officer (FCO) to oversee the federal response effort. The entire decision process is shown in Figure 9-1. In accordance with the FRP, the designated primary support agencies will begin to provide the necessary assistance to the affected state(s). Support agencies may be tasked by the FCO to provide assistance if they have special expertise that will contribute to the relief operations.



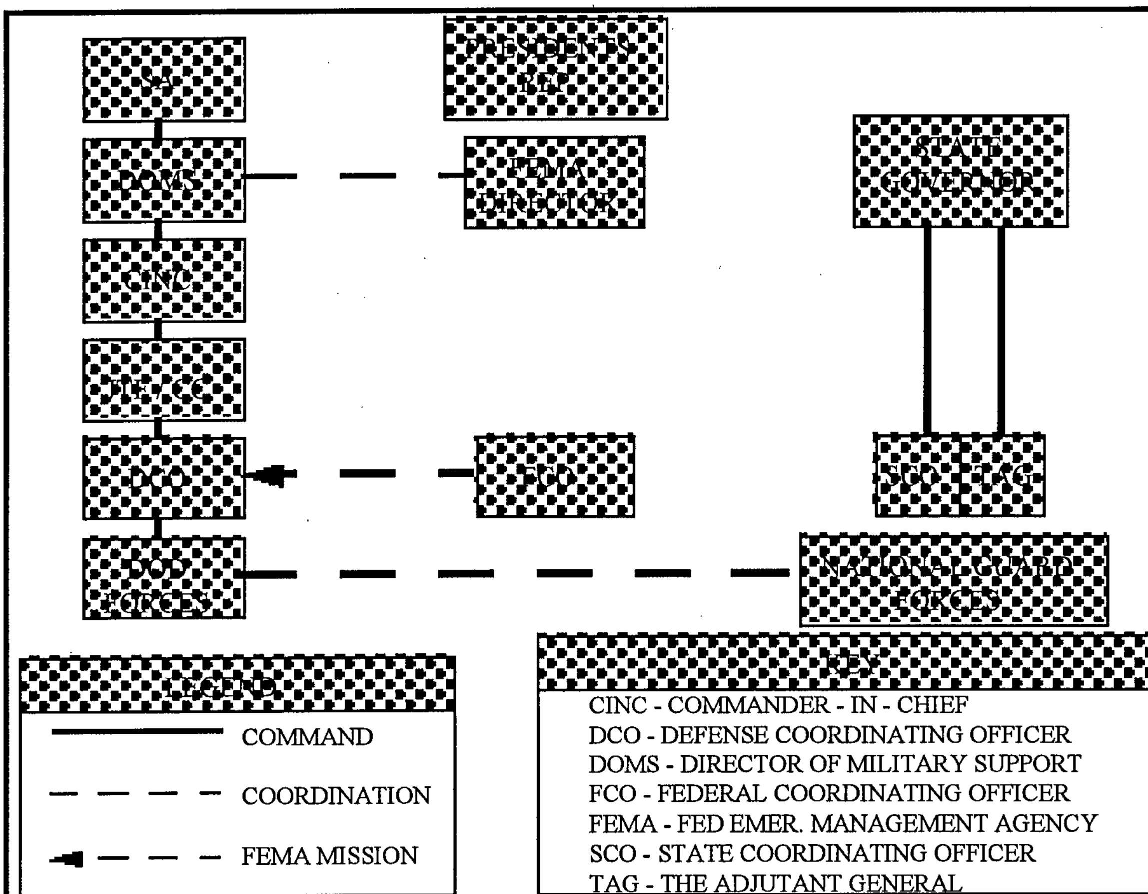
Source: FM 100-19

Figure 9-1. Strategic Decision Sequence

Operational Requirements. Figure 9-2 shows the command relationships that exist when the military participates in natural disaster response. DODD 3025.1 directs that CINCUSACOM and USCINCPAC shall serve as DOD Planning Agents, responsible for planning activities of all the DOD components within their assigned geographic areas. Planning to use DOD resources is done in conjunction with civil authorities and stresses centralized control and decentralized execution in time of emergency. Each of the Secretaries of the Military Departments has a detailed list of responsibilities regarding planning for, training for, and the execution of emergency operations in support of civil authorities.[17] As the designated DOD Executive Agent, the Secretary of the Army (SA) has an expanded role in disaster response operations. The SA manages Military Support to Civil Authorities (MSCA) assistance through the Director of Military Support (DOMS) and its associated support staff. The DOMS is ultimately responsible for the planning, coordinating, and managing of disaster response operations for all DOD assets. Execution of support plans is the responsibility of the geographically designated CINC. The CINC appoints a Defense Coordinating Officer (DCO), who is the central point of contact for federal military assistance requests from the FCO and state and local officials.[18] This effort may, depending on the magnitude of the task, be organized as a joint task force (JTF) at the discretion of the supporting CINC. The DOD's use of a JTF in response to Hurricanes Andrew and Iniki in 1992 demonstrates their belief that the JTF is effective in providing the comprehensive support needed in such catastrophic situations.[19]

Preparing for Disaster Assistance Support

Preparation for an NSD induced natural disaster will require some fundamental changes in the way the DOD views their role in disaster assistance. As we have mentioned, it is likely that the military will be thrust into the primary role in response to an NSD disaster, rather than having a supportive role. FM 100-19 depicts the military's conceptualization of the required military involvement in a humanitarian relief effort as it evolves from start to finish (see Figure 9-2). The military sees its role in domestic disaster operations as occurring in stages: response, recovery, and restoration; with the anticipated level of effort (i.e. peak effort) being greatest in the response stage, and decreasing steadily over time as the operation moves into the remaining stages.



Source: FM 100 - 19

Figure 9-2. Operational Command Relationships

This view is consistent with those coming out of the aforementioned NAPA and GAO studies, that see the military's primary role in a disaster as being providers of *mass care*. Mass care is synonymous, for our purposes, with that effort required to meet the initial and most obvious needs of victims of natural disasters. In this *response* stage, for example, relief workers (military or otherwise) are most concerned with providing food, water, medical care, and shelter for disaster victims, and with taking the necessary steps to provide for their safety and security. The military effort required in this stage is greatest for a combination of reasons, but primarily because civilian relief organizations with the capability to provide such assistance take more time, relative to the military, to organize and then respond to the emergency. In it's later stages, (i.e., *recovery and restoration stages)*, civilian relief organizations have mobilized and are positioned to continue the relief effort, so that military units on the scene gradually hand-off relief responsibility. When considering an NSD disaster, two changes occur in the military's conceptualization of the disaster relief effort. First, the peak efforts depicted in each of the stages of the operation will move up and to the right relative to past experience with natural disasters. That is, the level of effort to provide relief in the wake of an NSD disaster, regardless of which stage of disaster we are concerned with, is certain to be of greater magnitude, and will continue for a greater period of time. The second change is the relative movement of the peak efforts in each of the stages of the operation in relation to each other and the resulting absence of overlapping effort in each of the stages. The focus on providing mass care and life sustaining functions for disaster victims during the response stage is likely to last much longer. The resources that this *mass care* effort alone will take will likely exhaust supplies, since the military does not stockpile resources solely for domestic disaster assistance.[20] As a result, rather than being accomplished in conjunction with response efforts, the recovery and restoration efforts may be significantly delayed awaiting manpower and supplies dedicated to the response stage of the operation.

There is one final point to make concerning this topic. There is no mention of the relative benefits of both disaster preparedness and disaster mitigation. We envision a sliding scale whereby peak relief efforts in any NSD related natural disaster can be reduced relative to the levels of preparedness and mitigation that exist prior to the event occurring.

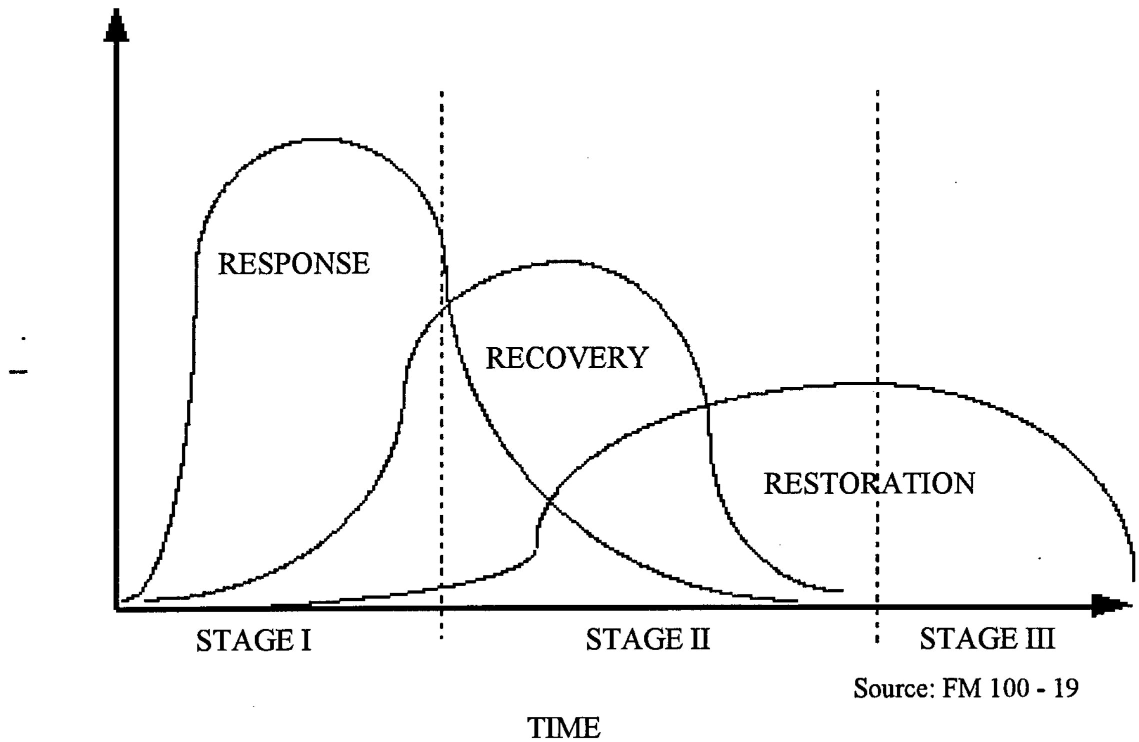


Figure 9-3. Disaster Stages and Levels of Effort

This is not always the case with natural disasters. Some natural disasters, like floods in a flood plain and earthquakes along a fault line, are conducive to preparedness and mitigation efforts, while others, like accidents and tornadoes, often happen without warning. Concerning NSD disasters, there may be ample warning and relative predictability of the occurrence, allowing for heightened preparedness and mitigation efforts prior to the event. Figure 9-4 depicts a level of military effort bounded by whatever is done to prepare for, or to reduce the effects of, the ensuing catastrophe. That is, the emphasis must be on reducing risks to people, property, and communities from NSD hazards. By doing so, the military will be in line with emerging national policy resulting from Vice President Gore's recently completed National Performance Review.

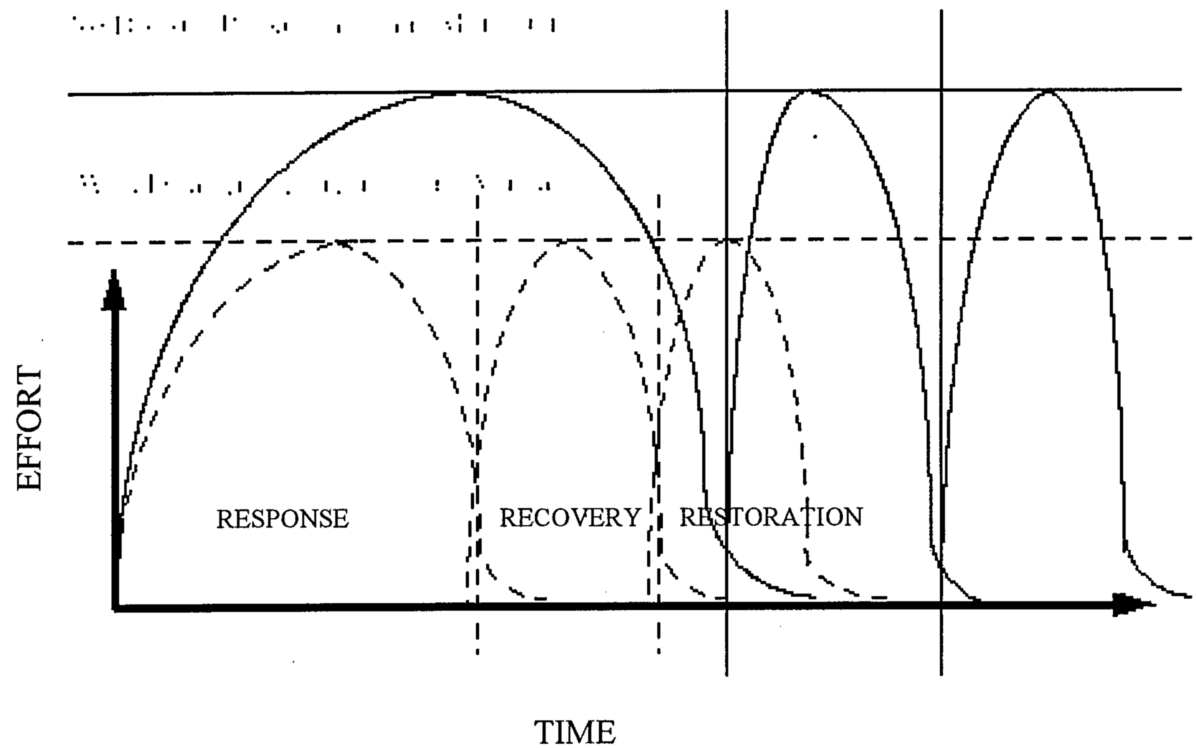


Figure 9-4. Effort vs. Time for an NSD Disaster

Disaster mitigation is among the major policy initiatives at FEMA as the Agency seeks to reinvent itself in response to close scrutiny over how recent disasters were managed.[21] An expanded discussion of mitigation efforts that we feel the DOD should consider in response to NSD threats will be discussed in the next chapter as one of the recommendations we make for further consideration.

NSD as a Natural Disaster: A Summary

The purpose of the above discussion is to establish for the reader the underlying premise that the military has an acknowledged role to play in response to natural disasters. An historical perspective of the military's involvement in natural disasters and the evolution of that involvement into today's current emphasis on *Operations Other Than*

War, serves as the basis for our contention that the military has reason to be concerned with the NSD threat. The domestic disaster relief framework, spearheaded by FEMA, was reviewed in order to formalize the task of providing disaster assistance to civil authorities. Military planners and commanders must know and understand the strategic and operational requirements currently embedded in pertinent doctrinal guidance, in order to be responsive within that framework. Most importantly, there must be a fundamental shift in the paradigm concerning the military's perceived role in disaster response. An NSD disaster is not like any other and should not be treated as such. The scope and magnitude of such a disaster requires that the military know and understand, not just it's role in disaster response as outlined in the Federal Response Plan, but the entire process from the perspective of DOD as lead agency by necessity rather than choice. At a minimum, military planners and commanders should understand the tremendous requirements, resources, and the scope of the task involved in providing mass care in the wake of an NSD disaster and plan accordingly.

Notes

[1] Peter J.May, *Recovering From Catastrophes: Federal Disaster Relief Policy and Politics* (Connecticut: Greenwood Press, 1985), 50.

[2] Ibid.

[3] Ibid, 54.

[4] *A National Security Strategy of Engagement and Enlargement* (Washington: U.S. Government Printing Office, July 1994), 9.

[5] Robert Graham, Senator of Florida, "Statement Given United States Senate, Committee on Appropriations, before the Subcommittee on VA, HUD and Independent Agencies, 27 January 1993.

[6] Keith Bea, "CRS Issue Brief: Disaster Management," *Congressional Research Service—The Library of Congress*: 6-14, (29 October 1993).

[7] Richard T. Sylves, "Ferment at FEMA: Reforming Emergency Management," *Public Administration Review Vol 54 No. 3*: 303-307 , (May/June 1994).

[8] U.S. General Accounting Office, *Disaster Management: Improving the Nation s Response to Catastrophic Disasters*, July 1993.

[9] U.S. General Accounting Office, Statement of Charles A. Bowsher, Comptroller General of the U.S., *Disaster Management: Recent Disasters Demonstrate the Need to Improve the Nation s Response Strategy* 29 April 1993.

[10] Dennis S. Mileti and John H. Sorensen, *Communication of Emergency Public Warnings: A Social Science Perspective and State-of-the-Art Assessment*, (Oakridge National Laboratory: 1990), 6-cxciv.

[11] Note: "Robert T. Stafford Disaster Relief and Emergency Assistance Act" PL 93-288, as amended.

[12] Note: "The Federal Response Plan For Public Law 93-288, As Amended." April 1992. ix.

[13] Ibid, 2.

[14] Departments of the Army and US Marine Corps, *Domestic Support Operations:* FM 100-19/ FMFM 7-10, (Washington: HQ USA, 1 July 1993).

[15] A. G. Smart, Major, USA. *Military Support to Domestic Disaster Relief: Doctrine for Operating in the Wake of the Enemy* Monograph, School of Advanced Military Studies , 39, (14 May 1993).

[16] Department of Defense, *Military Support to Civil Authorities:* DOD Directive 3025.1, (Washington: GPO. 15 January 1993), 6.

[17] Ibid, 9.

[18] Departments of the Army and US Marine Corps, *Domestic Support Operations:* FM 100-19 / FMFM 7-10, (Washington: HQ USA, 1 July 1993), 5-9.

[19] Ibid.

[20] Ibid, 5-4.

[21] Vice President Al Gore, *Creating A Government That Works Better & Costs Less: Federal Emergency Management Agency,* (Accompanying Report of the National Performance Review, September 1993), 26.

CHAPTER 10

Threat Mitigation

Decisions by national policy makers relating to the NSD threat and what can be done about it are complicated by many contextual elements. For example, we must be realistic about the chance of implementing threat mitigation measures considering the reality of shrinking budgets and the public's perception that the topic belongs to the realm of cheap sci-fi thrillers. As a result, in this chapter, our emphasis is on suggesting mitigation measures that we consider practical, based on realistic political, technical, and economic assessments. The measures presented herein are not all-inclusive, nor will the discussion be overly technical in nature. Instead, the measures we propose provide a starting point for the DOD to expand it's knowledge of the problem and to best decide what to do about it.

Mitigation to Reduce the Effects of the NSD Threat

History tells us that mitigation measures are indeed the key to reducing the effects of natural disasters. A report submitted by the Organization of American States (OAS) concerning natural hazards suggests:

> Improved warning and evacuation systems have cut the death toll of hurricanes dramatically. Combinations of structural and non-structural mitigation measures have been shown to alleviate the effects of earthquakes, landslides, floods and droughts.[1]

Thus, the emphasis of emergency managers and planners, in both the national and international arena, must be on those actions that can be taken to reduce the effects associated with an NSD induced catastrophe. Our recommendations take a slightly more parochial view concerning the NSD threat in that the observations and suggestions are tailored for DOD planners and commanders who will be tasked with providing domestic assistance in the wake of an NSD disaster. Essentially, we believe the risks of the NSD threat are identifiable, mitigation measures are possible, and that the benefits of reducing the risk and vulnerability to the threat are high in relation to costs. The cost of reducing the threat, is of course central to the NSD issue, as well as to our proposals for what to do about it. As the OAS report states:

> Rare or low-probability events of great severity are the most difficult to mitigate, and vulnerability reduction may demand risk-aversion measures beyond those justified by economic analysis. [2]

Though we have not performed a detailed cost analysis, we propose only those measures that we feel are affordable considering the reality of shrinking budgets and imposed fiscal constraints. When considering mitigation costs it is prudent to keep fully in mind the enormous cost (in the wake of an NSD disaster) to replace what is destroyed or damaged. The cost of rebuilding after a disaster is rising and will probably continue to rise in the future. The most expensive natural disaster in US history was the $25 billion spent to rebuild in South Florida, in the wake of Hurricane Andrew.[3] However Andrew's cost, both in economic terms and in loss of life, pales in comparison to the estimated $58 billion price tag and over 5,000 deaths resulting from the January 1995 earthquake in Kobe, Japan.[4] Again, no detailed analysis has been done, but we are convinced that the costs of recovering from an NSD disaster would be equally staggering.

Today, according to the OAS, only 10% of the funds spent on natural disasters are used to reduce the effects of the disaster, while the other 90% are used in relief and reconstruction efforts.[5] This trend is neither cost effective nor prudent considering the magnitude of the NSD threat. We believe that the military cannot afford its current plan: to handle an NSD disaster just like we would any other natural disaster (i.e. reactive versus proactive approach).[6]

The level of catastrophe we think possible goes far beyond what has historically been planned for, or experienced. So we should not be surprised to find that no substantive NSD threat mitigation plans exist.[7] They will have to be built from the ground up, and the first step involves educating the public on the threat. Beyond education, we believe the NSD threat can be mitigated (to some degree) at an acceptable cost through a combination of planning, preparedness (warning and alerting, and training), improved threat detection and characterization, and continued research aimed at protecting life and property from NSD debris large and small.

The reader will recall that Figure 4-8 graphically illustrates the NSD threat in terms of expected environmental impact as a function of the impactor's diameter. The size of the debris is important to our discussion because it ensures we propose mitigation measures only for those effects that we need be concerned about. As an example, consider the NSD threat resulting from debris that measures less than 56 meters in diameter, illustrated in Figure 10-1. Debris measuring less than 1 meter in size is predominantly a threat to satellites and spacecraft, since Earth and its environment are adequately protected by the atmosphere from such small debris. Debris measuring larger than 1 meter, but less than 56 meters, is of little concern to either space assets (although satellites are extremely vulnerable to larger objects, the risk of an impact is minimal), or Earth because the atmosphere provides the necessary protection. Therefore, in this example, you can see that only those mitigation efforts aimed at protecting space assets

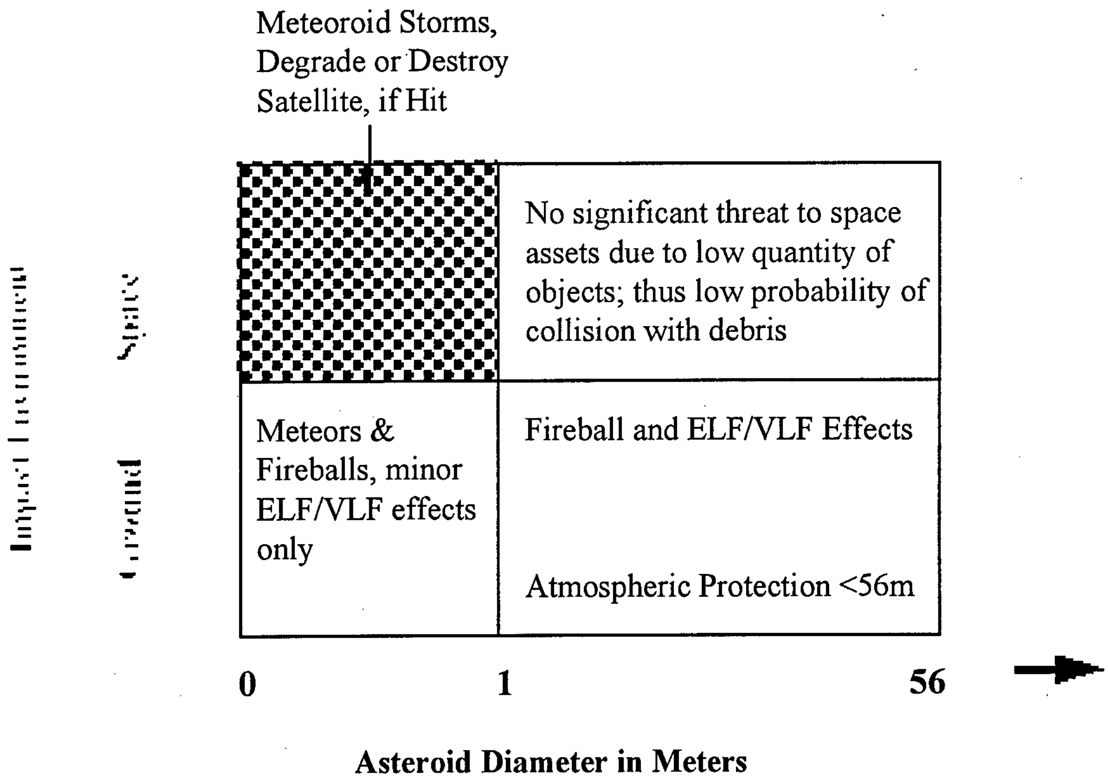


Figure 10-1. NSD Effect for Debris Less Than 56 Meters in Size

are necessary and worth pursuing. The same type of analysis must be performed across the entire NSD spectrum in order to ensure that the mitigation measures to be implemented are appropriate. Obviously, this is a simplistic example, but the point we want to make is that it is essential for policy makers to have a clear understanding of the threat before formulating courses of action. For this reason, the mitigation measures we propose directly relate to the NSD threats discussed in Chapter 4.

There are two additional observations worth mentioning at this point. First, not every mitigation measure will be as cost effective, or as practical as every other. The cost of planning, basic NSD research and a search program will probably be reasonably affordable However the affordability of an active defense system (such as alert missiles) to defend against the NSD threat is a matter for debate. The second observation is that the availability of multiple mitigation measures will have a synergistic effect on our ability to respond to an NSD disaster. This concept is illustrated in Figure 10-2, which shows the synergistic (multiplicative) effect of planning, preparedness, detection (search), and protection on the final outcome: *disaster response capability.* Just as in multiplication, any single multiplier (any one of the mitigation measures proposed) has the potential to limit the end product. In this case, if any of the mitigation measures are inadequate or non-existent the result would be an inability to effectively respond to (or prevent) an NSD disaster. This is important because, in order to be successful, the mitigation *program* will require long-term commitment and determination to ensure all parts of the program continue to perform their functions. Only in this way can we hope to sustain mitigation efforts, and our overall preparedness during those extended periods when the NSD threat is not imminent.

Mitigation Measures

Planning. Planning is probably the most beneficial and cost effective of all possible mitigation measures. With respect to NSD defense, we are less constrained by time than by money in our efforts to do something about the problem. Planning takes time, but costs very little. Right now, there is no immediate NSD threat, so we have time to plan. We should use it to begin developing these plans and procedures as soon as possible. Fortunately, much of the framework used in developing such plans has already been established. Existing national and international planning institutions and methodologies can, with slight modifications, accomplish the task in relatively short order.

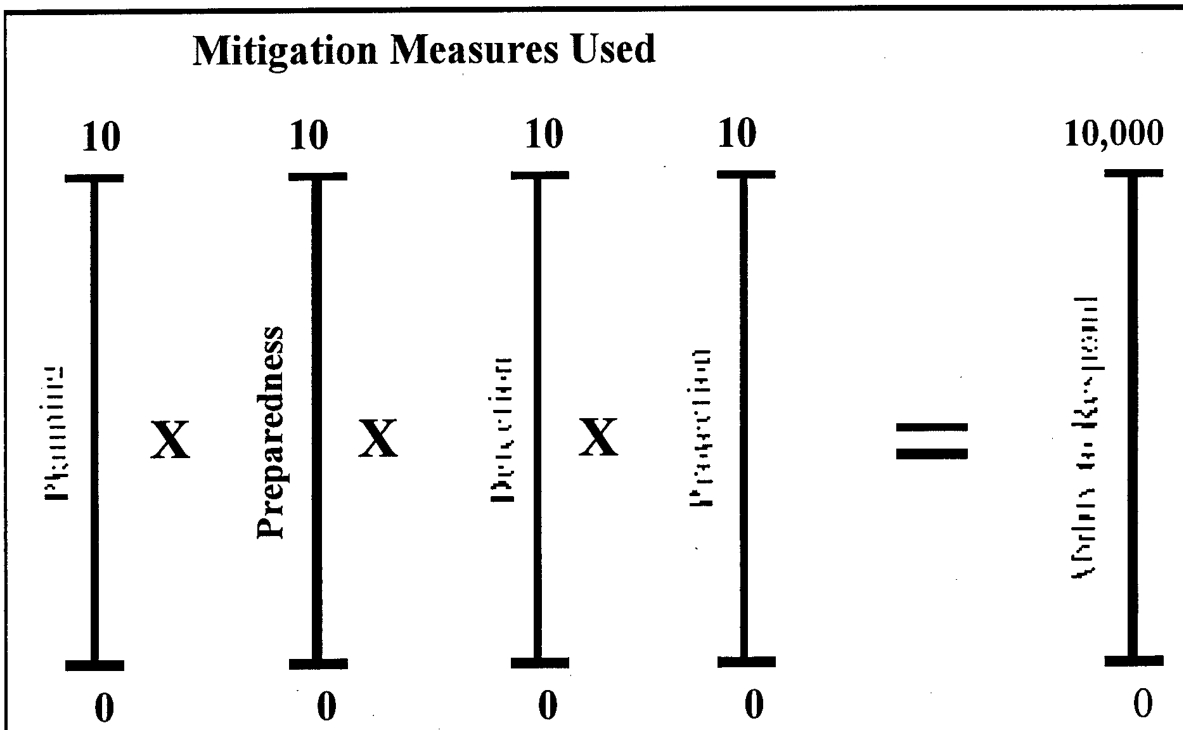


Figure 10-2. Synergistic Effect of Multiple Mitigation Measures

National Planning. As previously mentioned, FEMA is in the process of moving away from a two-track approach, (preparedness for a national security emergency (like a nuclear attack), and preparedness for a natural disaster) to an emphasis on preparing for and responding to all disasters.[8] With the end of the Cold War, FEMA's focus is shifting away from responding to a nuclear strike and toward other threats to national security.[9] Preparedness and planning for the continuance of government and the mobilization of the country's resources in the event of a nuclear strike was FEMA's main focus for many years. Functional plans involving industrial, economic, infrastructure, human resources, government and civil preparedness actions aimed at surviving such a strike have long been established.[10]

A significant number of FEMA's existing nuclear attack response plans are similar to what would be needed to respond to an NSD impact. For example, plans for: warning and notification, evacuation, mass care, and seeing to the basic needs of emergency victims, are vital considerations for both types of events. Although much of the information concerning FEMA's national security function remains classified, an *all disaster* philosophy necessitates the sharing of those plans when they are needed in order to respond to another type of disaster. FEMA's National Preparedness Directorate should take the lead in identifying those plans that have utility in an NSD disaster, and make that information available to other federal, state, local, and non-governmental agencies that would be involved in disaster preparedness and planning.

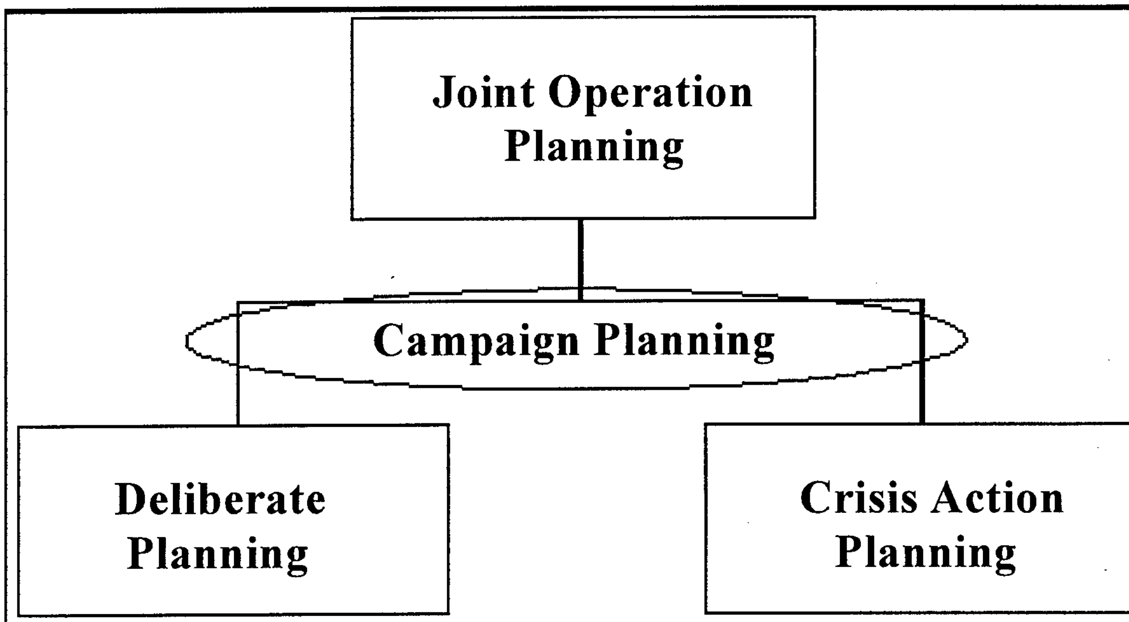
The Directorate's "Federal Preparedness Guide" offers planning guidance concerning functional responsibilities during a national security emergency, and is a suitable starting point to embark on planning for an NSD disaster.[11] The guide introduces the concept of Graduated Mobilization Response (GMR) to a national security emergency (nuclear strike or war). The concept is equally appropriate to an NSD disaster and should be considered as such:

> GMR is a system to undertake mobilization in response to early, ambiguous, and/or specific warnings. GMR actions are designed to enhance deterrence, mitigate the impact of an event or crisis, and reduce significantly the lead time associated with a mobilization should the crisis intensify. The heart of the concept is to prepare and present readiness and sustainability assessments and options as early as possible in planning for a crisis response.[12]

The GMR System is useful because it is based on assumptions that are consistent with our premise concerning threat mitigation. Specifically, GMR recognizes that mitigation efforts are beneficial in disaster response and that they are possible only to the extent that they are affordable (considering personnel and budgetary resources).[13]

The military is similarly well-suited to the task of planning for an NSD induced natural disaster. The planning function is critically important to DOD operations in both peace and war, and is fundamental to the department's national military strategy in support of national security objectives. For example, if the military were tasked as lead agent (i.e. a Joint Task Force is designated) by National Command Authorities (NCA), to plan for an orderly and efficient response to an NSD catastrophe, DOD planners have all the necessary resources at hand to develop such a plan. Joint doctrine and guidance, planning tools and techniques, and planning support functions are all in place to assist military planners with tasks of this sort. Joint Publication 5-0 offers doctrinal guidance for planning joint operations across the entire spectrum of military operations, to include those contingency operations other than war, of which disaster relief is a subset.[14] Whereas the GMR System includes three graduated stages of planning (*Planning and Preparation, Crisis Management, and National Security Emergency or War*[15]) the military's Joint Operation Planning and Execution System (JOPES) consists of two types of planning: *Deliberate Planning and Crisis Action Planning.*[16] The types of *Joint Operation Planning*, shown in Figure 10-3, are only important (in this discussion) to establish that a suitable framework for planning for an NSD event is already in place. Deliberate planning:

> Provides a foundation for and eases the transition to crisis resolution. Work performed during the deliberate planning process allows the development of processes, procedures, and planning expertise which are critically needed during crisis action planning.[17]



Source: Joint Pub 5-0

Figure 10-3. Types of Joint Operation Planning

Crisis Action Planning (CAP) is different from deliberate planning in the respect that:

> CAP is based on current events and conducted in time-sensitive situations and emergencies using assigned, attached, and allocated forces and resources. Crisis action planners base their plan on the actual circumstances that exist at the time planning occurs. They follow prescribed crisis action procedures that parallel deliberate planning, but are more flexible and responsive to changing events.[18]

A combination of both deliberate and crisis action planning provides ideal preparation for any military involvement, whether in war or in military operations other than war. History, however, is replete with crises for which deliberate planning had not been accomplished. In such cases, crisis action planning was performed in an *ad hoc* manner, without benefit of prior planning. Mission success was therefore jeopardized. The *Iranian Hostage Recovery* in 1980 is one such example. Although there were many contributing factors to the failure of that mission, a formal review of the reasons for failure found that inadequate planning (no deliberate plan existed) was a primary cause.[19] It seems obvious that prior planning is beneficial when the military responds to an emergency.

International Planning. Much of the previous discussion concerning the military's involvement in planning for disaster response is equally applicable to planning for participation in international disaster relief efforts. According to Joint Pub 3-07, disaster relief is a subset of humanitarian assistance (HA) that has positive impacts for both the US Government and the host nation.[20] The Department of State's Office of Foreign Disaster Assistance coordinates US military assistance in international disaster relief operations, usually at the request of the United Nations. The military's role is to "assess the extent of the damage as well as the host nation's capabilities to deal with the emergency."[21] Assuming individual countries participating in an international relief operation are responsible for, and in fact accomplish, the necessary planning for their designated role in disaster response, there remains a broader issue for international consideration.

There are no agreed upon criteria, or known conditions, for the deployment of Military and Civil Defense Assets (MCDA) to provide international disaster relief.[22] The Department of Humanitarian Affairs (DHA) in Geneva is currently working to formalize the guidelines and conditions under which the international community provides disaster assistance, but until that is done, countries providing assistance will do so in an *ad hoc* manner. One DHA proposal, particularly significant to research concerning an NSD disaster, is to build a register of MCDA participants, and the type of assistance to be provided.[23] Such a register could eventually be used to assign functional areas of assistance to participating countries, enabling nations to plan and allocate resources based on that responsibility. This concept funtionalizes the various areas of concern involved in providing international disaster assistance, and is similar to FEMA's breakout of Emergency Support Functions (ESF's) in the Federal Response Plan. For example, the US military might be assigned functional responsibility for such things as transport, survey, reconnaissance, or communication. Knowing their responsibilities, the military (and other parties) would ensure that the appropriate planning was performed.

Preparedness. Adequate planning for an NSD disaster is of little consequence if the level of preparedness is so low that the nation's resources cannot be mobilized sufficiently to enact those plans. Essentially, a nation's level of preparedness can only be determined after considering all of the requirements that must be met in order to respond to a particular catastrophe. Our level of preparedness will be determined by the steps we take to improve our ability to respond to that threat. We will discuss two distinct steps to a better state of readiness: *warning and alerting, and training.*

Warning and Alerting. So far in this chapter, we have discussed the need for continued education aimed at increasing knowledge and awareness of the NSD threat, as well as the requirement for adequate planning to meet that threat. Acceptable mitigation of the threat will also require experimentation aimed at the development of hardware and the necessary support infrastructure to defend against NSD. Chapter's 7 and 8 of this paper offered a detailed discussion of the most pressing requirement for readiness related to NSD; specifically the *search systems necessary for detection and discrimination of NSD*. The important point of that discussion, is that mitigation efforts are greatly enhanced by selecting those systems (assuming cost and engineering feasibility) that permit the greatest possible warning time. It is obvious that we must be aware of the threat in order to do something about it. It is equally true, but less obvious, that interception and protective measures against the approaching asteroid or comet are made easier when given more time to react.[24] More accurately defined orbits, the possibility of precursor missions, and the desirability of, and relative ease of, interceptions far from Earth, rather than close to Earth, are all compelling reasons for maximizing warning time.[25] Additional warning time is equally beneficial to those agencies tasked with evacuation, and disaster response in the wake of an impact.

The military's role in alerting government officials, the international community, and the general public about an impending impact is likely to be significant. As we have stated, large asteroids or comets impacting Earth pose environmental threats similar to those of nuclear detonations (minus the radiation). Therefore, we suggested the possible need to activate civil defense plans developed for use in a national security emergency (nuclear attack), in response to an NSD event. If this were done, FEMA officials would be authorized use of the National Warning and Alert System (NAWAS), as well as the Civil Defense Warning System to disseminate the impact warning.[26] The military, because it has hardened communications equipment and trained communication's personnel, would assist in the alerting process.[27]

A side issue for those who deal with warning systems is the potential for false alarms caused by the natural detonation or impact of an asteroid or comet. Unfortunately, an unsophisticated nation may not be able to quickly distinguish between a natural event and the detonation of a nuclear weapon. Because of the proliferation of nuclear devices, there is the danger that a nation may someday misinterpret a natural event for a nuclear strike. Large bolides detonate in the atmosphere several times a month.[28] If one of these detonations were to happen at a time when tensions between nuclear powers were high, one of these powers may think it has been attacked, resulting in *unprovoked retaliation.* Although this sounds far fetched, experience with our own sensors proves it is a real possibility. As we pointed out in Chapter 1, our systems have detected the detonation of small asteroids in Earth's atmosphere and flagged them as possible nuclear detonations.[29] Our sophisticated systems and analysts are able to quickly tell the difference between natural and man-made events. Other nations may not be able to do the same. During time of heightened tensions, it would be wise to consider the possible reaction of an adversary to an NSD event.

Training. Training involves early planning and serious preparation for the specific task of providing domestic disaster relief. We envision a joint-service force deliberately designed to employ military personnel and equipment in natural disasters. This force would have a clear and precise mission, unmistakable lines of command, clear policy direction, and widely accepted standards incorporating earlier experiences with responding to natural disasters. With the proper training, military *consultants* could be provided to advise and assist military and civilian personnel with the many technical problems (such as logistics and communications) that invariably arise in such disasters. Currently, DOD has no such dedicated force. Fortunately, the military readily acknowledges the *Disaster Assistance* mission; hence the institutional framework for this mission is already in place. The next logical step (the course of action we propose) is to firmly establish the disaster assistance mission by dedicating the necessary resources.

Defending Against the NSD Threat. We have already discussed the requirement to understand the NSD threat in terms of the effect (Figure 4-8) to be mitigated. NSD effects range from damage or destruction of space-based assets caused by meteor storms to the myriad of direct and indirect effects resulting from asteroid or comet impacts with Earth. The important point to remember is that mitigation measures are available for each part of the overall problem. Although we are currently defenseless we do not have to stay that way.

Use of Existing Military Assets. A number of the Spaceguard Near-Earth-Object Interception Workshop findings and recommendations rely heavily on existing military systems for the cost effective development of an NSD detection (search) and defense system.[30] For example, many workshop participants felt that upgrades to existing military assets (such as optical and radar sensors and facilities) would allow us to do the *acquisition and tracking* missions without building entirely new systems.[31] Similarly, existing missiles and energy devices (such as various nuclear and conventional weapons) could be used to deflect or destroy objects on a collision course with Earth. The Intercept Workshop found that there currently no near-term, cost effective alternatives to the use of existing military vehicles and payloads for such a mission.[32]

Military satellites could also be helpful in an effort to characterize the meteor stream threat. Although Spaceguard did not consider the threat to satellites by meteor storms, the military will probably be involved in determining and enacting measures necessary to mitigate this aspect of the threat. We have a vested interest in protecting our own satellites, so we will need to support studies to characterize the active meteor streams and determine ways to protect our assets. In addition, we have space-borne sensors that could contribute a lot of data on the meteor flux.[33] This data would be very helpful to those who are striving to characterize the streams. For example, the fireball observation of a 10 kiloton explosion in the atmosphere over the western Pacific Ocean in 1990 was recorded by DOD satellites.[34] These examples illustrate the need for military involvement in NSD defense.

For the record, there are no DOD programs dedicated to, or actively working the NSD issue.[35] The military, particularly the Air Force, has existing assets and infrastructure that are both necessary and appropriate for the NSD defense mission. Further, as we have said, the military has an acknowledged role in disaster preparedness and relief. For these reasons, we are convinced that the DOD should officially accept the responsibility for NSD search and defense. We conclude this chapter with a brief discussion of some of the potentially useful military and civilian systems currently available.

Threat Detection and Characterization Systems. The use of fielded technologies for purposes other than for which they were designed, offers an affordable way to mitigate the NSD threat. For example, the All-Hazard Situation Assessment Prototype (ASAP) combines databases in a Geographic Information System (GIS) (an application for which GIS was not specifically designed) to estimate and assess the effects of natural disasters.[36] ASAP does not specifically address impact disasters, but with modifications it possibly could. The point of this example is that the creative use of existing assets can allow us to do useful new things with little new investment. With a little research and creative thinking, we should be able to find ways to use existing military systems to mitigate and possibly prevent NSD disasters. One example of this can be found in the discussion of potential solutions to the search problem in Chapter 8, where with some crude analyses, we were able to show that existing space surveillance systems (with augmentation) could meet the NSD search requirements. A similar study focused on other aspects of the NSD problem (i.e. meteor stream characterization, meteor storm warning and asteroid deflection or destruction systems) could lead us to find additional cost effective solutions. Because of current fiscal constraints and the general lack of appreciation for the NSD threat, we realize that a stand-alone NSD defense program is unlikely to become a reality. The implication is that some (appropriate) existing systems will need to incorporate the NSD mission requirements into their primary functions. In other words, we need to develop dual-use systems capable of meeting the requirements of several, hopefully complementary, missions.

Protecting Life and Property from the NSD Threat. We believe that it will be politically and economically unacceptable to stand a small fleet of nuclear missiles on alert just to defend against an asteroid impact. Given that this statement is true, there are two conditions that must be met before we can expect the development of systems to actively defend Earth from NSD. First, the threat must be validated (i.e. meteor storm predicted; an asteroid or comet on a known, or highly probable, collision course with Earth). In other words, as we pointed out in Chapter 5, we must demonstrate that the threat is real and then successfully communicate the threat to military and civilian leaders. Second, we must be capable of providing sufficient warning time to give leadership some reasonable expectation of being able to react. If these conditions cannot be met, it is unrealistic to believe that any system will be developed. The potentially high cost of development, as well as the gap that exists between what is necessary and what is technologically feasible in the near-term (relating mostly to NSD deflection and destruction), make protection systems impractical if no known threat exists or if the time available to react to the threat is insufficient to give some reasonable expectation of successfully preventing disaster. The question is: have these two conditions been satisfied for any portion of the NSD threat?

In Chapter 6, we discussed the requirements for a system to characterize meteor storms. We believe the threat has been validated; however, as of today it still has not been successfully communicated to those in a position to do something about it. As for warning time, we do not yet have a meteor storm warning system. But with a reasonable amount of study it appears that a warning system could be developed. Obviously, as far as the active streams are concerned we already know when storms can occur (when Earth crosses the orbit of the stream). All we need to determine is the distribution of material within the stream.

Even if a warning system could be developed, some have questioned whether it would do any good. After all, what can we do about the storm threat? For existing satellites, our available mitigation measures are limited but not non-existent. Some possible measures include: re-orienting the satellite so that it is streamlined to the direction of meteor approach, thus minimizing the vehicle's cross-section; disabling the vehicles propulsion system to guard against punctured fuel lines; or reducing the electrical load on the system to minimize the effect of power loss due to battery or solar panel damage. Another step could include increasing the number of ground station contacts and subsequently the level of ground team monitoring of critical spacecraft functions to maximize our ability to recognize and correct anomalies. Essentially, mitigating the meteor storm threat requires a plan to *batten down the hatches* for the duration of the predicted storm activity.

Finally, the meteor storm threat should be considered when developing future systems. Especially long-life satellites (greater than five years) that are expected to be in orbit during significant storms. In this way, protective measures can be designed into the satellite.

The terrestrial asteroid/comet threat is in a similar condition. We believe Chapman and Morrison, and Shoemaker have successfully validated at least part of the terrestrial NSD threat.[37] As we said in Chapter 6, the threat model we have right now is very limited in that it really only has two thoroughly investigated elements: life and civilization. As a result, it seems we have only validated the threat for large debris. With the development of a detailed economic element, we are convinced that the threat from smaller objects could be validated. Unfortunately, as with the meteor streams, we have not yet successfully communicated the terrestrial NSD threat for any size of object. The second condition, warning time, was addressed thoroughly in Chapter 8. The bottom line was that we can develop a system capable of providing a reasonable warning time for most objects (comets may be an exception). Further, this system can be had for a reasonable cost using existing, albeit augmented, systems.

So, if we know it's coming, what can we do about it? Most of the suggestions for defensive systems begin by considering the utility of existing technologies. Essentially, the question is whether military propulsion vehicles and weapon payloads can be used to develop a credible NSD deflection and/or destruction capability. Unfortunately, the answer to this question changes depending on what assumptions you make regarding, among other things, the amount of warning time we have to carry out required defensive actions. Those actions necessary to defend against an asteroid several years prior to a predicted collision are much different from those to be taken when the object is less than a few months away, and collision is imminent.[38] Additionally, answering this question requires a great deal of information gathering and research in order to have the knowledge base for developing a feasible defense system. Table 10-1 summarizes a number of the issues pertinent to the development of an asteroid defense system.

There are other areas of concern, pertaining to NSD, for which existing military technologies and equipment might be used. For example, systems currently in use for hazard evaluation and assessment, for formulating vulnerability analyses, for mapping hazard areas, and for managing resources in response to a disaster could, with slight modification, be useful in preparing for and responding to an NSD disaster.

The above discussion, though conceptual, emphasizes the need for a *practical and cost-sensitive approach* to the NSD threat. Many viewpoints expressed in the last few years regarding NSD do an injustice to the subject of defending Earth from asteroids and comets. Therefore, we have elected not to discuss many of the deflection and destruction options suggested in the Spaceguard Survey's, Interception Workshop report (such as antimatter, fleets of missiles standing alert for asteroid defense and new nuclear weapons programs).[39] The serious discussion of such things before we have decided to develop a warning system is ridiculous, and only reinforces the *Buck Rogers mentality* of a problem too far removed from reality to merit serious consideration for solution, an image that already plagues those who study the NSD threat.

Table 10-1. Issues Affecting NSD Defense Systems[40]

Technical Issues:	**Effect on System Development:**
Size of the Object:	Smaller objects may be more difficult to detect, but require less energy to either deflect or destroy. Large objects, though more easily detected, require much more energy to do something about it.
Distance of the Object from Earth:	The further an object is from Earth, the more easy the defense mission. For a given size object, less energy is required, since smaller deflections suffice. Travel time is less of an issue. Opportunity to shoot, look, shoot again. Greater distance allows more propulsion, deflection, and destruction options. Objects close to Earth require much greater energy to deflect; make travel time important; permit fewer attempts to defend.
Object Composition: Stone, metallic, ice crystals, gaseous, etc.	More reflective composition permits easier detection. Denser objects require greater energy to deflect or destroy. Must be known to choose deflection or destruction technique. May necessitate precursor mission to determine results of fragmentation and associated risks of breakage.
Propulsion Options:	Chemical rockets are only near-term and feasible technology options available.
Political Issues:	
Use of Nuclear Weapons:	Surface burst or stand-off mode. More energy than kinetic energy weapons. Insensitive to composition, thus no need for precursor missions. Possible fragmentation problem. Unknown distance vs. yield relationships. High potential costs. Political and moral questions and implications. Security concerns.
International Participation: Control and Access	What country(s) will manage the overall system? Who will contribute what assets to the overall international effort? What country(s) will control access to space and coordinate the detection, defense, and if necessary, the relief effort?
Economic Issues:	
Cost Benefit Analysis	How much is available to spend on a defense system. What options, based on cost, are practical? Stand-alone system vs. "Piggy-Backing" on existing systems. When is a predicted impact not worth the cost of intercepting? Who will pay?

Source: Spaceguard Survey: Near Earth Object Interception Workshop Report, January 1992.

Mitigating the NSD Threat: A Summary

In this chapter we have discussed how the NSD threat can be mitigated and the conditions under which we think leadership can be expected to take action on the development of an NSD defense program. Essentially, those who believe the NSD threat is real must continue to improve the threat model and to communicate that threat to those in a position to take action. Our cursory look at possible mitigation measures indicates many cost effective options are available. Much of the threat can be mitigated using existing systems and military infrastructure. We can defend ourselves against the asteroid and comet threat, as well as protect our spacecraft from meteor streams. Further, this protection does not have to be terribly expensive.

The mitigation measures we suggest seek a cost-effective and practical approach to the NSD threat through a combination of planning, preparedness, and the development of detection, tracking, characterization and defense systems. The use of existing technologies, as well as a shared international approach to the NSD problem (if possible) are all suggested ways to meet the requirement for an affordable system with a realistic chance of being developed.

Notes

[1] Department of Regional Development and Environment, Executive Secretariat for Economic and Social Affairs, Organization of American States, *Disasters, Planning, and Development: Managing Natural Hazards to Reduce Loss* (Washington: GPO, December 1990). ix.

[2] Ibid., 13.

[3] US General Accounting Office: Statement of J. Dexter Peach, Assistant Comptroller General of the US, Resources, Community, and Economic Development Division, *Disaster Management: Recent Disasters Demonstrate the Need to Improve the Nation s Response Strategy* 25 May 1993.

[4] Paul Alexander, "Japan Offers Loans to Quake Victims," *The Montgomery Advertiser*, 25 January 1995, sec. A:9. Note: Quoted costs are for rebuilding infrastructure only.

[5]Department of Regional Development and Environment, Executive Secretariat for Economic and Social Affairs, Organization of American States, *Disasters, Planning, and Development: Managing Natural Hazards to Reduce Loss* (Washington: GPO, December 1990). ix

[6] Colonel Bruce Tripp, USA. Office of Director of Military Support, Federal Emergency Management Agency, Washington DC. Telephone interview. October 1994.

[7]Mr. John Darrah, Chief Scientist, Air Force Space Command, Personal interview, December 1994. Note: Mr Darrah spoke of existing military initiatives related to gathering data concerning NSD, but opinioned that data collection was unofficial and that U.S. Space Command is now beginning to consider the NSD problem and its implicatins.

[8] Vice President Al Gore, *Creating a Government That Works Better & Costs Less: Federal Emergency Management Agency* (Accompanying Report of the National Performance Review), 5, September 1993.

[9] Ibid., 5 &26.

[10] Federal Emergency Management Agency, *Federal Preparedness Guide* (Washington: GPO. 1 June 1992), 2-2.

[11] Ibid., 2-1.

[12] Ibid., 2-1.

[13] Ibid., 2-2.

[14] Office of the Chairman of the Joint Chiefs of Staff, *Joint Doctrine For Military Operations Other Than War:* Joint Pub 3-07 (Draft Final Pub), (Washington: GPO, 10 April 1993).

[15] Ibid., *Federal Preparedness Guide*, 2-2.

[16] Office of the Chairman of the Joint Chiefs of Staff, *Doctrine for Planning Joint Operations:* Joint Pub 5-0, (Washington: GPO, 15 August 1994), I-11.

[17] Ibid., I-12.

[18] Ibid., I-12.

[19] Final Report: Iranian Hostage Rescue and Recovery Mission, (Class Handout-JO 513, Military Operations Other Than War), Air Command and Staff College, Maxwell AFB AL, February 1995.

[20] Ibid., Joint Pub 3-07., V-9.

[21] Ibid.

[22] United Nations: Department of Humanitarian Affairs, *Workshop on Use of Military and Civil Defense Assets in Disaster Relief, Final Report* DHA/93/57, 14-15 December 1993, 5.

[23]Ibid., 9.

[24] Gregory H. Canavan and Johndale Solem, *The Spaceguard Survey: Near Earth Object Interception Workshop Summary.* Sponsored by NASA Headquarters, Hosted by Los Alamos National Laboratory, Los Alamos, New Mexico, 14-16 January 1992, 24-25.

[25] Ibid., 8.

[26]Jack Daniels, Federal Emergency Management Agency National Command and Control Center, Cheyenne Mountain., Colorado Springs, CO. Personal interview, 29 November 1994. Note: The National Warning and Alerting System and the Civil Defense Warning System are capable of broadcasting emergency notices through regional centers to entire field network within 7 minutes.

[27]Ibid.

[28] J. Kelly Beatty, "Impacts Revealed," *Sky & Telescope* 26-27, (February 1994). Note: Eugene Shoemaker estimates one 10 kilo-ton atmospheric detonation per year and Rabinowitz calcualtes Earth should have at least one 20 kilo-ton detonation per month with a 100 kilo-ton detonation once per year. Slightly smaller but still significant detonations would occur more than once per month.

[29] Ibid., 24.

[30] Gregory H. Canavan and Johndale Solem, *The Spaceguard Survey: Near Earth Object Interception Workshop Summary.* Note: Many of the articles implied the use of existing military systems and infrastructure, because there is no other department or agency within the government at any level that has the resources to do the NSD mission. A quick read through the Executive Summary and findings of the report makes this position clear.

[31] Ibid., 211, section 5-5.

[32]Gregory H. Canavan and Johndale Solem, *The Spaceguard Survey: Near Earth Object Interception Workshop Summary.* Sponsored by NASA Headquarters, Hosted by Los Alamos National Laboratory, Los Alamos, New Mexico, 14-16 January 1992 , Chapter 6, 233.

[33]John Darrah, Chief Scientist, U.S. Space Command, Personal interview, December 1994.

[34] D.A. Reynolds. "Fireball Observation Via Satellite," *The Spaceguard Survey: Near Earth Object Interception Workshop* . Chapter 5, 221.

[35]Mr. John Darrah, Chief Scientist, Air Force Space Command, Personal interview, December 1994.

[36] Adrian Linz and Paul Bryant, "The All-Hazard Situation Assessment Prototype," *Research and Applications of TIEMES Emergency Management and Engineering Conference* (Dallas: TIEMES Press, 1994) 175-179..

[37] Clark R. Chapman and David Morrison, "Impacts on the Earth by Asteroids and Comets: Assessing the Hazard," *Nature 367:* 35, (6 January 1994).

[38] Johndale C. Solem, "Interception of Comets and Asteroids on Collision Course with Earth," *The Spaceguard Survey: Near Earth Object Interception Workshop:* Chapter 3, 131.

[39] Canavan, Chapter 6, Table 6-1., 228.

[40] Gregory H. Canavan and Johndale Solem, *Spaceguard Survey: Near Earth Object Interception Workshop* 14-16 January 1992. Note: This table is a compendium of many issues relating to defense systems discussed in this report.

CHAPTER 11

Future Considerations

At the risk of completely destroying our credibility, there are a couple of final issues that we want to mention. None of these are really germane to the natural space debris threat discussion per se; however, one doesn't have to stretch the imagination too far to see how a search and/or defense program, once it exists, may be called upon to address these topics.

Asteroid Mining

For many years, scientists have speculated on the value and feasibility of mining resources from asteroids and comets. Materials such as water, frozen gasses, metals, silica and hydrocarbons have all been found to exist on various asteroids. Although no one yet has the capability to mine and process these materials in space, there will come a time when such things will be possible, and that time may not be too far away.

The benefit to having a ready supply of raw material for use in orbiting factories is obvious. Given today's tremendous launch cost (about $30,000 to $40,000 per pound of payload) a pound of material in orbit is worth about six times its weight in gold. With that amount of money at stake, eventually someone will decide to mine an asteroid.

An NSD defense program could one day provide very useful information to those who would mine asteroids and comets. For example, an extensive database of objects, including information on their composition, would be built by the search system. Such information would be invaluable for selecting objects. In a way it would be much like someone giving you the map to a gold mine. All you have to do is go get it.

Once the target is selected, we would probably need to bring the asteroid into Earth orbit for the actual mining operation. Here's where detailed studies and experiments on the deflection and destruction of NSD would be extremely valuable. Almost every part of an NSD defense program would be applicable to the mining tasks. Thus, an NSD defense program would not only reduce the possibility of an impact generated catastrophe, it would also provide very valuable information for use in future space manufacturing endeavors. In effect, its much like conducting a mineralogical survey of a new land-mass.

Like a coin, the asteroid mining issue has two sides. The down side is the part where we actually attempt to divert an asteroid into Earth orbit. The obvious concern is: *what if we mess it up drop an otherwise harmless asteroid on Earth*? Bringing a large asteroid into Earth orbit seems an incredibly foolish and risky venture.[1] Only when concepts have been proven and thoroughly tested (away from Earth), and appropriate safeguards implemented, should this be attempted. Even then, we should stick to small (50 meter class) objects. Unfortunately, the US may not be the only country capable of mining asteroids. To illustrate the point, consider the following.

Russian scientists visiting Los Alamos National Laboratories last fall expressed an interest in mining asteroids.[2] Russia is faced with tremendous economic difficulties; yet has a ready supply of launch vehicles and scientists capable of maneuvering an asteroid into Earth orbit. Of course, without an economic boost in the arm, they may not be able to sustain their space program for much longer. As a result, a *use-it-or-lose-it* mentality might develop. At least some scientists in Russia see asteroids as a potentially profitable way to use the space program and perhaps prevent its collapse. While everyone recognizes that no one is prepared to begin mining and manufacturing in space, this small detail may not matter. Faced with losing their space-faring capability it might be logical to capture the asteroid now, while you still have the capability, and worry about selling the resources later.

If the Russians, or anyone else for that matter, were to mount an asteroid mission in the near future and try to maneuver one into Earth orbit, we would have two things to worry about. First, if successful, they could gain a significant economic advantage over us when space manufacturing becomes a reality. However, the most pressing concern is the potential for the object hitting Earth rather than going into the intended orbit. We are not suggesting that they would do this intentionally. Most likely it would be the simple result of an ill conceived or rushed program.

The point the reader must understand is that we, (the US) may not be able to decide whether asteroid mining in near-Earth space is safe. Other countries have the capability to divert asteroids and may decide to make the attempt whether we like it or not. Further, as long as nuclear devices are not used, the country would not be obliged to tell us what it was planning to do. Our investigation (though admittedly cursory) did not turn up any treaties or agreements that would prevent them from doing this, or require notification of other countries.

We believe that any attempt to maneuver an asteroid into Earth's vicinity poses a threat to every nation on the planet. While not an immediate concern, the day will come when we will have to face the prospects of another nation's effort to maneuver an asteroid or comet. We should begin thinking about how we would handle the situation. As a minimum, we should diplomatically pursue agreements wherein all parties agree not to attempt such a thing without consulting other signatories to the agreement.

Extraterrestrial Artifacts[3]

In 1991, Jim Scotti, Director of the University of Arizona's Spacewatch telescope found what he believed to be an asteroid. Designated 1991VG (~10 meter diameter), subsequent observations by other instruments found that 1991VG has some extraordinary properties and, according to some astronomers, may not be just another asteroid.

Observations by Richard West and Oliver Hainaut made near the time of 1991VG's closest Earth approach found that the object had a decidedly non-asteroidal signature. It exhibited very strong and rapid brightness variations that are normally associated with transient specular reflections from the surface of a rotating (shiny metallic or painted) spacecraft.

In addition to its unusual optical properties, it is in a rather unique orbit. Essentially, 1991VG is in a heliocentric orbit, almost precisely within the Earth's orbit plane and has a very high probability for impacting our planet. In fact, it will pass very close to Earth about every 16.75 years. This means that if the object were natural it could not have been in this orbit very long because the orbit is unstable. It would hit Earth or be ejected in a relatively short period of time. Given that it must have recently entered this orbit, one could wonder where it came from. Scientists are debating two equally improbable possibilities: an old booster stage or early space probe, or an extraterrestrial space probe.

Initially, you might think the first option the more likely; however according to Duncan Steel (Anglo-Australian Observatory and The University of Adelaide) the object does not fit the expected orbits of any known Earth-originating probes or rocket bodies. Since the orbit of 1991VG was accurately determined by observations from Kitt Peak observatory, Steel has been able to project the last time the object encountered the Earth. In its present orbit, that would have been in February 1975. Thus, if the object were an Earth spacecraft it would have had to be launched around that time. Steel has only been able to identify two probes (no rocket bodies) that could possibly fit the scenario: Helios 1 and Venera 9. However, correlation with either of these would require some non-gravitational influence to put them into the observed orbit of 1991VG (such as leaking fuels). In his opinion, the object is not either of these probes. With the known man-made objects accounted for, it would seem we are left with, at least a possibility that the object originated somewhere other than Earth.

The debate over the origins of 1991VG are likely to continue for some time. Short of a rendezvous mission, we won't see it again for several years. The point of this discussion is that 1991VG was found by the Spacewatch telescope; the only system dedicated to finding asteroids and comets in the US. If there are extraterrestrial artifacts orbiting in the vicinity or Earth, a deep space surveillance network such as that proposed herein would greatly increase our probability of finding and recognizing them.

Notes

[1] Note: Given the risk of dropping the asteroid on an unsuspecting population there is no way the asteroid could be valuable enough to make such risk worth while.

However, someday technology may allow us to reduce the risk to a very low level. Only then would it be safe to try bringing an asteroid home.

[2] Jack G. Hills, Theoretical Division, Los Alamos National Laboratory, Los Alamos NM. Personal interview regarding asteroid mining, detection issues for Atens asteroids and impact effects.

29 November 1994.

[3] Brown, Peter. Department of Physics and International Meteor Organization, University of Western Ontario Canada. Electronic message regarding object 1991VG. 27 March 1995. Note: Message is a compendium of E-mail exchanges between Dr. Brown and D. Steel, as well as a release written by D. Steel.

CHAPTER 12

Recommendation Summary

This chapter summarizes the recommendations made throughout the preceding chapters. We have attempted to provide a brief statement of what needs to be done, followed by a brief explanation. In the interest of brevity, we only hit the highlights. The reader should consult the Table of Contents for the location of the detailed discussion. Also, since no new information is presented, references (endnotes) are not represented.

Recognize the Natural Space Debris Threat

The first and most important thing we must do is recognize the threat NSD poses to our society, people and assets. As discussed in Chapters 5 through 6, the NSD threat is very real and is being ignored by the US military (and just about everyone else). Effective threat mitigation requires that the Department of Defense acknowledge the existence of this threat and formally define their roles in the mitigation effort. This would mean writing new doctrine to define roles and assign responsibility for various pieces of the mitigation effort. We envision the Air Force taking the lead in developing an asteroid and comet defense program as well as providing for a meteor storm warning system.

Plan for the NSD Threat Now

The military should recognize the primary role they will have in responding to an NSD induced natural disaster, understanding that no other federal organization or agency has the necessary organizational base and resources to do so. Military planners should review doctrinal guidance to ensure clearly defined tactics, procedures, and techniques to be used in disaster response. The Army should take the lead in planning for evacuation and disaster relief in the wake of an impact, and in integrating military plans with existing civil defense and disaster preparedness plans. Regarding these plans, FEMA needs to identify those existing plans having utility in an NSD disaster, and make this information available to other federal, state, local and non-governmental agencies involved in disaster response. In addition to prior planning, the military must train for the employment of personnel and equipment in the disaster relief mission. Planning for and response to the NSD threat should be an international effort. As such, a register of participants must be built to apportion each nation's resources and functional responsibilities to the overall disaster relief effort.

Institute an Asteroid and Comet Search Program

The responsibility for conducting an asteroid and comet search should be assigned to US Space Command. Space Command's space surveillance network already has much of the infrastructure and expertise that's required for the rapid and cost effective development of an NSD system. However, before a search program can begin, there are several critical issues that must be resolved. Most pressing of these is the rigorous definition of a set of system requirements. With that in mind, we presented a preliminary set of requirements in Table 8-1 to use as a starting point, as well as a list of questions that should be answered in the requirements definition process (end of Chapter 8). Based on our discussions in Chapter 8, we believe that an effective NSD search system can be developed within Space Command for between $56.5M and $71M, ($19M and $34M without IR capability) and operated for between $12.6M and $19.3M per year, ($2M less without IR capability). Refer to Table 8-6 through Table 8-9 for the cost details (remember +25% margin).

Recognize the Meteor Stream Threat

The natural meteor environment has been kind to us since the early days of our space program. There are at least 25 well defined meteor streams of which 11 are known to have produced significant storms; yet there have been only two meteor storms since 1965. This means our intricate modern space networks have never had to endure a meteor storm. Unfortunately, the *calm* may not last much longer. A new model of the Leonid meteor stream (one of the more active streams) indicates a moderate storm will take place in November of 1998 and a very severe storm will occur on 17 November 1999. During a very intense storm the probability of a satellite being hit and seriously damaged by a meteor is high. When the entire set of active spacecraft is taken as a whole, some damage is almost certain.

The US, and particularly the DoD is becoming increasingly dependent on complicated, expensive and integrated space systems. Therefore, our increasing dependence on space systems makes it all the more important that we fully understand the vulnerabilities of these systems, as well as the environment in which they operate. Today, very little is known about the meteor streams and the threat they pose to our satellites. We need to recognize that our systems are vulnerable and begin taking the steps necessary to understand and mitigate the meteor storm threat.

Characterize All Active Meteor Streams

Of the 25 known streams, only three have been studied in detail and only two (the Leonids and Perseids) have been characterized well enough to permit us to predict storms. At a minimum, we must fund studies to characterize the 25 known streams so that we can begin to quantify the threat. Further, we should investigate the building of models that will allow us to predict the occurrence of storms. In addition to studying the known streams, we should attempt to determine whether other significant streams exist, and if so whether these new streams are a potential threat. We estimate the cost to be approximately $3.2 million over eight years (see Chapter 8). Considering that most satellites have a replacement cost exceeding $300 million, the costs of such a study would be low in comparison to the cost of not having this information.

Develop a Meteor Storm Warning Capability

Once we have the capability to predict meteor storms, we need some way to deliver the notice to various satellite programs along with detailed information that might help them reduce the potential for damage. Information such as storm severity (flux), the time of maximum flux, the direction of approach for the meteoroids, size and density estimates, meteoroid velocity could all be useful. The Air Force already has people who track *space weather* (i.e. solar activity). We envision the meteor storm warning function becoming their responsibility.

Encourage Satellite Programs to Develop Meteor Storm Procedures

Obviously, once warning is possible and the warning systems are in place, we need to have plans available (for each satellite in orbit) to minimize the threat. We see two possible threat mitigation methods: design satellites for the meteoroid environment and/or develop procedures to minimize the possibility of damage . The first method would only be of use to future satellites. Once the warning systems are validated, new satellites could be designed to accommodate the meteoroid environment as it is expected to exist during their design life. Because of the space station meteoroid research, many design features have been identified that can help a satellite survive meteoroid strikes. The second method involves determining the vulnerabilities (to meteoroid impacts) of each satellite on a case-by-case basis, then devising creative ways to minimize the potential for serious damage. Many ideas have been suggested that could help our existing systems survive the upcoming storms in 1998 and 1999. For example, programs should plan to perform attitude maneuvers and slew attachments (such as solar arrays) to achieve and maintain a minimum frontal area with respect to the debris stream for the duration of the storm. Obviously, some programs will have more luck with this than others, but that cannot be helped. Other measures could include: closing all (backup or isolation) propulsion valves to guard against propulsion leaks, and charge batteries before the storm and minimize power usage during the storm to increase safety (power) margin in case of problems. Finally, for those satellites not in constant ground contact, extra contact time could be scheduled to provide increased visibility into the satellite's condition and improve the ability of the ground team to react promptly to malfunctions.

In order to do these things, *procedures and plans must be developed and validated before they are needed.* At this time, few if any such plans exist. If the 1998/1999 storm predictions are correct, we have very little time to prepare. We need to begin immediately to educate satellite operators and system program offices on the meteor stream threat and task them to develop mitigation procedures appropriate for their systems as soon as possible.

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