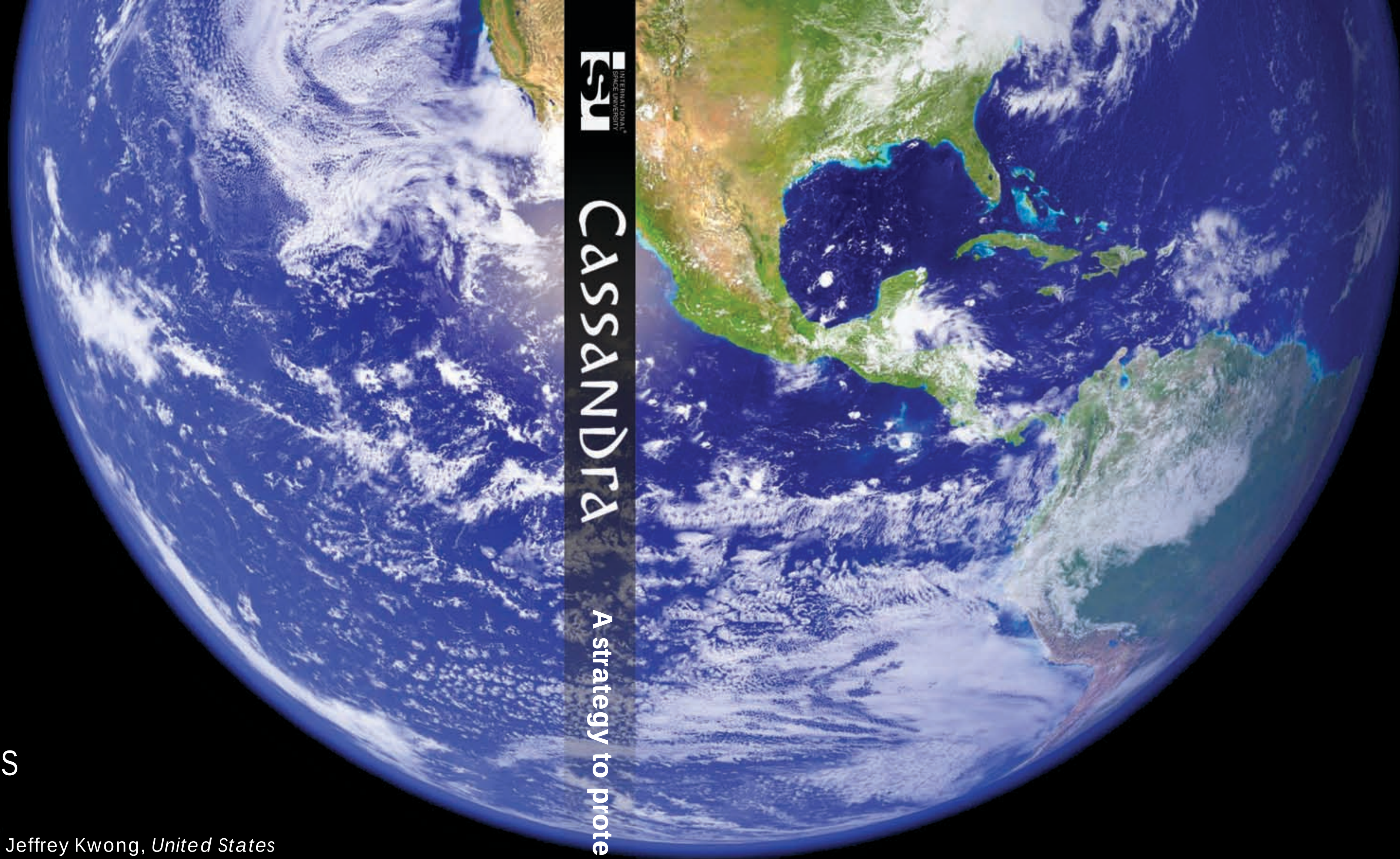

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Cassandra

A strategy to protect our planet from Near-Earth Objects

SSP 2005

Cassandra

A strategy to protect our planet from Near-Earth Objects

FINAL REPORT

CASSANDRA

A Strategy to Protect our Planet From Near Earth Objects

Final Report

International Space University

Summer Session Program 2005

Cover designed by: Amaury Solignac
Image credit: True-color image of the Earth. (NASA - U.S. Geological Survey).

Apollo granted Cassandra the gift of prophecy but he also added a twist to the gift: Cassandra was doomed to tell the truth, but never to be believed. Today, we call someone a "Cassandra" whose true words are ignored, since Cassandra's doom was to predict what others refused to believe.

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Additional copies of the Executive Summary and the Report may be ordered from the International Space University Headquarters. The Executive Summary, ordering information and order form may also be found on the ISU web site at http://www.isunet.edu

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Abstract

Our species is currently unprepared to deal with the very real threat posed by Near Earth Objects. The Earth has been struck repeatedly by asteroids and comets throughout its history as part of the regular, dynamic processes of the solar system that continue to this day. These impacts have caused devastating damage on global and regional scales, leaving their mark on the land in the form of craters, and on the people of the Earth, as seen in the stories and oral histories of cataclysmic "fireballs" present in many of the world's cultures throughout history. The most catastrophic of these collisions have caused mass extinctions of life on the planet. Scientists generally accept that the extinction of the dinosaurs 65 million years ago was caused by an impact from a Near Earth Object. Yet, although these impacts occur with regular frequency for the history of the Earth, they are extremely infrequent on our human time scales. As a result, we have currently underappreciated, and unprepared for, this significant threat.

This report reviews the scientific literature on the characteristics of Near Earth Objects, including their composition, orbits, populations and the probabilities and consequences of their collision with the Earth. It examines current systems utilized for the detection of Near Earth Objects focusing on the coordination of these systems and the management of the data. The report proposes avenues for further research in detection technologies and outlines various methods for deflecting or disrupting collisional Near Earth Objects. Because of the inverse relationship between the distance at which deflection measures are begun and the energy required for a successful implementation, improvements in detection technology are highlighted as the best short-term method of increasing the probability of a successful mitigation mission.

In the discussion of the assessment, detection and mitigation of the Near Earth Object threat, special attention has been paid to high inclination long-period comets. Current detection programs are unable to provide adequate warning of incoming objects at high inclinations. As a result, potentially impacting high inclination objects would only be detected with very little time (likely less than a year) to prepare a mitigation strategy. Deflection or disruption, through use of a nuclear device, is shown to be the only possible means of mitigation in such circumstances. Emphasis is placed on our current lack of appropriate infrastructure, including heavy launchers, necessary for such a mission. The hypothesized scenario of the Cassandra Comet highlights the particular aspects of responding to a threatening high inclination object.

Detection, characterization, and mitigation of hazardous celestial objects involve programs in which of all humanity has a stake. This report explores cultural reactions to Near Earth Objects and the threat they pose and discusses potential public reactions to a mitigation strategy employing a nuclear device. It also reviews the potential for mass media both to strengthen and weaken useful communication between scientists and the public.

Near Earth Objects are indiscriminately threatening to the entire planet; all nations, all times. International cooperation is therefore vital to a concerted, long-term effort to defend the Earth from potential impacts. The report identifies a serious gap in command and control of Near Earth Object detection, characterization, and mitigation efforts. It proposes a command and control solution that includes a multi-lateral international framework, the International Near Earth Object Committee (INEOC). The INEOC will serve as the primary forum of international discussion regarding an identified threat and will serve to focus global discussion on detection coordination, mitigation technique development, and command and control.

Faculty Preface

Three powerful motivations affect human behavior: curiosity, profit and fear. The study of Near Earth Objects fits well into any of these categories. Some wish to study them to learn about the early Solar System, some see in them a source of revenue from the exploitation of their resources, and some fear that one day one of them will collide with the Earth and cause loss of human life or the extinction of our civilization. The last is what has motivated this study of Near Earth Objects.

Developed by a group of 30 participants attending the 2005 Summer Session Program of the International Space University, the Cassandra report addresses many of the concerns of scientists, decision-makers and general public about the threat posed by Near Earth Objects: what we can do to detect them well in advance, and more important, what we can do in case astronomers discover that one of them is en route to collide with our planet. In recent years, the Near Earth Object threat has received increasing attention from an expert community, but the uniqueness and strength of the Cassandra report resides in the people that performed it: an international group with representatives of 13 different countries and different backgrounds ranging from science and engineering to business, law and policy. This unbiased and fresh approach to the problem, performed by such a group of mixed cultures and backgrounds, is missing in other efforts to craft a Near Earth Object mitigation strategy.

We recommend the reading of the Cassandra report to those who know about Near Earth Objects and wish to find new and interesting ideas on the topic, and to those who do not and want learn why this is a problem that must be faced. No matter your motivation, we hope you will enjoy it as much as we did.

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Student Preface

In 2005, students at the International Space University Summer Session Program in Vancouver, Canada were asked to write a report on how to save the world. We were asked to think about saving the world from a particular threat, that of Near Earth Objects. You hold in your hands our response, the Cassandra Report.

It was a Herculean task to absorb the extensive literature on the subject, to debate our ideas and to propose realistic solutions, all within strict page limitations and time constraints. Throughout the process, individuals from different cultures and professionals who spoke different technical languages needed to reach a common understanding so that we could speak with one voice. Although initially a source of frustration, our differences were quickly recognized to be our strengths, strengths that enabled us to offer a truly international, interdisciplinary and intercultural response to the Near Earth Object threat.

During our research we were struck by the parallel between the common reaction to warnings of the danger of a Near Earth Object impact and the reaction to the dire predictions of the cursed seer, Cassandra. In Greek mythology, the young maiden Cassandra was gifted with an ability to know the future, but cursed to have her warnings forever unheeded. It would seem, given our species' current inability to effectively respond to a collisional Near Earth Object, that those who warn of the very real risk that these bodies present to our civilization are afflicted with a similar curse. We have entitled our report Cassandra to remind the reader of the dangers of ignoring prophetic warnings.

The students of the Near Earth Object team project would like to thank all faculty, staff and visiting lecturers who have assisted with the report. Special thanks go to our dedicated teaching associate Cristina de Negueruela and to our co-chairs Prof. Pete Worden and Prof. Ray Williamson whose expert knowledge, guidance and encouragement were an inspiration to us all.

Lastly, we would like to thank all astronomers and scientists whose dedicated observations and research on Near Earth Objects have laid the groundwork that this report has been built upon. We, and all of humanity, owe them a great debt of gratitude. We hope that their incisive warnings do not ultimately suffer the same tragic fate as those of cursed prophetess Cassandra.

"There are risk and costs to a program of action. But they are far less than the long-range risks and costs of comfortable inaction."
- John F. Kennedy

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List of Acronyms

A

AFB	Air Force Base
AIAA	American Institute of Aeronautics and Astronautics
AMCM	Advanced Mission Cost Model
AMOS	Air force Maui Observing Station
AOCS	Attitude Orbit Control System
ATV	Automated Transfer Vehicle
AU	Astronomical Unit, approximately the mean distance between the Earth and the Sun

C

C	Celsius
C&C	Command and Control
CfA	Center for Astrophysics
cm	centimeter
C&C	Command and Control
CCD	Charge-Coupled Device
COTS	Commercial Off the Shelf
CSA	Canadian Space Agency
CSS	Catalina Sky Survey

D

dB	decibel
Delta V	change in velocity
DLR	Deutschen Zentrum für Luft-und Raumfahrt (German Aerospace Center)
DND	Department of National Defense
DSN	Deep Space Network

E

EAC	Earth Approaching Comet
EC	European Commission
e.g.	exempli gratia
EGNOS	European Geostationary Navigation Overlay Signal
EI	Earth Impact
ELV	Expendable Launch Vehicle
ESA	European Space Agency
ETS	Experimental Test Site

F

FEMA	Federal Emergency Management Agency
FOV	Field Of View

G

g	gram
GDP	Gross Domestic Product
GEODSS	Ground-based Electro-Optical Deep Space Surveillance
GMS	Ground Monitor System
GN&C	Guidance, Navigation & Control
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
Gt	Gigaton (4.184 10^{18} J)

H

HCO	Harvard College Observatory
HMT	Hard Mirror Telescope
HRI	High Resolution Instrument

I

IADC	Inter-Agency Space Debris Coordination Committee
IAU	International Astronomical Union
ICE	International Cometary Explorer
IGA	Intergovernmental Agreement
IGO	Intergovernmental Organization
INEOC	International Near Earth Object Committee
ISAS	Institute of Space and Astronautical Science
ISDR	International Strategy for Disaster Reduction
ISEE	International Sun-Earth Explorer
ISS	International Space University
ITAR	International Traffic in Arms Regulations
ITU	International Telecommunication Union

J

J	Joules
JAXA	Japan Aerospace eXploration Agency
JHUAPL	Johns Hopkins University Applied Physics Laboratory
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope

K

kg	kilogram
km	kilometer
KBO	Kuiper Belt Object
KTB	Cretaceous-Tertiary Boundary

L

L	LaGrange Point, a unique point in the plane of two orbiting bodies where a third body experiences no forces and can remain effectively motionless in equilibrium
LEO	Low Earth Orbit
LINEAR	Lincoln Near Earth Asteroid Research
LMT	Liquid Mirror Telescope
LONEOS	Lowell Observatory NEO Search
LSST	Large Synoptic Survey Telescope project

M

m	meter
MIT	Massachusetts Institute of Technology
MLSS	Mt. Lemon Survey
mm	millimeters
MOCD	Mission Operation Cost Model
MoU	Memoranda of Understandings
MPC	Minor Planet Center
MPCORB	Minor Planet Orbits
MPML	Minor Planet Mailing List
MRI	Medium Resolution Instrument
MSSS	Maui Space Surveillance Site
Mt	Megaton (4.184×10^{15} J)
MTCR	Missile Technology Control Regime
Myr	Million years

N

NAFCOM	NASA/Air Force Cost Model
NASA	National Aeronautics and Space Administration
NEA	Near Earth Asteroid
NEC	Near Earth Comet
NEAR	Near Earth Asteroid Rendezvous
NEAT	Near Earth Asteroid Tracking
NEO	Near Earth Object
NEOCP	NEO Confirmation Page
NEOSSat	Near Earth Object Surveillance Satellite
NGO	Non-Governmental Organizations
ns	nanosecond

O

OCA	Observatoire de la Côte d'Azur
ODAS	OCA-DLR Asteroid Survey
OOSA	Office for Outer Space Affairs (United Nations)

P

PanSTARRS	Panoramic Survey Telescope and Rapid Response System
pH	Potenz Hydrogen
PHA	Potentially Hazardous Asteroid

S

s	seconds
SAO	Smithsonian Astrophysical Observatory
SCAP	Schmidt CCD Asteroid Program
SETI	Search for Extraterrestrial Intelligence
SNR	Signal to Noise Ratio
SOCM	Spacecraft Operations Cost Model
SOHO	Solar and Heliospheric Observatory
SSO	Sun Synchronous Orbits
SSS	Siding Spring Survey

T

TDI	Time Delay Integration
TNT	Trinitrotoluene
TRL	Technology Readiness Level

U

UBC	University of British Columbia
UK	United Kingdom
UN	United Nations
UN-BPCR	UN-Bureau for Crisis Prevention and Recovery
UNCOPUOS	UN Committee on the Peaceful Uses of Outer Space
UNDP	UN Development Programme
UNSC	UN Security Council
US	United States
USAF	United States Air Force

V

VASIMR	Variable-Specific-Impulse Magnetoplasma Rocket

W

WG	Working Group

Chapter 1
Introduction

If one ever needs proof that devastating impacts have occurred on the Earth, one need only visit any of over 170 confirmed impact crater sites that are spread all around the globe. From the truly massive Vredefort site in South Africa, an impact that occurred some 2 billion years ago and left a crater 300 km in diameter, to the comparatively recent 1 km wide Barringer Creator in Arizona, which formed about 50,000 years ago, our planet is literally pock-marked with evidence of cosmic impacts (Spray 2002). Billions of years ago when the Earth was still a roiling molten ball, and before life had arisen, our planet was repeatedly struck by huge impacts during the period known as the Heavy Bombardment. During this time the Earth suffered a cataclysmic encounter with another celestial body approximately the size of Mars. As the planet was torn asunder by the force of the collision, a giant mass of material was ejected and was gravitationally drawn into an orbit around the re-forming Earth. This material coalesced into our companion in our annual trek around the solar system, the Moon. Without this impact there would have been no Moon and thus, there would have been no proximal gravitational force to pull on the Earth's oceans to cause the tides, which have long provided a bounty of shellfish to coastal dwelling humans. Even the female menstrual cycle synchronizes with the Moon's rotation around the Earth. Every day, the effects of this most awe-inspiring of Earth impacts can still be seen.

Although it is hard to compete with the impact that created the Moon, the Chicxulub Crater in the Yucatan Peninsula of Mexico is the remnant of one that provides a good contest. About 65 million years ago the Dinosaurs, who had ruled the Earth for some 100 million years, were nearly instantaneous wiped out. Their disappearance, known as the KT Extinction, was hotly debated for many years. However, in 1980, Dr. Louis Alvarez suggested that the cause of the extinction was, in fact, a collision with an asteroid. Here, yet again, is an impact which has profoundly affected our lives as it was only when the dinosaurs had been fully dethroned by this impact could the small, insignificant family of creatures known as mammals began to thrive and eventually evolve into Humans.

For humanity as a whole these seem to be the two most important impacts in Earth's history. The citizens of Sudbury, Ontario make their living from the results of a third. Space visionaries and futurists sometimes ask, "When will humanity begin exploiting asteroid mineral resources?" The truth is, as anybody from Sudbury can tell you that we have already begun to make use of asteroid resources. Sudbury is a Canadian mining town that provides approximately 10% of the worlds nickel and has a US$3 billion dollar a year mining industry derived entirely from an impact that occurred some 1.85 billion years ago when a 6-12 km asteroid impacted the Earth (Motta 2000). Sudbury is a perfect example of the myriad and unexpected ways that impacts have shaped humanity.

Collisions between our Earth and Near Earth Objects (NEO) have usually not been so kind to humanity. It is often offered in most assessments of the NEO threat that no one has ever been killed by a meteorite. However, a growing body of literature suggests that humans have already been fatally affected by impacts from cosmic bodies and that such events have been recorded. Indeed, one would expect impacts to have affected humanity and then to have been documented during our species few thousand years of documented history, given what we believe about the regularity of such events. Recently writers have shown that there are, in fact, an abundance of such historical records of extra-planetary impacts (Lewis 1999). Identifying them as such is not difficult, however, caution must be used when looking at pre-scientific "accounts" of NEO impacts. For example, it is only in the last century or so that we have truly begun to scientifically categorize what were once described as "mysterious explosions", "fireballs", or "acts of God" as impacts from asteroids and comets.

Some writers have been bold enough to state that common "flood myths" of many cultures around the globe correspond to a period of intense bombardment after an ancient comet first broke apart and formed the Taurid Meteor Stream (Napier and Clube 1990). When the Earth passed through this stream it was struck by many cometary fragments that produced violent tsunamis all over the world. Although this story is entirely speculative, some ancient descriptions can leave little doubt in the astute modern reader as to their true causes. Take, for example, the following passage from *The History of the Franks*, written by Bishop Gregory of Tours: "580 AD In Louraine, one morning before the dawning of the day, a great light was seen crossing the heavens, falling toward the east. A sound like that of a tree crashing down was heard over all the countryside, but it could surely not have been any tree, since it was heard more than fifty miles away…the city of Bordeaux was badly shaken by an Earthquake…a supernatural fire burned down villages about Bordeaux. It took hold so rapidly that houses and even threshing-floors with all their grain were burned to ashes. Since there was absolutely no other visible cause of the fire, it must have happened by divine will." (Lewis 1999, p. 3)

Around 1200 A.D. the South Island of New Zealand suffered widespread fires, levelling the island and leading to the extinction of the Moa bird (Verschuur 1996, p. 108). Maori legend attributes the fire to "a big explosion in the sky." Near the town of Tapanui there is a crater that geologists have been slow to identify as extraterrestrial in origin. Furthermore, "there is…evidence of Maori myth, legend, poetry and song which speak of the falling of the skies, raging winds, upheaval of the Earth, and mysterious devastating fires from space." (Steel and Snow 1992, cited Verschuur 1996, p. 110) The legends seem to have at least a kernel of truth as studies of fallen trees dating conform to the results of an expected blast, with trees within 80 km of the crater pointing radially outwards. It is interesting to note that in Maori, Tapanui means "the big explosion" or "the big devastating blow".

Even the Tunguska event of 1908 which occurred in remotest Siberia, caused two reindeer herders to be thrown off their feet and flung into the air, causing serious injuries that eventually cost them their lives (Gallant 1994). Had such an event happened over a more populated area the fatalities would easily have numbers in the tens of thousands. John Lewis has compiled a list of some 159 events with historical records of impacts that have resulted in "damage, injuries, deaths, and very close calls." One can very well question the precise veracity of any particular event or story, especially with regard to oral histories and medieval and non-scientific records. However, the quantity of these stories and records seems too much to ignore entirely, especially considering that we would wholly expect there to have been many such events during the millennia of recorded human history. The bulk of the evidence from both historical records and from what we know of the probabilities of impact sends a clear message; humans have already been significantly and fatally affected by these objects from deep-space and it is only a matter of time before it happens again. An uninformed public might be excused for succumbing to a "giggle factor" when confronted with the seemingly remote possibility of an impact. However, we as a species are collectively giggling at a natural disaster that has claimed human lives and damaged property in the past and will surely do so in the future.

1.1 The Cassandra Scenario - Introduction

Throughout the report the particular problems that high inclination comets pose are emphasized. To further highlight these aspects, we have developed a case study that is developed through the report of an encounter with such an object - a comet named Cassandra - during the year 2015. Cassandra is a high inclination, long period comet with the characteristics described in Table 1-1:

Table 1-1 Characteristics of Cassandra Comet

Parameter	**Value**
Earth Impact Date	August 8, 2015 (240 days)
Diameter (First estimate)	600 m
Inclination	135°
Albedo	10%
Semi-major Axis	10000 AU
Eccentricity	0.99997
Distance to Perihelion	0.3 AU

Given these characteristics, it is assumed Cassandra approaches Earth after a perihelion swing-by.

Each section of this report will use the Cassandra scenario to illustrate our methodologies for an international response to the assessment, detection, mitigation and social implications of an Earth-impacting high inclination NEO.

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Chapter 2

Assessing the Threat

This chapter outlines what is already known about NEOs and the threat they represent to life on Earth. The origins, composition, structure and population of NEOs, particularly comets, will be reviewed based on current knowledge, and the current impact probabilities will be examined and presented. Some information about historical impacts and their consequences will be outlined along with estimates of the human and economic cost. Different impact scenarios and their effects will be described.

2.1 Scientific background

2.1.1 What are NEOs?

NEOs are defined as any comet, asteroid, or large meteoroid that crosses or comes near to the Earth's orbit. More specifically, a Near Earth Asteroid (NEA) is defined as any asteroid that has a perihelion distance (closest approach to the Sun) of less than 1.3 AU. NEAs are classified into three groups: Atens, Apollos and Amors. A Near Earth Comet (NEC) is classified by having a perihelion distance of less than 1.3 AU, but is limited to having an orbital period of less than 200 years. There is currently no classification for comets with longer periods. Figure 2-1 is a schematic diagram of NEA locations in the Solar System.

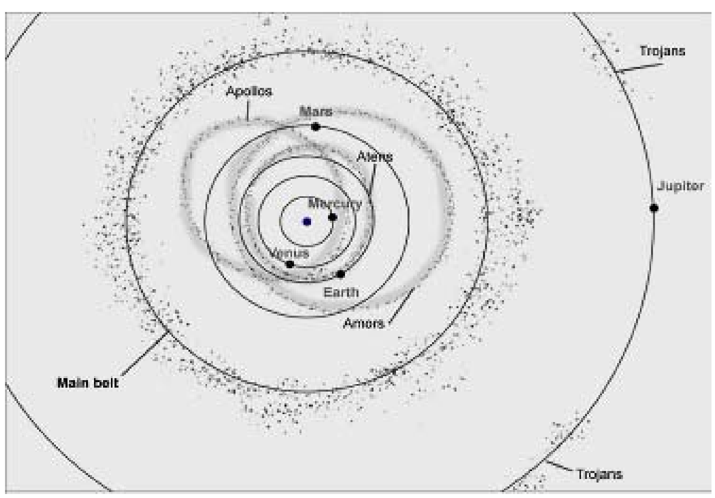

Figure 2-1 Locations of Near Earth Asteroids in the Solar System

shows a schematic of the solar system viewed from the ecliptic plane, which is defined as the plane that contains the Sun and most of the planets. Asteroids typically orbit in the ecliptic plane whereas comets can orbit in any and all planes. Pluto and Comet 1P/Halley are shown to contrast the bodies on the ecliptic plane as they orbit the sun at different (higher) inclinations.

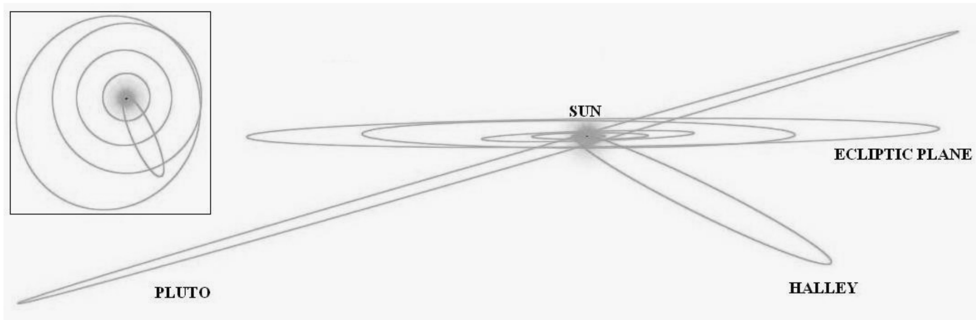

Figure 2-2 Scheme of the Solar System Viewed from the Ecliptic Plane and Above (inset)

Table 2-1 gives a list of the total number of each different group of NEOs found to date.

Table 2-1 Number of Detected NEOs of Different Classifications (JPL 2005)

Date	Aten	Apollo	Amor	PHA+18	PHA	NEA+18	Total NEA	Total NEC	Total NEO
2005-08-02	284	1802	1349	153	716	794	**3438**	**57**	**3495**

Magnitude (*H*) is a measure of how bright the object is; the larger the magnitude, the fainter the object. "PHAs" are Potentially Hazardous Asteroids with $H \leq 22$. "PHA+18" and "NEA+18" are PHAs and NEAs with $H \leq 18.0$.

2.1.2 What do we know about Comets?

Orbits, Origins, and Populations

Comets are divided into groups depending on their orbital period (i.e. the time it takes them to complete one orbit around the Sun). There are short-period comets (P < 200 years) and long-period comets (P > 200 years). The short-period comets are subdivided into two groups: Jupiter family and Halley family comets. Jupiter family comets have a period of less than 20 years, and Halley family comets have a period between 20 and 200 years.

The inclination (i) of the comet orbit indicates the direction of travel of the comet. The range of i is 0º to 180º. All i from 0º to 90º are travelling in the same direction as the planets around the Sun, all i from 90º to 180º are travelling in the opposite direction (retrograde orbit). If an object is approaching the Earth with an inclination of 90º to 180º, then it will impact the Earth with a much higher energy yield as the relative speed will be greater.

Comets' orbits differ from those of asteroids; they are not always found in the ecliptic plane. Comets can have higher inclinations with large eccentricities. This is a major contributing factor of why comets are hard to detect. Instead of searching for them on the narrow band of the ecliptic, astronomers must search the entire sky and as a result, these comets may not be detected until they are relatively close to Earth.

The question of where comets originate has long been an area of study and speculation. In 1950 J.H. Oort postulated the concept of a very large reservoir of cometary nuclei surrounding the Solar System in a spherical cloud. This is referred to as the Oort Cloud hypothesis and, with a few modifications, it is the most widely accepted view of the origins of comets, even though no direct observations have yet been made (Brandt and Chapman 2004). The Oort Cloud is 10^4-10^5 AU from the Sun, and its population of comets is estimated to be ~10^{12}-10^{13} comets. A comet coming into the inner Solar System from the Oort cloud for the first time will have a semi-major axis (*a*) greater than ~10,000 AU (Levison et al. 2002).

In addition to the Oort Cloud, there is a disc of objects in the ecliptic plane beyond Neptune's orbit called the Kuiper Belt (also known in Europe as the Edgeworth-Kuiper Belt). It lies 30-500 AU away from the Sun and contains comets and asteroids. The total number of Kuiper Belt Objects (KBOs) larger than 5km is estimated at $8x10^8$ (Brandt and Chapman 2004). This region is where most short-period comets (Jupiter and Halley family comets) are believed to originate. The idea was postulated when the source of some Jupiter-family comets could not be traced back to the Oort Cloud. Hundreds of KBOs have been observed to date (Figure 2-3). These include Pluto, Sedna, Quaoar, and 2003UB313. The last is the discovery announced on July 29, 2005 by astronomers at Palomar Observatory (Brown et. al. 2005). This object has reopened the debate about the definition of a planet as it is bigger than Pluto. Objects with $a < 10,000$ AU rarely make it directly to the inner Solar System because of the gas giants' gravitational fields, (Levison et al. 2002) so the Earth is not likely to be hit unexpectedly by an object from the Kuiper Belt region.

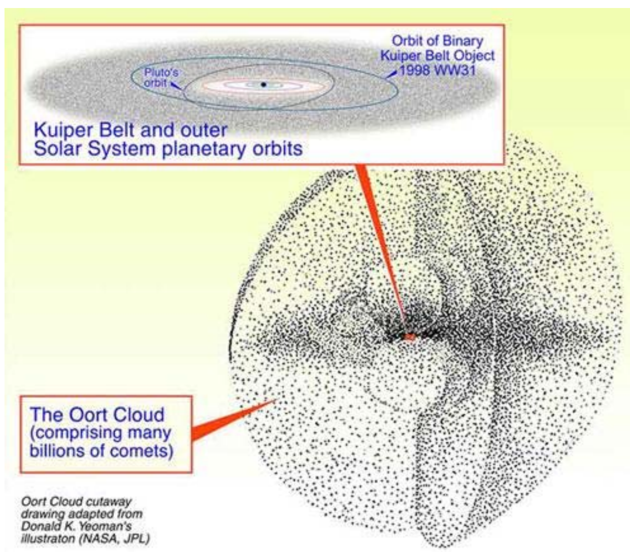

Figure 2-3 The Kuiper Belt and the Oort Cloud (Yeoman 2003)

Composition and Structure

Asteroids are rocky irregularly-shaped bodies while comets are composed of a nucleus, coma (the atmosphere surrounding the nucleus), and tail (sometimes divided into dust and gas tails). As the comet nucleus approaches the Sun, the volatiles heat up and sublime as gas and lift dust grains from the surface. Typically, only a small fraction of the surface (< 10%) is active in this way, suggesting that most of the surface is covered in non-volatile material. This outgassing activity produces the coma and tail of the comet.

While scientists have been studying meteorites for many years to gather clues about the composition and structure of asteroids, similar data for comets is far less available. It is known that comets are composed of ice and dust (volatiles and mineral aggregates). Molecular species that have been identified in the coma include H_2O, CO_2, HCN, CO, NH_3, H, OH, CH, NH, and CN. The majority of the ice is water ice. Mineralogical characteristics can be inferred using visible and near-infrared spectroscopy, though space rendezvous missions are needed to provide definitive data. For example, ESA's Giotto mission identified two major classes of dust particles in Comet 1P/Halley: the first was dominated by the light elements (C, H, O, and N), the second was rich in mineral-forming elements (Na, Mg, Si, Fe, and Ca) (ESA 2005).

In the 1950s, Fred L. Whipple put forward the icy-conglomerate model of the cometary nucleus. This is commonly termed the "dusty snowball" model. This model has been continually refined over the years by many observations of the spectra of comets and the distances at which different gases sublime from the nucleus. The model is now sometimes termed the "icy dirtball". Current understanding of the composition is based on observing the spectra of comets and measuring how far away from the nucleus each gas species starts to sublime.

Many questions remain about the density, porosity and structure of cometary nuclei. While it has not yet been possible to directly measure the mass of any cometary nucleus, there are various indirect approaches (e.g. examination of slow rotational periods of 5-70 hours). These methods suggest that the densities are very low and in the 0.2-0.8 g/cm^3 range (Levasseur-Regourd et al. 2005).

Comets may stop outgassing either because their entire surface has been covered by an insulating layer that prevents volatiles from being heated by the Sun (dormant comets), or because their volatiles are exhausted (extinct comets). Both of these types are difficult to distinguish from asteroids and impossible to distinguish from each other. Collisions of small rocks with dormant comets could expose the ice again, and an active comet would be reborn. There are many examples of asteroids believed to be dormant or extinct comets because of the characteristics of their spectra (Weissman et al. 2002; Chamberlin et al. 1996; Harris et al. 2001; Davies et al. 2001). For example, asteroid 1979VA was identified as the same object as comet P/Wilson-Harrington. The percentage of dormant/extinct comets in the NEO population will be discussed in Section 2.1.3.

The average size of cometary nuclei radii that are accessible to photometric measurement is 1-20 km (Crovisier and Encrenaz 2000). The shape of a comet nucleus will generally be non-spherical because of its low mass and hence low gravitational field. The images of comets captured so far show craters or other depressions visible on their surfaces. These areas could be the remains from jets or active areas of sublimation, or they could have been formed by collisions with smaller bodies.

Various comets and asteroids have been visited by spacecraft; Table 2-2 lists these missions detailing their objectives and key findings. There is not much data on the internal structure of cometary nuclei yet, a situation that will be remedied by ESA's Rosetta and NASA's Deep Impact missions. However, there are clues to the internal structure from observations. There have been an increasing number of comets in which partial fragmentation or complete disruption has been observed, the most famous example of comet fragmentation is D/Shoemaker-Levy 9 that collided with Jupiter in July 1994. There is mounting evidence that partial fragmentation is more frequent than complete disruption (Levasseur-Regourd 2005). For example, the huge cloud of particles encountered by NASA's Stardust mission is thought to have resulted from the progressive disintegration of a one meter diameter fragment. Giotto might have observed a similar event with its second flyby of 26P/Grigg-Skjellerup. There are observations of other comets showing fragmentation over several orbits. It is possible that fragments might always be present inside the comae of active comets. As a result of their composition and low density, it is probable that comets are more likely to fragment than asteroids.

Table 2-2 Past and Future Spacecraft Missions Related to Comets and Asteroids

Mission Name	Mission Date	Target Object	Main Objective/Findings Related to Asteroids/Comets
International Cometary Explorer (ICE) Originally named International Sun-Earth Explorer (ISEE-3) (NASA)	1978-1997	Comet 21P/Giacobini-Zinner Comet 1P/Halley	Studied the interaction between the Earth's magnetic field and the solar wind Passed through the plasma tail of Comet 21P in 1982 Encountered Halley in 1986 Measured energetic particles, waves, plasmas, and fields
VEGA-1 (USSR)	1984-1986	Comet 1P/Halley	Landed on Venus Flew past Comet 1P/Halley
VEGA-2 (USSR)	1984-1986	Comet 1P/Halley	Landed on Venus Flew past Comet 1P/Halley
Giotto (ESA)	1985-1992	Comet 1P/Halley Comet 26P/Grigg-Skjellerup	Europe's first deep space mission First close-up images of a comet nucleus (Halley) Determined elemental compostion, gas production rate, dust mass distribution First s/c to encounter two comets
SUISEI (PLANET-A) (ISAS)	1985-	Comet 1P/Halley	Observed solar wind interaction with Comet 1P/Halley
SAKIGAKE (MS-T5) (ISAS)	1985-1999	Comet 1P/Halley	Technology demonstration Observed space plasma and magnetic field in interplanetary space
Hipparcos (ESA)	1989-1993	Comet Shoemaker-Levy 9 (D/1993 F2)	First space mission for astrometry The Hipparcos and Tycho Catalogues, published by ESA in 1997 Helped to predict impact of Comet Shoemaker-Levy 9 on Jupiter
Hubble (ESA, NASA)	1990-2010	Various objects	Revolutionized modern astronomy High-resolution images of Pluto, Charon, asteroid Vesta, Comet Shoemaker-Levy 9 impacting Jupiter
SOHO (ESA, NASA)	1995-2007	Various comets	Making discoveries about the Sun Discovered ~1000 comets
Near Earth Asteroid Rendezvous (NEAR Shoemaker) (NASA)	1996-2001	Asteroid 433 Eros	First long-term, close-up study of an asteroid Crash-landed on an asteroid

Table 2-2 (continued)

Mission Name	Mission Date	Target Object	Main Objective/Findings Related to Asteroids/Comets
Deep Space 1 (NASA)	1998-2001	Asteroid Braille (1992 KD). Comet 19P/Borrelly	Technology demonstration. Returned images and other data from comet Borelly
Stardust (NASA)	1999-2006	Comet 81P/Wild 2	First comet sample return mission Detected fragmentation
Hayabusa (MUSES-C) (ISAS)	2003-2007	Asteroid Itokawa (1998SF36)	Asteroid sample return mission Technology demonstration
Rosetta (ESA)	2004-2015	(Original target Comet 46P/Wirtanen) Comet 67P/Churyumov-Gerasimenko Asteroid 21 Lutetia Asteroid 2867 Steins	First controlled landing on a comet with Philae lander Will provide in-situ observations of increasing cometary activity as comet journeys towards the Sun
Deep Impact (NASA)	2005-2006	Comet 9P/Tempel 1	Impactor made an artificial crater to investigate the subsurface of the comet
Dawn (NASA)	2006-2015	1 Ceres and 4 Vesta	Will investigate the internal structure, density and homogeneity of two asteroids, 1 Ceres and 4 Vesta
New Horizons (NASA)	2006-2020	Pluto, Charon and other Kuiper Belt objects	Will map and characterize Pluto, Charon and other Kuiper Belt objects
Gaia (ESA)	2011-2020	Faint moving objects	Will create a 3D map of our galaxy Unprecedented sensitivity to faint moving objects will contribute to inventory of asteroids and comets
Mars-Aster (RSA)	2015-2020	NEO asteroid after Mars fly-by	Will land on an asteroid or extinct comet Possible sample return

2.1.3 Impact Probabilities

Impacts from NEOs are an extreme case of a low-probability/high-consequence hazard. Figure 2-4 and Figure 2-5 show recent graphs of impact probability versus size of object. Figure 2-5 also shows the contribution from several detection systems.

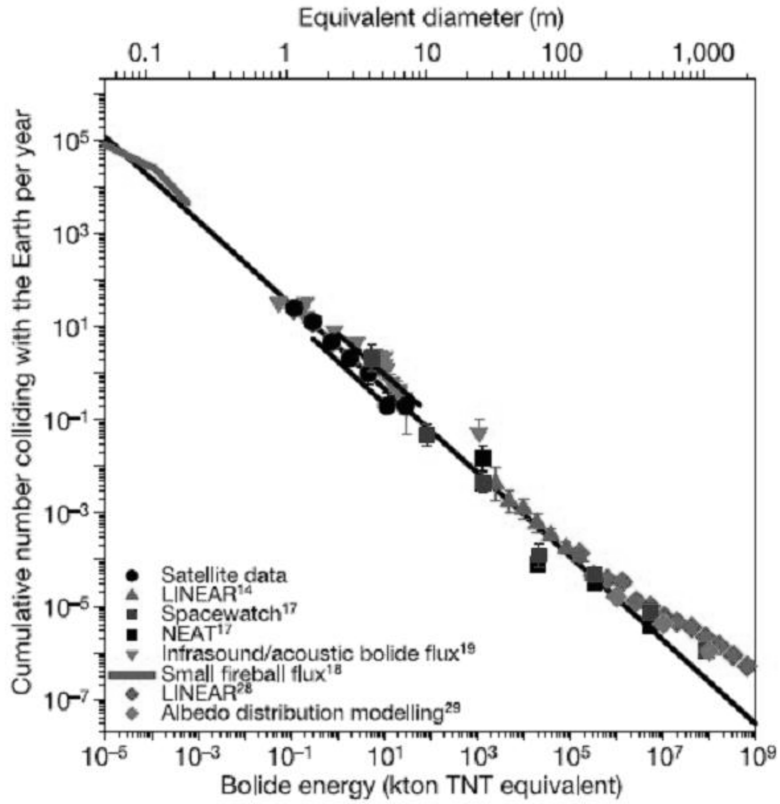

Figure 2-4 The Flux of Small NEOs Colliding with the Earth (Brown et al. 2002)

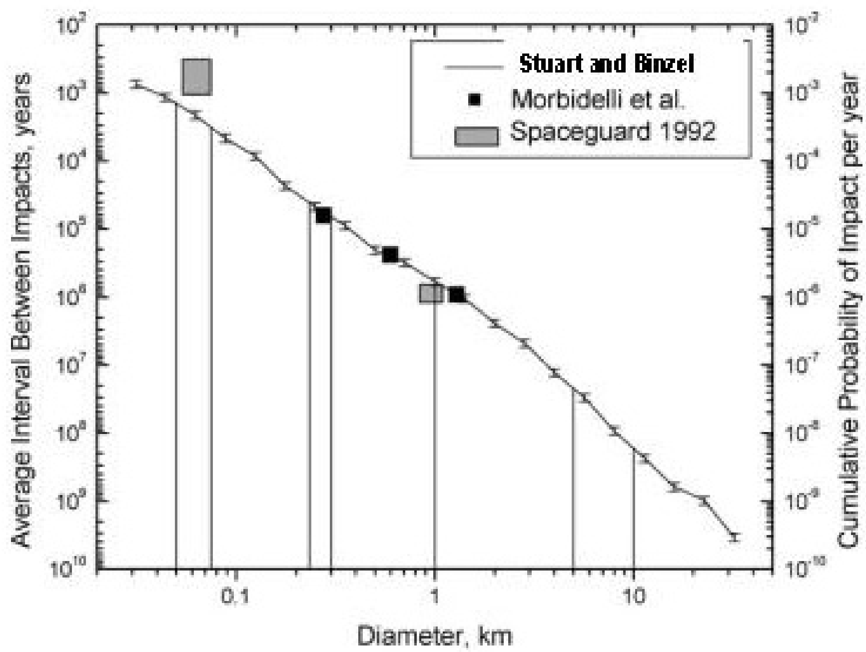

Figure 2-5 Probability of NEO Earth Impact vs Diameter (Stuart and Binzel 2004)

In Stuart & Binzel (2004), the following is estimated: globally destructive collisions of objects 1 km or larger strike the Earth once every 600,000 ± 100,000 years; regionally destructive collisions of ~200 m diameter objects occur on the Earth every 56,000 ± 6000 years; local-scale events (e.g. Tunguska) occur every 2000–3000 years (Stuart & Binzel 2004). However, it should be noted that these are the average times between impacts. Impacts are random events, and they are not evenly distributed in time.

There are many estimates of the percentage of the NEO population that are dormant or extinct comets. These estimates have been as high as ~50% (Wetherill 1988). An estimate of 2-10% was made for a given magnitude range of $13 < H < 22$ (Bottke et al. 2002). The percentage estimate of the NEO population above any given diameter that are dormant comets was set at 10-18% (Binzel et al. 2004). Methods of determining the percentage include analyzing various dynamical parameters, the albedo of the object and taxonomic class statistics.

The percentage of the NEO threat from comets, whether active or dormant, is ~1% according to a 2003 NASA study (Stokes et al. 2003). However this figure could be an underestimate of the number of dormant comets in the NEO population. There is a possible observational bias against detecting dormant comets, as they are very hard to distinguish from asteroids unless they are exhibiting cometary activity (i.e. outgassing). Also, modern detection techniques have not been used for very long in comparison to the orbital periods of some of these objects. They may have been too faint to see before the arrival of modern telescope optics and/or they may have been missed before the systematic surveying of the sky which is currently taking place. It is important to distinguish dormant comets from asteroids, as their internal structure and composition are different. This influences which mitigation strategies are used in the event of a NEO threat. Refer to Chapter 4 for more details.

Determining the percentage of the NEO threat from long-period comets is very difficult because of the low-number of long-period comets observed and the short time we have been able to look for them compared to their orbital periods, but the percentage is certainly very small.

There is also the possibility that cometary flux will change with time. A comet shower may be triggered by a star passing close to the Oort cloud or by material in the galactic plane causing perturbations in the Oort cloud. This possibility has not been examined in great detail in this report as in (Stokes et al. 2003) as changes in cometary flux would happen over a timescale longer than one hundred years.

2.1 Consequences of a NEO Encounter

2.1.4 Overview

Once a NEO intercepts the Earth's orbit, the gravitational attraction from our planet may be a significant factor in altering the object's orbit and speed. Depending on the trajectory, a number of different encounter scenarios will occur. A small percentage (~1%) of bodies will approach at very low entry angles and experience skip-out of the atmosphere (Baker 1958; Jacchia 1974; Borovicka 1992), while others will be captured into a low Earth orbit as in the case of the 1996 El Paso object (Lewis 1999).

If approaching or captured with a high angle of attack, the object will eventually enter the Earth's atmosphere. The final fate of the NEO may be a potential break-up, partial or complete ablation, an airburst (e.g. Tunguska 1908; Kashmir 2002 with potential geopolitical consequences), or an impact with land or water. Impacts over land are generally less devastating than impacts over ocean for the same explosive yield. Similarly, airburst explosions near the surface will devastate a much larger region than an impact directly at the surface. A description of each scenario is described below, followed by some case study examples.

Atmospheric Entry

As a cometary body enters the atmosphere it experiences a number of phenomena including deceleration, ablation, fragmentation and luminous emission of energy. The deceleration is proportional to the exposed cross-sectional area, and becomes negligible once the mass of the body exceeds the mass of a column of air of the same cross-sectional area.

Atmospheric break-up depends on the angle of entry and the effective density of the object. Adushkin (1993) shows that for an icy body such as a comet, there is a critical threshold diameter (R_b) above which the body will not break up.

$$R_b = \frac{H\sqrt{\dfrac{\rho_{atm}}{\rho_{body}}}}{\sin(\theta)}$$

In this equation, H is the characteristic scale of the atmosphere (for Earth, H=8.5 km), ρ_{atm} is the atmospheric density, ρ_{body} is the density of the impactor, and θ is the angle of inclination of the trajectory from the horizon.

For an entry angle of 90º and an icy body density of 1 g/cm^3, R_b is calculated to be 270 m. For an entry angle of 45º, R_b increases to 380 m. Cometary bodies of sizes greater than this will therefore successfully penetrate the atmosphere and impact the surface without significant break-up or fragmentation.

Teterev et al. (1993) have performed simulations of small comets interacting with the atmosphere, showing that they gradually lose mass from surface blow-off and Rayleigh-Taylor/Kelvin-Helmholtz instabilities. Numerical simulations of a 200 m diameter icy body, traveling at 20 km/s demonstrate that the body is deformed during descent through the atmosphere and assumes a conical shape. Cometary bodies of such small size do experience fragmentation, yet are shown to produce a single bow shock wave (on impact of all fragments) with 70% of the initial kinetic energy. Studies of larger comets in the order of 400 m diameter exhibit similar deformation phenomena but do not fragment and reach the ground with less than a 10% loss in mass.

Airbursts

During atmospheric entry the aerodynamic forces exerted on a weakly bound object are significant, and will cause it to deform in shape – flattening out as it descends (Chyba et al. 1993). At a specific point (estimated to be 540 m for icy cometary bodies), a critical diameter is reached at which the body needs to deposit so much energy over such a short distance that it explodes in an airburst. Airbursts can cause much greater destruction over a much larger area than if the impacting body had survived to reach the surface. A case study of the Tunguska airburst is examined in Section 2.2.2.

Impact Over Land

Bodies with a sufficiently high strength and low velocity will often survive passage through the atmosphere and will impact the Earth at the same speed with which they entered the atmosphere. Impacts at several kilometers per second would result in the excavation of a large crater (Melosh 1989) and would produce seismic effects (Kisslinger 1992). The terminal explosion on impact would result in a blast wave propagating radially from the impact site.

The explosion would also cause the ejection of a large mass fraction of the impactor into the atmosphere. Data from simulations and nuclear test results show that for a 16 Mt explosion, the dust cloud reaches 35 km in height and stabilizes within a few minutes (Carrier et al. 1985). The maximum height reached depends on local atmospheric conditions. Dust raised by such impacts would have devastating climatological consequences lasting for several years (Gerstl and Zardecki 1982). Changes in the scattering and absorption of light could reduce photosynthesis by a factor of one thousand.

Impact Over Ocean

Approximately 70% of the Earth's surface is covered by ocean and therefore any incoming object has a higher probability of impacting over ocean than over land. The average depth of the world's oceans is between 4-5 km. A NEO impact into deep ocean would result in the ejection of a large volume of superheated water into the atmosphere and the creation of a transient ocean crater. This transient crater then collapses back upon itself and rebounds, producing a train of tsunami waves propagating outward from the impact location (Hills et al. 1994).

Nemchinov et al. (1993d) have simulated the impact of a 200 m diameter comet into an ocean four kilometers deep with a velocity of 50 km/s. Results indicate that within 30 seconds of impact, a transient water crater is formed with lips of 30-35 km in height. The ejected water is dispersed as small droplets, and thus has a density much lower than normal water. Such large volumes of water vapour in the atmosphere would significantly change the chemistry and heat budget processes underway, forming a layer of mesospheric noctilucent clouds (McKay and Thomas 1982). The large volume of salt (3% by mass) contained in the ejected water is likely to dissociate and would result in reduced ozone concentration.

As the transient water crater relaxes, propagation of the tsunami waves would begin. In an airburst explosion, the total energy is dissipated over an expanding spherical surface and thus the intensity falls off quickly as one over the square of the distance from the explosion ($1/r^2$). However, the energy in a propagating tsunami wave dissipates over a two dimensional circular surface and therefore only falls off as one over the distance from the impact ($1/r$). This means tsunami waves can travel over very large distances without losing much energy. When the wave encounters the continental shelf, the speed of propagation is reduced, and the wave height increases dramatically. Tsunami "run-up" is defined as the final height of the tsunami wave in units of the height of the propagating wave in deep water. The average run-up is in the order of 10 or 20 fold (Mader 1991).

For example, in 1960 an earthquake in Chile generated a tsunami wave that traveled 17,000 km around the planet to cause devastation on the coast of Japan with wave heights of 2-5 m (Takashasi 1961).

Once the tsunami wave reaches the shore, one of the prime factors in determining the destructive power is the extent to which the wave propagates inland, inundating coastal settlements. The maximum distance of "run in" depends on the tsunami wave run-up height, the shore water depth, the slope of the shore, and the roughness of ground that the water encounters. The Manning number (n) is a measurement of the roughness of terrain that the water encounters, and ranges from 0.015 for very smooth surfaces (e.g. ice) to 0.070 for rough surfaces (e.g. dense forest). Most developed coastal settlements have a Manning number of approximately 0.035. Assuming a tsunami run-up height of 15 m, this will result in a typical flood-water inundation of 1.8 km for coastal settlements (Bretschneider and Wybro 1977).

In most Western nations, 30-70% of the population lives within 100 km of the coast. In Australia this figure is over 70%. In the December 2004 Indian Ocean tsunami, an estimated 10.4 million people were living within one kilometer of the affected coastal area, with this figure rising to 18.9 million people within two kilometers. It is clear from these figures that the devastation caused from even a moderate-sized ocean impact would result in substantial loss of life.

2.1.5 Local Scale Event: Tunguska Airburst of 1908

On June 30, 1908, in a remote region of central Siberia nearby the Tunguska River, an explosion triggered the destruction of approximately 2150 km^2 of forest and burned over 200 km^2 of flora. A subsequent earthquake was reported, accompanied by measurements of a sonic event and a local magnetic disturbance (Vasilyev 1996). Reports from as far west as England cited an intense anomalous glowing of the night sky for several evenings following the event (Bronshten 2000).

The cause of this startling event was determined to have been an airburst of a cosmic body. There has been much debate as to the origin and composition of this object. Most believe that it was either an asteroid or a comet fragment. The comet fragment theory was first proposed by Shapely in 1930 and is currently the favorite, having been recently upheld by Bronshten in 2000. (Shapely, 1930; Bronshten, 2000)

The most accurate predictions of the parameters of the Tunguska object are that upon entering the Earth's atmosphere, it had a mass of approximately $2x10^6$ kg and a velocity of approximately 30 km/s. During the descent and subsequent ablation of the object, the mass decreased to approximately $1x10^5$ kg and the object slowed to a velocity of approximately 17km/s (Bronshten, 2000). Once the object reached an altitude above the Earth's surface of approximately 7.5 km, it exploded in mid-air. The resulting shock wave flattened and burned the forest below, caused a seismic event, and generated an electromagnetic storm.

It was fortunate that this event occurred in a non-populated area and there were no reported deaths. The strength of the blast has been estimated at 10 - 15 Mt, which is 500 – 750 times the strength of the atomic bomb dropped on Hiroshima. Similar events have occurred since Tunguska, including one in western Brazil in August 1930, one in Guyana in 1935 and one in Kashmir in 2002. (UK POST Report, 1999)

The area of devastation caused by an airburst is greater than that caused by a ground explosion. A relationship for estimating the area of lethal damage caused by an asteroid or comet is

$$A = 100Y^{2/3}$$

where A is the area of lethal damage in km^2 and Y is the explosive yield in Mt (Chapman and Morrison 1994). Using this equation, it can be seen that the Tunguska event had a lethal damage area between 460 and 600km^2. Depending on the location of impact, an event like Tunguska could have a dramatic human toll, not to mention economic effects. In a typical metropolitan area such as Hong Kong, which has a population density of 6,635 persons per square kilometer, a Tunguska-type event could cause between three and four million deaths (Thorton, 2003), as well as causing severe infrastructure damage. If an impact or airburst were to occur over water rather than land, a tsunami would result. This would increase death tolls by as much as a factor of ten (Chapman and Morrison 1994). An impact or airburst by a Tunguska-sized object (60 – 80 m diameter) occurs roughly every 2000 years (Brown et al. 2002). However, impacts from smaller objects occur more frequently, as shown earlier in Figure 2-4

2.1.6 Regional Scale Event: Eltanin Tsunami

The Eltanin impact into the Bellingshausen Sea 1,500km southwest of Chile is a good example of a regional scale event. Occurring 2.15 million years ago, it is estimated to have been the result of an impact of an asteroid 1 - 4 km in diameter. The total energy released in the impact is estimated to be equivalent to the explosive power of 100 billion tons of TNT. The Eltanin impact was discovered during deep sea drilling in the 1960s when scientists on the research vessel "Eltanin" detected high levels of iridium enrichment in core samples retrieved from the floor of the Bellingshausen Sea.

The impact of a body this size into the deep ocean water would have excavated a transient crater approximately 60 km in diameter and 5 km deep. A column of super heated water would have been ejected 5 km into the atmosphere. As the ejected water collapsed back upon itself, a set of oscillating tsunami waves would have been generated. Simulations of the tsunami show that within 5 hours, waves 50 m in height would have inundated the Antarctic and the western coast of South America. Within 15 - 20 hours, tsunami waves 25 m in height would have impacted Australia, the west coast of North America and, a few hours later, Japan (Ward and Asphaug 2002). Figure 2-6 shows this simulation.

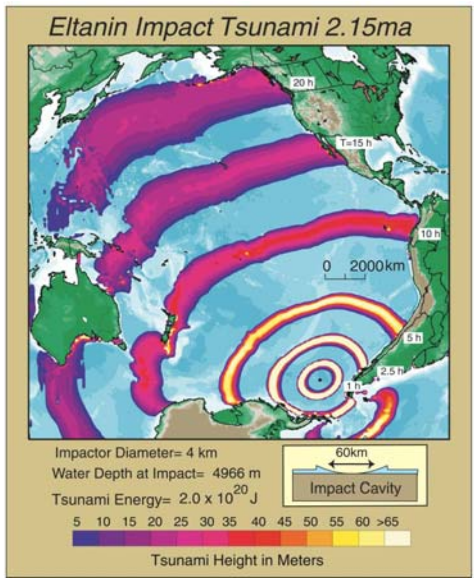

Figure 2-6 Image from a Simulation from Eltanin Tsunami Impact (Ward 2000)

These tsunami waves would have run-in distances of hundreds of meters along the coastlines of the Pacific Rim. Although little geological evidence of this tsunami remains on the coast, it helps explain the discovery of disrupted coral fragments located hundreds of meters above sea level on the Hawaiian Islands.

The impact appears to have resulted in the complete vaporization of the asteroid itself, as no obvious impact crater exists on the ocean floor. However recent surveys suggest the possible signature of a crater 132 km in diameter located at 53.7°S and 90.1°W (Glatz et al. 2002).

Although the Eltanin impact is the only known ocean impact, it is estimated that over 500 similar scale impacts have occurred over the past 500 million years. It is clear that the tsunamis generated from the Eltanin impact would have devastated the coastal environment throughout the Pacific Rim region. In addition, the mass of water vapor and sediment ejected into the atmosphere would have resulted in climate change. A distinct period of global cooling is known to have occurred at this time, but whether this can be attributed entirely to the Eltanin impact is still an open question.

2.1.7 Global Scale Event: The K-T Boundary

Fossil remains, available in abundance mainly for the last 570 million years, demonstrate that five biological crises have occurred during this period. The most recent of these biological crises took place 65 million years ago in the boundary between the Cretaceous and Tertiary periods (KTB, “K” is used instead of “C” to avoid confusion with the older Cambrian period) leading to the extinction of many groups of organisms (Russell 1975). The KTB mass extinction is the best documented of the large extinction events in Earth's history, especially because it included the demise of the dinosaurs which, in turn, probably made possible the early Tertiary evolution of mammals, leading ultimately to human evolution (Bromham et al, 1999). Currently, the most prominent hypothesis to explain the majority of the biological and physical evidence regarding the KTB mass extinction is that of Alvarez et al. They suggested that an asteroid or comet with a diameter of approximately 10 km struck the Earth with dust-sized material ejected from the crater reaching the stratosphere and spreading around the globe (Alvarez et al. 1980). The bolide impact is widely accepted to have formed the ~100km diameter Chicxulub crater, the largest known Phanerozoic impact structure, at the Yucatan Peninsula in Mexico (Morgan et al. 1997).

The precise size and morphology of the Chicxulub crater has been in dispute; it has been interpreted as a ~180km peak-ring crater, a ~250km peak-ring crater, and a ~300km multiring basin (Hildebrand et al. 1991, Pilkington et al. 1994, Pope et al. 1996, Urrutia-Fucugauchi et al. 1996). This lack of conclusive evidence on the size and properties of the crater has limited the ability to estimate the potential for environmental perturbation, because of magnitude-size calculation shifts in impact energy. More recently, Morgan et al. used seismic data imaging to demonstrate that the crater's excavation cavity diameter is 100 km. They used the estimated size of the transient cavity to calculate the energy of the KTB impact via the Schmidt–Holsapple Pi-group scaling law, reporting an impact energy of approximately $5x10^{23}$ J (Morgan et al. 1997, Holsapple and Schmidt 1982). In turn, this calculation was used to estimate the size of the KTB bolide resulting in a diameter of approximately 12 km in the case of an asteroid impact, or a 10 – 14 km diameter – depending on impact velocity – if the object was a comet (Morgan et al. 1997).

Ejected dust from the impact crater was initially considered the major contributor to mass extinctions stemming from the KTB impact (Alvarez et al. 1980). Indeed, using size estimations of the transient and excavated cavity of the crater, the total volume of ejecta has been estimated to be as high as 50,000 km^3 (Morgan et al. 1997). Although this mass of ejected dust effectively prevented sunlight from reaching Earth's surface, causing global cooling and halt of photosynthesis, this state is believed to have been relatively transient lasting no more than one year (Covey et al. 1994, Pope 1997).

The major contributor to mass extinctions stemming from the KTB impact is now believed to be the volatile content of the impact site, with several studies highlighting the potential of volatiles to perturb the atmosphere and climate (Pope 1997, O'Keefe and Ahrens 1989). Indeed, as the area of the KTB impact was a volatile-rich sedimentary marine terrace, tremendous amounts of SO_2, CO_2 and H_2O are thought to have been transferred from the rock to the atmosphere within 30 seconds post-impact (refer to Figure 2.6) resulting in severe environmental perturbations (O'Keefe and Ahrens 1989). Calculations of the total sulfur released into the atmosphere range from $6x10^{13}$ - $1.5x10^{14}$ kg (Ivanov et al. 1996, Morgan et al. 1997). Although it is unlikely that these volumes were sufficient to generate dramatic pH changes in the environment, sulfuric acid aerosols were produced over a decade of severe global cooling known as the "impact winter" (Ivanov et al. 1996, Morgan et al. 1997, Pope 1997). Major changes in ocean temperature and circulation, severe acid rain, as well as ozone depletion have also been attributed to the emitted sulfate aerosols from the KTB impact (Pope 1997).

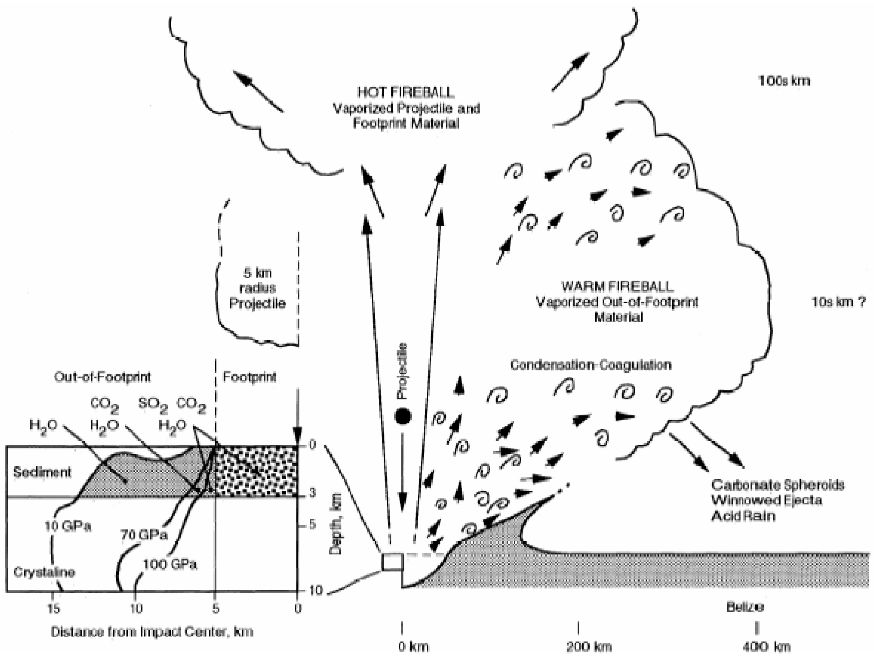

Figure 2-7 Model of Vapour Plume Formation (Pope 1997)

Figure 2-7 shows vapour plume formation. The left side of the diagram depicts results of a 2D hydrocode model of a vertical impact of a 10 km, 20 km/s object into a wet sedimentary layered target. Shown are the impact regions with shock pressures and relevant volatile released species. The right side of diagram presents a schematic view of the origin and trajectories of the hot and warm fireballs evolving from the impact.

Precise estimations of the atmospheric CO_2 concentration-shift have proven elusive to date, limiting the potential for understanding the specific causal mechanisms of the abrupt KTB mass extinctions shown by the marine and terrestrial fossil records. Recent geological estimations suggest that a total mass of between 6,400 - 13,000 Gt of CO_2 escaped the carbonate-rich rock of the Chicxulub crater by the KTB impact (Beerling et al. 2002). Applying these values to current climate and radiative-transfer models indicates a rise in atmospheric CO_2, increased climate forcing by +12 W/m^2, resulting in a mean global warming of ~7.5 ± 3.0 °C within 10,000 years of the KTB impact (Hansen et al. 2000). This global rise in temperature was latitude-dependent, with significantly higher temperatures at high latitudes and lower temperatures at lower latitudes (Hoffert and Covery 1992). Similarly, oxygen isotope evidence suggests a temperature increase of ocean surface waters in mid to high latitudes by 10-12 °C. This substantial increase in temperature, lasting several thousand years after the KTB impact, contributed significantly to the mass extinction at the KTB by stressing ecosystems previously affected by the very low temperatures and lack of sunlight during the immediate "impact winter" (Beerling et al. 2002).

The effects of the KTB impact were worldwide, affecting all life on the major continents and oceans. The aforementioned severe environmental perturbations together with other consequences, like devastating wildfires, are believed to have caused the extinction of more than half the species on Earth, including both marine (~80 families) and continental (~100 families) organisms within a few tens of thousand of years from the KTB impact (Wolbach et al. 1988, Chapman and Morrison 1994, Benton 1995). The casualties included most of the large creatures of the time, but also some of the smallest, in particular the plankton that generate most of the primary production in the oceans. Almost all the large vertebrates on Earth died out, together with most plankton and many tropical invertebrates, especially reef-dwellers. Furthermore, carbon isotope measurements across the KTB suggest that productivity and ocean circulation were suppressed for a period as long as 2 million years following the impact, devastating both terrestrial and marine ecosystems.

2.4 The Economic Cost of a NEO Impact

Extra-terrestrial impacts have already imposed economic costs on humanity. Even if we arbitrarily leave out all evidence prior to the 19th century and count only instances verified by scientists, we still have the Tunguska event that devastated over 2,000 km^2 of forest worth millions of dollars to the timber industry and also providing similar value to the global economy as carbon sinks. Clearly the costs are high even when an impact occurs in a relatively isolated and uninhabited part of the world.

There have been attempts made to calculate the expected losses from NEO impacts to get a sense of how much should be spent to mitigate the threat. Although these estimates are very imprecise, they do give a good sense of the order of magnitude of costs to be considered. Gregory Canavan uses a very simple method. First he calculates the cumulative impact frequency, which is the integral over the collision probability (the area under the line of a graph plotting size against probability such as in Figure 2-4) for a given diameter and larger. He then multiplies that by the area that would be damaged by an object of that diameter, using the amount of energy released as the primary determinant, as a fraction of the Earth's surface, and he next multiplies that by the annual gross domestic product (GDP) of the world. He also assumes that the area devastated is unproductive for 20 years, and he discounts those losses at 5%. His figures have been adjusted to 2003 dollars. This method gives Canavan an estimate for the expected cost of an impact, that is the cost of an impact multiplied by the probability of the impact occurence. He calculates the expected losses for three categories of objects: small < 200 m, intermediate 200 m - 2 km, and large > 2 km. His estimates for the cost resulting from small object impacts are sensitive to the minimum penetrating diameter of extra-terrestrial bodies. Canavan uses Hills' and Goda's estimate of 50 m being the minimum penetrating and which implies an expected integral loss of about US$12 million/year for small bodies. He notes that, "while small NEOs make a large contribution to the total number of impacts, except for extreme assumptions about collision frequencies and distributions, they do not make a significant contribution to the total loss from all NEOs." (Canavan, 1994).

For intermediate bodies, the damage resulting from hypervelocity impact, like for the smaller bodies, is still relatively low at around US$10 million/year. However, the damage that these objects can wreak on coastal settlements from ensuing tsunamis is much greater. About 70% of the Earth is covered in water and the coastal regions are home to many of the world's major cities, making the tsunamis scenario by far the most likely and dangerous. Taking into account these effects, Canavan estimates the expected costs generated by impact-derived tsunamis to be US$200 million/year. This number seems quite plausible in light of the 2004 Indian Ocean tsunami, which was the most costly natural disaster in history at that time. The United Nations (UN) estimated that the reconstruction cost would be US$12 billion dollars, a cost that does not include the loss of some 294,000 lives. (Anon., 2005) If a tsunami occurred in the Atlantic or in the Pacific, where there are more extensive and expensive infrastructures to damage, the cost would total hundreds of billions of dollars. As shown earlier, such a tsunami could be created by a relatively small, and thus relatively frequent, body of some 200 m. Given what we know now about the potential costs of tsunamis, Canavan's estimates of the expected cost of intermediate impacts of US$200 million/year may well be an underestimate. Whether or not there is a moral imperative to defend the human species from a NEO threat, it makes good financial sense to invest a few hundred million dollars on a system that can detect smaller bodies which can, at a minimum, give warning enough to mount an evacuation of the affected areas, thereby reducing the major component of the loss, human capital.

The single largest component of Canavan's expected loss from impacts is loss from a "global killer." In calculating these costs, he assumes that an object 2 km or larger would effectively wipe out the entire GDP of the world for 20 years. This leads him to calculate an expected cost of US$800 million/year from impacts of large bodies. This leads to a total expected loss of all three categories of US$1.12 billion dollars a year. Although this may seem very high, if one remembers that tsunami effects similar to those experienced in 2004 occur at sizes > 200 m and, that at sizes > 2km, there are situations similar to one which wiped out the entire superorder of dinosaurs, this expected cost may not seem so outlandish.

It should be pointed out that Canavan's cost estimation strategy has not gone uncriticized. Duerfeld noted that Canavan's estimates assume a homogenous distribution of population across the globe, so Duerfeld accounted for the fad that the Earth's GDP is concentrated in relatively small areas (2002 cited in Gritzner and Kahler, 2004). Duerfeld's calculations, which took into account differences in population density, estimated a much lower expected cost of around US$60 million dollars a year from the impact threat. However, this large difference derives entirely from his assumption about how the population was distributed on Earth and one rather extreme assumption that any impact to the 70% of the Earth that is water would not cause any damage. This assumption is dangerously wrong as the discussion of tsunamis shows (Duerfeld 2002 cited in Gritzner and Kahler, 2004). Duerfeld has entirely ignored the threat and damages related to impact-derived tsunamis, which are greater than a land impact as a tsunami can cause a relatively small impact's energy to be transmitted to an entire region. Duerfeld's estimate therefore leaves out perhaps the most important aspect of the threat from intermediate and small bodies, which occur far more frequently than larger impacts.

We now have a range of possible expected costs in dollars per year for the impact threat and therefore a range of possible expenditures which would make economic sense, on an annual basis, to invest in order to prevent these impacts from occurring. At the low end we have Duerfeld's estimate of around US$60 million/year, an estimate which completely ignores the significant threat that impacts pose via a tsunami. At the high end is Canavan's estimate of US$1.12 billion/year in expected losses, which accounts for the tsunami threat but erroneously assumes a homogenous population distribution around the Earth. The truth, undoubtedly, lies somewhere in the middle, likely in the range of a few hundred million dollars a year. But what is instructive about looking at this range of estimates is that even the lower estimate, which ignores one of the most significant aspects of the threat, is still much, much higher than the amount that currently spent on detection, around US$5 million. The amount that we are currently spending on detection and mitigation strategies is currently much less than what is makes sense to fund. It would make sense to spend up to US$60 million/year on a continual, annual basis, purely as a form of insurance.

Perhaps, the most important analysis of the cost of NEO impact is a more intuitive calculation of the cost of a "global killer." Impacts that have killed all higher animals have happened in the past, and they could easily happen again. In this case, the real cost is not the loss of the GDP for some amount of time, but rather the cost is an infinite one: the cost of humanity losing everything for all time. No matter how low the probability of such an event happening, the expected cost is infinite. Although that does not mean that it makes sense to spend all of our productivity looking and preparing to mitigate incoming asteroids, it does mean that it is logical to spend as much as is necessary on detection until we are satisfied that we are currently facing no such imminent threat and enough on mitigation technique development that should such an event be poised to occur, we would be equally poised to do something about it. Given the current low investment in search programs and nearly non-existent funding on mitigation technique development, there is no question that the demand for vital information on the potentially extraordinarily costly NEO threat has not been yet.

2.5 Conclusions and Recommendations

Although the probability of a large impact occurring is low, one cannot afford to be complacent since the probability, though small, is not zero. In order to be able to propose mitigation strategies in case of an imminent NEO impact, we must better understand the structure and composition of these objects and examine the results from recent cometary missions such as Stardust and Deep Impact. Continued efforts must be made to build a catalogue of comets and asteroids, particularly those in near Earth orbit, and to be able to identify dormant comets. There is a need to include all consequences in the economic cost models.

2.6 Cassandra Scenario

Using the scenario outlined in the Introduction of this report, the following additional assumptions are made:

- Comet density: 1 g/cm^3
- Impact velocity: 62.4 km/s

Given the impact probabilities from Figure 2-4, the probability of an impact for a 600 m object is 1 every 250,000 years. As Cassandra is a long-period comet, this makes Earth impact even more unlikely. Using 1% as the percentage of threat resulting from long period comets, the impact probability is 1 every 25,000,000 years (Stokes et al. 2003).

The consequences of an impact depend on its location on the Earth's surface. Taking the example of an impact in the middle of the North Atlantic ocean, which has an average depth of 3 km, the energy released in the impact would be in the order of $3x10^{10}$ Mt. This would excavate a transient crater 12 km in diameter and generate a wave of tsunamis. At a distance of 3000 km, tsunami wave heights of 7 m would impact the coasts of Europe and North America. This would cause widespread devastation to low-lying areas such as Long Island and Delaware in the United States, and countries such as The Netherlands and Denmark in Europe.

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Chapter 3

Detection

This chapter begins with an overall description of the detection process. It then summarizes characteristics of existing and planned detection systems, both ground-based and space-based, including their limitations. The chapter then describes two possible avenues of future research and provides a synthesis of the detection systems with recommendations for improved detection. Finally, all the aspects of detection are applied to the Cassandra comet.

3.1 The Detection Process

The three main steps of the detection process for a high inclination NEO are the initial detection, follow-up monitoring, and characterization of the object. During these steps, large amounts of data must be managed. These processes need to be well coordinated in order to achieve the best results.

3.1.1 Initial Detection

Early detection is a crucial step in mitigation because the greater the time between detection and impact, the more mitigation options will be available. There are several detection options, either existing or planned, and each with its limitations.

Sky Coverage vs Limiting Magnitude

The main limitation for all systems is the trade-off between limiting magnitude and sky coverage. The limiting magnitude of a telescope is the magnitude of brightness of the faintest object it can see. The fainter the object is, the higher its magnitude. This is primarily a characteristic of the telescope aperture, but it can be improved by allowing more time to be spent observing an object. However, the more time spent on one area of the sky, the less area of sky as a whole that can be covered in a certain amount of time.

A minimum coverage of ~200 deg^2/hr is required in order to cover the local sky every month, which was established to be optimal for a NEO survey (Vasilyev 1996). Ideally, a system will cover as much of the sky as possible at a desired magnitude. The magnitude of an object in space can be approximated with calculations based on the object's albedo, size, and distance from the Earth. Figure 3-1 and Figure 3-2 show how these parameters can affect limiting magnitude and also give a sense of scale. Both graphs assume a worst-case angle between the line from the comet to the Earth and the line from the comet to the Sun of 0°. The graphs show that in order to allow the detection of a hazardous high inclination NEO in time to deter a threat, new survey systems should combine a high coverage rate with high magnitude (>24).

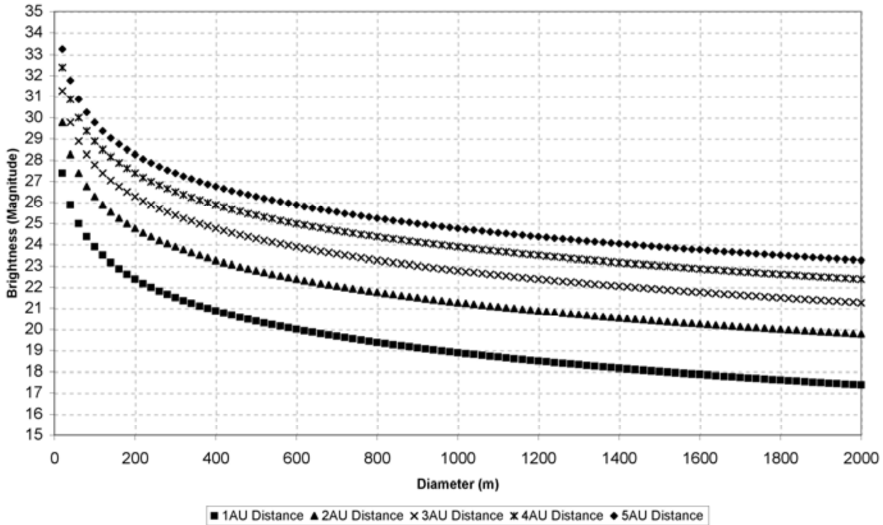


Figure 3-1 Graph of Comet Brightness vs Comet Diameter (10% Albedo)

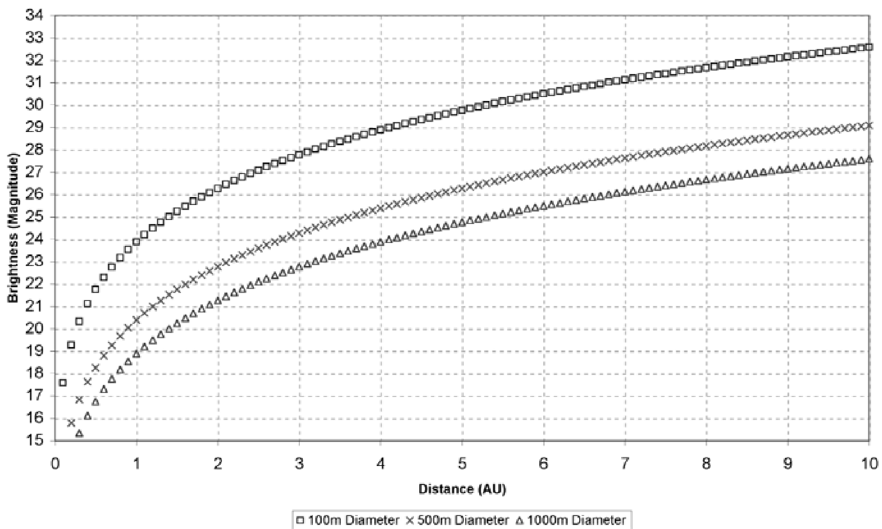


Figure 3-2 Graph of Comet Brightness vs Distance to Earth (10% Albedo)

False Detections

One consequence of looking for faint objects at the limit of magnitude of the telescope is the increasing number of false detections. At present, the countermeasures require costly efforts in terms of operator time. Some systems already use mathematical algorithms to track false detections using correlation within sequences of images (e.g. Sextractor).

Galactic Plane and Star Clutter

Most detection systems avoid searching in the galactic plane where many stars obscure an observer's ability to detect NEOs. This problem is particularly important when looking at a high inclination NEO, if such an object has its orbit within this plane. In this case, current systems would probably be unable to detect it.

3.1.2 Monitoring

Monitoring of the near space environment is carried out by optical telescopes, which are aided by the new Charge-Coupled Device (CCD) imaging revolution. Several programs around the world, both large and small, are currently dedicated to searching the skies for potential impactors. Monitoring also includes the use of computer systems (both software and hardware) that keep track of tens of thousands of asteroids and comets that have been discovered, and search for possible orbital intersections with the Earth. Given their high cost and high global demand, when large telescopes are used, they are often used primarily to find NEOs instead of performing ongoing monitoring and cataloguing. Cataloging requires detection of the same object twice within 7 days and 3 times within 21 days (Stokes et al. 2003).

Monitoring a NEO is necessary for numerous reasons. By monitoring, the number of NEOs that are discovered but then lost as a result of trajectory changes will be reduced. It will also allow for follow-up tracking and observations of cometary behavior. Monitoring will also allow radar imaging of the object in order to understand its characteristics (Hildebrand 2005).

Current Limitations

Monitoring encounters all the previously mentioned limitations that affect the initial detection of a NEO, as well as several more limitations. Technically, monitoring is made difficult by the fact that the NEOs are fast moving objects whose orbits may change because of outgassing. This lack of monitoring leads to the loss of NEO tracking. From an operational standpoint, monitoring is currently limited by the amount of NEOs observation time. The limited number of telescopes detecting NEOs have only minimal time to focus on a discovery, because the telescopes scan the celestial sky rapidly to increase sky coverage. This amount of time is not adequate for orbit determination. The amount of information on newly discovered NEOs is increasing but there is limited human and processing power to cover everything.

3.1.3 Characterization

Once astronomers spot an asteroid or comet in their telescopes, they use radar tracking to determine its orbit and velocity. This allows a determination of whether or not its orbit intersects the Earth's orbit. The fundamental problems associated with potential impactors of the Earth are the assessment of their numbers and impact rates, and their physical and mineralogical characterization.

Very few telescopes are dedicated to NEO characterization. Nevertheless they have proved extremely useful in helping to understand these objects. As the search for ever-fainter objects continues, using telescopes of the size of the Keck Observatory (10 m diameter) located on Mauna Kea, is becoming a necessity.

Knowledge of the NEO physical and mineralogical characteristics, which were discussed in the Assessment Chapter, is essential in crafting a successful mitigation measure. Table 3-1 lists the methods used to examine certain characteristics of NEOs and the limitations of these techniques are provided below.

Table 3-1 NEO Characterization Methods

Characteristics	Method
Identification	Best accuracy: Radar astrometric observations
	Other method: Optical telescope observations
NEO Classification	Photometric data and orbital parameters
Size	Non-comet: By measures of both visible/thermal infrared flux densities using infrared telescopes for example.
	Comet: Radar only possible since very little infrared emissions.
Albedo	See size. Obtained if both visible and thermal properties are known.
Mean-Diameter	Obtained if both visible and thermal properties are known.
	If only visible properties are known, estimate using an albedo based on spectral classification
Rotation (Spin rate)	Light curves: Using repeated observations at a single wavelength
Surface Roughness and Shape	Radar
	Thermal infrared observations (for non-comet type)
Emission of Dust/Gas	Visible telescopes
Surface/Mineralogical Composition	Spectrographs: Spectrophotometric or spectroscopic observations
	Radar: In favorable cases only
NEO Satellites	Occultation, adaptive optics, coronagraphic techniques

Current Limitations

Certain effects limit the process of characterization. The low albedo of comets makes the objects difficult to see and characterization requires greater detail than detecting the object. In fact, most comets can be studied only when they are within one or two AUs, when dust grains warm up. Hale-Bopp was unusually active and could be detected easily in the infrared although it was still far from the Sun. Detecting the finer details is limited by the medium photo resolution caused by CCD's pixel size limitations. There are also difficulties defining the object's velocity/trajectory when the object is headed directly towards the Earth. Characterization creates more data and there are limited personnel to process and analyze it.

3.1.4 Data Management

The large amount of data derived from the initial detection and the characterization and monitoring is processed and shared as valuable information for researchers of the Solar System.

Currently, the Minor Planet Center (MPC) is the main node for data sharing among amateurs, professionals, and official programs. The MPC operates at the Smithsonian Astrophysical Observatory (SAO), which is part of the Center for Astrophysics (CfA) along with the Harvard College Observatory (HCO) in the UK (Minor Planet Center 2005b).

Under the auspices of the International Astronomical Union (IAU), the MPC is the official organization in charge of collecting observational data for newly-discovered minor planets (asteroids) and comets and calculating their orbits (including those that are on orbits that might one day impact the Earth), and publishing this information. It also operates a number of free on-line services for observers to assist them in observing minor planets and comets. The complete catalogue of minor planet orbits (MPCORB) may also be freely downloaded.

The Institute for Theoretical Astronomy in St. Petersburg, Russia, fulfills a complementary function by publishing the ephemerides of minor planets each year, which contain the orbital elements of all numbered asteroids, together with their opposition dates and ephemeredes (Darling 2005 and AI SpbU 1997).

The MPC is funded by a few institutional and individual contributors (50% by NASA). However, the funding is only sufficient to allow the MPC to focus on gathering incoming data, processing it and making the resulting information available. The ability of the MPC to propose and promote new and powerful data management or world strategies (detection program coordination) remains very low.

3.1.5 Coordination

There are few official and/or national programs of NEO detection and characterization. NASA provides the largest percentage through the Near Earth Object Program Office (Jet Propulsion Laboratory, Pasadena, CA) (see Section 3.2.1 on ground-based systems). There are some other programs existing or planned in the UK, Canada, and other countries, but each country is developing its own strategy and program.

The only international coordination program is organized by the Spaceguard Foundation which has involved astronomers, professional or amateurs from all over the world since 1996. The Spaceguard Foundation Home Page (2005) mentions:

"... the Association is therefore an entity eminently oriented within the most general framework of scientific research and shall pursue the following purposes:

- to promote and coordinate activities for the discovery, pursuit (follow-up) and orbital calculation of the NEO at an international level;
- to promote study activities - at theoretical, observational and experimental levels - of the physical-mineralogical characteristics of the minor bodies of the solar system, with particular attention to the NEO;
- to promote and coordinate a ground network (the Spaceguard System), backed up by possible satellite network, for the discovery observations and for astrometric and physical follow-up. …"

The Spaceguard foundation is a good, but very preliminary, base for international coordination of detection and characterization systems. Its influence remains weak, and countries' national programs are not clearly structured according to its recommendations.

3.2 Existing and Planned Detection Systems

3.2.1 An Overview of Ground-based Detection Systems

Ground-based detection systems have played a major role in the history of discovering NEOs. Many of these systems make discoveries using only visible band search telescopes. Despite their limitations in performance caused by the atmosphere, observations from Earth have led to most of the discovered NEOs. More than 90% of the discoveries of NEAs from ground-based systems have been made by five dedicated programs funded by the US (NASA 2005a) as shown in Figure 3-3.

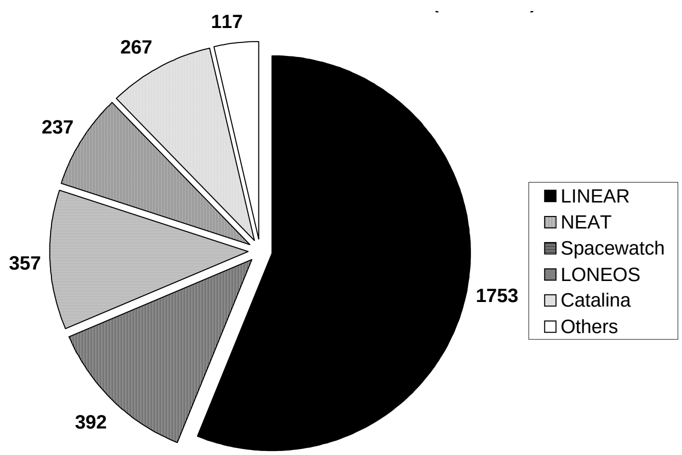


Figure 3-3 Evolution of NEA Discoveries 1995-2005 (NASA, 2005a)

All five systems use basically the same technology: visible band search telescopes connected to CCD digital cameras and high speed computers. Most of them focus their research on finding NEAs close to the ecliptic plane.

This subsection will introduce some existing programs as well as some planned future programs and compare their performance based on their detection characteristics. Some of their limitations will also be examined, particularly in the scope of high inclination NEO research.

Existing and Planned Ground-based Systems

Table 3-2 compares the different ground-based systems with respect to their technical characteristics. Appendix 1 summarizes the primary characteristics of existing and planned ground-based NEO detection systems. The data associated with the different systems have been extracted from the official related websites, Maury (2003), Stokes et al. (2001), or have been estimated (in italics).

Table 3-2 Parameters of Existing and Planned Systems

Name	Dia. (m)	Focal ratio	CCD Size	Pixel Size (μm)	Scale ("/pix)	Angle (deg²)	Exp. Time (s)	Hourly Coverage (deg²/hr)	Limit Mag.
Catalina CSS	0.68	1 .8	4096x4096	15	2.5	8.14	60	366.2	20
Catalina SSS	0.5	3.5	4096x4096	15	1.8	4.06	60	183	20
Catalina MLS	1.5	2.0	4096x4096	15	1.0	1.2	180	*18*	22
LONEOS	0.59	1.91	4096 x4096	13.5	2.5	8.14	45	390	19.3
Spacewatch 1	0.95	3.17	4x2048x4608	13.5	1	2.9	120	43.5	21.7
Spacewatch 2	1.81	2.7	2048x2048	24	1	0.32	150	7.4	23.3
NEAT 1	1.2	2.5	3x4080x4080	15	0.85	3.8	60	308	21
NEAT 2	1.2	1.9	4080x4080	15	1.24	2.5	45	174	19
LINEAR	2x1.0	2.2	2560x1960	24	2.25	1.96	6	1200	20.5
PanSTARRS	4x1.5	4	$1x10^9$	15	0.3	9	30-60	*900*	24
LSST	8.4	1.25	$3x10^9$	10	0.2	10	10-20	*1200*	24

Limitations of Ground-based Systems

Table 3-2 shows the limitations of the current survey systems, none of which combines a relatively high (22-23) limit of magnitude with a sufficient high hourly coverage. In this sense, the currently planned ground-based systems (e.g. PanSTARRS, LSST), using bigger telescopes, high performing CCD detectors, adaptive optics, and powerful data analysis software as well as being located on very appropriate sites, will bring technical improvements. After several sky coverage repetitions performed during sufficient long time period, they should be able to detect objects with magnitude higher than 26. The current systems are mainly restricted to the Northern hemisphere. Unfortunately, the presence of the atmosphere and the restrictions in sky coverage from the presence of the Sun and the Moon are immutable drawbacks of ground-based detection system.

Amateur Astronomers

Amateur astronomers have been the primary source of discoveries since the 18th century. As seen on the following chart (computed from the MPC database (Minor Planet Center 2005b) including all the minor planet discoveries), their contribution has been waning during the last five years. This conclusion is valid for all NEOs (including NECs).

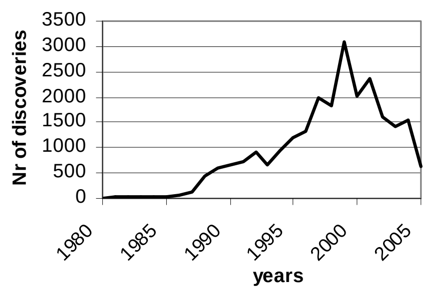


Figure 3-4 Cumulated Minor Planet Discoveries by Amateur Astronomers

The causes of this decrease are mainly technical and linked to cost.

- Amateurs' telescopes are limited to a visual magnitude of 12 to 14.5 (500 mm telescope), roughly 18 if they are equipped with CCD cameras
- Many of the low magnitude NEOs (≤16) which are "easy to detect" have been or are being discovered
- The costs of a 500 mm telescope is roughly US$10,000 and increases exponentially with performance (though costs have been decreasing recently)

For the specific case of high inclination NEOs and comets, amateur astronomers can be an effective and low cost resource to increase the sky and hourly coverage. In this way, they can help to reduce the delay between detection and a possible impact of comets that can come from any part of the sky.

The efficiency of amateur astronomers depends on their coordination and motivation. This could be easily achieved by:

- Harmonization of the hardware and software they use (cooperation by the main manufacturers and developers) in order to receive data in a common format
- By offering prizes for comet discoveries (following the example of the Edgar Wilson Award)

3.2.2 An Overview of Space-based Detection Systems

Despite their complexity and higher costs compared to ground-based telescopes, space-based telescopes have one undisputable advantage: they operate above the Earth's atmosphere. Additionally, most space telescopes are located in Sun Synchronous Orbits (SSO) with solar arrays constantly facing the Sun. Such a location allows continuous operation, which is not possible for Earth-based telescopes limited by duration of the night and Moon phase.

As mentioned by The Spaceguard Home Page (2005) space-based sensors have the following added value over ground-based sensors:

- Are capable of good sensitivity using small telescope apertures
  - For example: A 0.5 m LEO telescope out-performs a 4.0 m ground ground-based telescope in both cataloguing and warning cataloguing
- Can look close to the Sun
- Can be inexpensive if using microsat type satellites
- Create radar-imaging opportunities in daylight sky
- Interrogate "impact keyholes" in daylight sky
- Have continuous availability and higher productivity

The general advantages of space-based telescopes have been proven by the unprecedented results from the Hubble, Spitzer, and Chandra telescopes.

Past, Current, and Future Missions

In recent years, ESA's Giotto, Johns Hopkins University APL's NEAR, and JPL's Deep Impact observed and explored NEAs and comets. Within the next several years, JAXA's Hayabusa mission will bring back samples from the surface of an asteroid, JPL's STARDUST will bring back tail particles of a NEO and ESA's Rosetta will collect information about surface composition of a comet. Recently, with the success of Deep Impact, mission scientists received an enormous amount of information. This information is not only about the surface, but also about the composition of the comet's deeper layers.

Presently, no single space telescope is dedicated exclusively to NEO detection, although a few space-based instruments have discovered asteroids and comets as bonus results of their primary mission objectives. The prominent example is the Solar and Heliospheric Observatory (SOHO) (SOHO 2005), which has been used to discover almost a thousand comets near their perihelion in the vicinity of the Sun.

Future plans of the international space community include the Canadian NEOSSAT mission (Hildebrand et al. 2005) and the European Don Quijote (ESA 2005c). NEOSSAT is a space telescope with a limiting magnitude of 20.5 dedicated to NEA detection. Don Quijote will be the first attempt to alter an asteroid's orbit, which will produce valuable data for future mitigation techniques.

Detailed information about NEO related missions is included in the report by the UK Government Task Force (2000) which has references for each mission.

Existing Systems Reusability

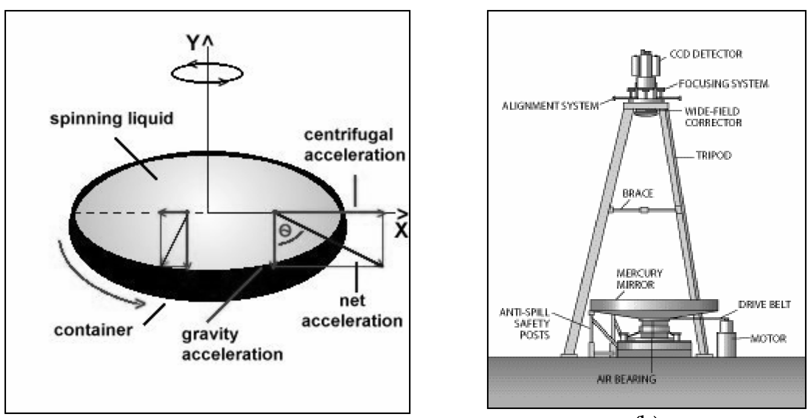
In parallel to the development of specialized detection mission, already existing space-based telescopes might be used for detection of NEOs. Several spacecraft have completed their primary and extended mission objectives. The most recent example is the Deep Impact flyby spacecraft (JPL, 2005a) which completed its mission with "smashing success". NASA sent a request for Mission of Opportunity proposals to utilize the fully operational spacecraft for science research. The High and Medium Resolution Instruments (HRI, MRI) onboard of the spacecraft were designed specifically for the Deep Impact mission requirements, but offer capabilities useful for NEO detection. Specifically, MRIs offer functionality comparable with the NEOSSAT mission (Hildebrand et al. 2005), which has a 12 cm mirror and ~0.06 deg^2 FOV. Such an instrument could be used to survey space in regions not available to Earth-based observatories. The HRI instrument might be used for follow-up observations or parallel observations due to their bigger mirrors that have a narrow FOV.

3.3 Possible Future Research

Numerous possible systems and technologies could be utilized in the future to improve the detection of high inclination NEOs. This subsection discusses several possible ground and space-based systems. These descriptions are not meant to suggest limitation of other avenues of research, but to show specific examples of technologies and systems that are required to improve the current detection situation.

3.3.1 Liquid Mirror Telescopes

Liquid Mirror Telescopes (LMTs) are reflector telescopes with a uniformly rotating liquid mirror, as illustrated in Figure 3-5. This primary mirror is typically created with mercury inside a parabolic frame with a centrifugal acceleration. The parabolic shape of the reflective liquid is typical of a reflecting telescope and helps focus the light to a focal point at which point a CCD camera is placed. This configuration is standard amongst similar hard mirror telescopes (HMTs) of its size and type.



(a) (b)

Figure 3-5 Liquid Mirror Telescopes (a) Concept and (b) Setup

Motivation for the Use of a Liquid Mirror Telescope

Survey telescopes, with their wide viewing angle, are an essential part of a NEO detection system but the detection requirements are very demanding of precious telescope time. The cost of the Keck Telescope was US$183.1 million and the cost per night of usage is US$47,400. The NASA/USAF NEO Search Program's total budget is US$10.5 million over a 3-year period (NASA 1999), which results in a yearly budget of US$3.5 million. This is equivalent to just 73 days of operation time at Keck for all the dedicated NEO detection programs per year.

Furthermore, if the aim is to detect a high inclination NEO at approximately 4 AU from the Earth, it would mean seeing it at a magnitude of 24.9, but Keck has a limiting magnitude just barely reaching that limit on the best of nights. With this in mind, cost itself would be one of the biggest drivers of the use of LMTs for the detection of NEOs.

The practical limitations and advantages of liquid mirror technology have been well studied, as seen in the physical realization of a LMT at the University of British Columbia (UBC). The UBC telescope is one of the top 20 largest telescopes in the world (Hickson et al. 1994).

Use of LMTs for High Inclination NEO Detection

Many variables may be considered in an analysis of a telescope system but this study will primarily focus on aperture size, Field Of View (FOV), CCD camera requirements and Signal to Noise Ratio (SNR) in terms of brightness of the incoming high inclination NEO on the CCD relative to the noise from the sky. Since LMTs are easily compared to hard mirror reflecting telescopes, analysis is similar. The main difference is the fixed nature of the primary mirror of an LMT that will limit the tracking capabilities of the telescope.

Aperture Size

In the analysis of diffraction limited reflector telescope, one of the most important characteristics is the size of the receiving mirror. Looking specifically at detection of high inclination NEOs, the limiting magnitude can be approximated as seen in Figure 3-6 (see the appendix for mathematical details).

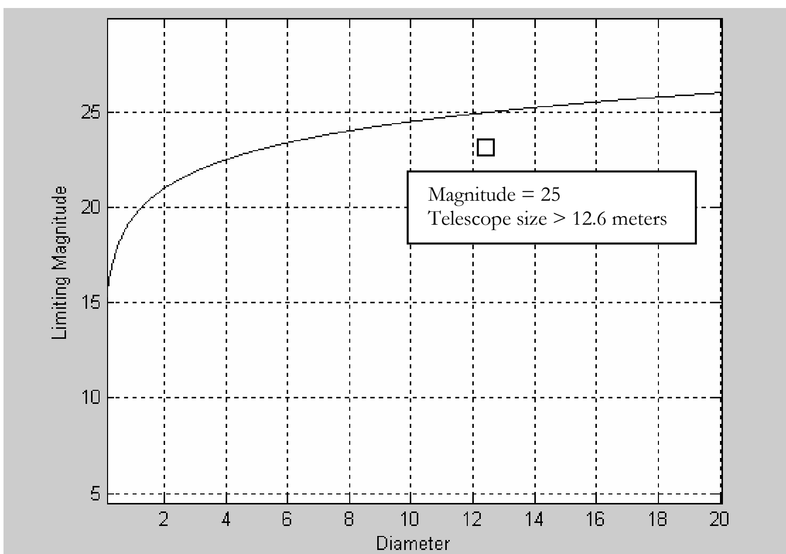


Figure 3-6 Telescope Diameter (m) vs Limiting Magnitude

With the assumption that the required magnitude is 25, a telescope of at least 12.6 meters is required. This is just a first approximation in sizing the telescope primary mirror.

CCD Camera Requirements

With the onset of CCD cameras, the liquid mirror has become possible. LMTs of the past were not able to keep up with the rotation of the stars across the FOV. New processing algorithms such as Time Delay Integration (TDI) are able to drift the potential wells that define the pixels of the CCD, at the same speed as the image of the sky moves in the focal plane of the telescope (Borra 2001). One of the important considerations is the required FOV. The basic equations governing the dynamics of a CCD are available in the appendix.

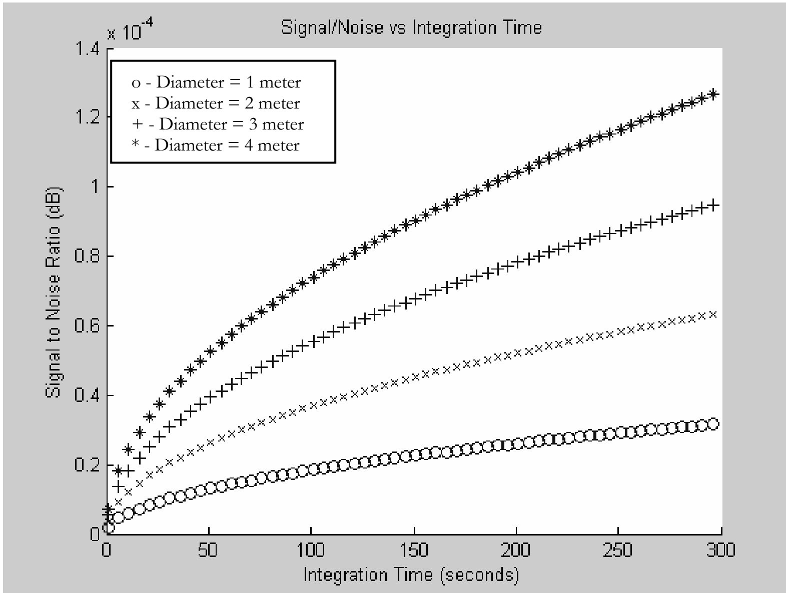


Figure 3-7 Signal to Noise Ratio vs Integration Time

As seen in the above diagram, when dealing with the CCD camera, an important consideration is the integration time. An increase in the integration time makes the Signal to Noise ratio go up, but at the same time, one has to keep in mind that it is logarithmic in nature and to obtain gains on the order of a few dB would require longer and longer integration times.

<u>Signal to Noise Ratio (SNR)</u>
SNR is a critical consideration when dealing with objects with a very faint magnitude. The SNR is defined as the strength of the signal divided by the strength of the noise. The flux of the light from surrounding sky may overshadow that of the image especially if one considers the large field of coverage requirements for NEO detection. This large FOV means that the CCD would detect not only the object of interest, but also the background sky noise.

<u>Additional Considerations</u>
As previously mentioned, one of the marked features of the LMT is its inability to track an object by physically moving the telescope. The movement of stellar objects on the mirror, and specifically high inclination NEOs, is compensated through image processing techniques and utilizing the movement of the Earth for natural tracking of the sky.

Location of any ground-based (Earth or Moon) telescope is an important practical consideration in the design of the telescope. For example, light pollution on Earth is a big factor in determining optimal locations for telescopes.

Proposed Solution I: LMT Earth Network

One of the primary problems with large telescopes today is the relatively small number of nights available for repeated observations. As a consequence, it takes years to gather relatively small amounts of data to reach conclusions that suffer from small number statistics as well as poorly understood systematic effects (Borra 2001). Providing astronomers around the world LMT imagery that could rival the best HMTs in quality could overcome this problem of viewing time. It can also inherently serve as a powerful monitoring tool for achieving the depth of viewing needed for high inclination NEO detection for a fraction of the cost.

As illustrated in Figure 3-8, the implementation of a network of LMTs at various latitudes is proposed to provide cost-effective global coverage for NEO detection, as well as offer possibilities for other astronomical research.

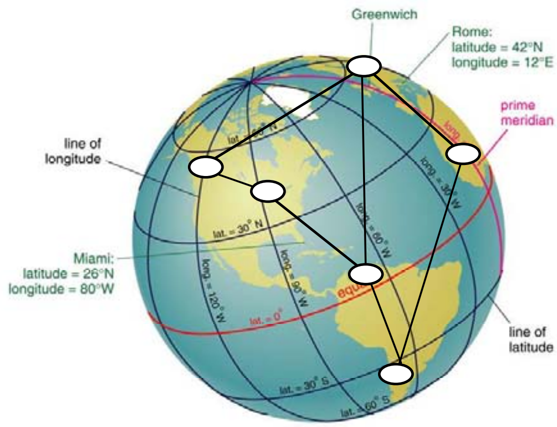


Figure 3-8 International LMT Network Proposal

Proposed Solution II: Lunar-based LMT

Similar to the Earth-based solution, a lunar telescope can provide significant benefits not only as a monitoring tool for high inclination NEO detection, but also for the purpose of deep space astronomy. One of the many advantages of a lunar-based telescope is the high SNR due to the low sky noise associated to the lack of atmosphere. This would make possible the detection of objects much farther away than what is achievable from the Earth, providing more available time in case a threatening object is identified and a mitigation strategy needs to be implemented. Other important considerations include the sidereal rotation of the Moon, which would provide a rotational speed significantly slower than that of the Earth and would provide longer integration times for deeper viewing for NEO detection.

When dealing with an LMT on the Moon, important technical considerations are the presence of dust that can cause contamination of the primary mirror; the choice of a liquid required to be able to survive the cold temperatures of the Moon; the lack of models of background sky noise on the Moon; power requirements; weight constrains imposed by the choice of the launch vehicle; and the choice of the location that would allow to optimize the sky coverage for NEO detection and scientific research.

Proposed Solutions: Summary

Table 3-3 and Table 3-4 summarize the design characteristics of the proposed solutions compared to the existing UBC and Keck telescopes. It is important to note that, for both of the proposed solutions, the limiting visible magnitude has been set to 25. The cost estimates are based on UBC's LMT (cost/meter = CDN$1,000,000/6 = CDN$166,667/meter)

Table 3-3 Technical Parameters for Existing and Proposed Solutions

Telescope	Latitude	D (m)	Focal Ratio	CCD Dimension	Pixel (μm)	Estimated Cost
UBC LMT	14	6	f/1.5	2048x2048	15	CDN$1 million
Keck Telescope	19	10	f/1.75	2048x4096	15	US$183.10 million
LMT Earth Network	30	12.6	f/1.5	2048x2048	15	~ CDN$2.1 million
LMT Moon Solution	45	20	f/1.5	2048 x 2048	15	~ US$3.3 million

Table 3-4 Derived Parameters for Existing and Proposed Solutions

Computed	Pixel ("/pix)	Pixel (°/pix)	FOV ("/exp time)	Exp. Time (s)	Hourly Cov. (arcmin)	SNR	Limiting Magnitude
UBC LMT	0.34	0.0057	11.74	341.99	123.53	6	~20.4
Keck Telescope	0.18	0.0029	12.07	48.65	893.21	6	~24.5
LMT Earth Network	0.16	0.0027	5.59	144.36	139.35	6	~25.0
LMT Moon Solution	0.10	0.0017	3.52	26.71	474.58	6	~26.0

3.3.2 A Specific Space-based Detection System Proposition

The main goal of any proposed detection system is to monitor the sky and transmit the gathered information for further processing to ground stations. The complete system consists of the orbiting spacecraft and the data processing centers on Earth.

The comparison of system cost against percentage of discovered objects suggests that the most effective systems would operate in sun synchronous Low Earth Orbit (LEO) with an optional satellite in orbit around the Sun in Lagrange point L5 at distance of 1 AU. (Stokes et al. 2003)

LEO-based Telescopes

Because constant monitoring of the whole sky is required for a warning system, a minimum of two observing spacecraft should be deployed, with redundant systems where it is possible. Such a configuration would allow high availability of the system, even if two elements fail.

The space elements of the system would have a 10-15 year mission lifetime. It is very important to keep the mission time as long as possible to limit additional costs of spacecraft replacements. Because of the limited lifetime of various spacecraft elements, the first spacecraft would have to be replaced to keep the whole system operational. In the future, new generation spacecraft should be developed and be ready for launch around the time that one of the already orbiting spacecraft reaches it's the end of its operational life. New versions will be cheaper and have better performance than those initially developed.

The two operational LEO spacecraft used for the proposed system could be utilized for observations other than high inclination NEO detection. The proposed solution requires both spacecraft to be fully devoted and regular operations might be disturbed for important observation opportunities.

Optional Telescope in Lagrange Point 4/5

The presence of the Sun limits the sky coverage of telescopes observing space from LEO to an area of ±20º around the Sun. The unobservable area is only ~3% of the whole sky area, but, in very unfortunate conditions, the incoming object can hide behind the Sun for most of its orbit giving short warning time after the discovery. This problem can be overcome by placing an additional spacecraft in stable orbit far away from Earth, preferably in Lagrange point L4 or L5 as shown in Figure 3-9. Having two observatories in different locations around the Sun allows almost complete coverage of space. Additionally, it allows the use of the parallax effect to calculate the trajectory of a discovered object. To limit the amount of data transferred to Earth, especially from distant location like L4, the onboard software will have to pre-process the images, select the interesting ones and compress them before transmission.

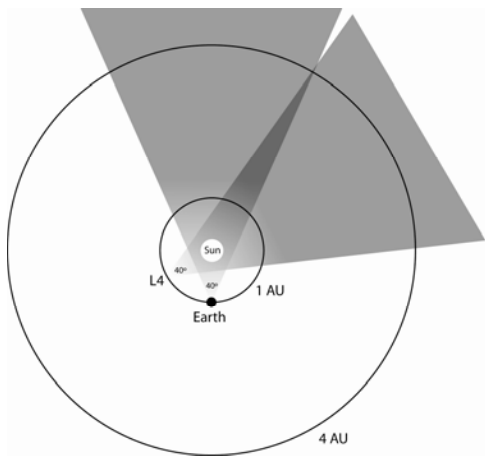


Figure 3-9 FOV Limitations Due to the Sun

The spacecraft can be delivered to LEO and the L4 or L5 point by currently available launch vehicles, like the Delta II rocket, with different number of boosters (Stokes et al. 2003). The spacecraft should have enough propellant to de-orbit or move it into a graveyard orbit after the mission is completed. The proposed telescope and its system elements are described in the appendix.

Future Development

To extend the warning time of an incoming NEO to several years, more powerful telescopes have to be launched and installed in LEO and other orbits. Current solid mirror technology is reaching its limits in size and mass for space applications. Extremely large and heavy telescopes cannot be sent to LEO because of launcher and cost limitations. Therefore, alternative approaches to telescope design have to be considered. The development in light collecting elements needs to be followed by the design of new types of light sensors like CCD and image processing software. The construction of a complete, very precise catalogue of visible space will also increase the NEO discovery ratio.

The next step in space telescope development is represented by the James Webb Space Telescope (JWST). This telescope will use a large 6 m, light, deployable mirror. It will be an infrared telescope with very stringent requirements for the cooling of mirrors and instruments. Versions of such telescopes, working in the visible light range, will be much lighter and cheaper. Stiff, but deployable mirrors, which overcome launch vehicle fairing imitations, could be used in future detection systems.

Deployable surfaces that can be used as antennas or mirrors have already been tested in 1997 on board the Space Shuttle (L'Garde 2005). The first test was partially successful and future development and correction of discovered flows should be carried out. The development of an inflatable, accurate mirror will require serious investment, but this might be one of the ways to control costs of creating large space telescopes.

The future breakthrough technology of large mirror (~25 m) development was recently presented at the 2004 Planetary Defense Conference (The Aerospace Corporation 2005) and was suggested as a solution to the problems with early detection of long period comets. The idea is based on a structure-less piezoelectric adaptive membrane launched into orbit folded and would be unfolded and shaped by a scanning electron beam. The whole system would consist of free flying elements: an electron beam instrument, membrane mirror, and a secondary mirror with detector. The system design is still in the conceptual phase, but within the next ten years, and with technology development, it might become ready for implementation. A telescope with a 25 m mirror would be able to detect comets as far away as 12 AU, giving 6 years warning time.

3.4 Conclusions and Recommendations

After the detailed description of existing, planned, and future detection and monitoring systems, this section compares these systems based on the main performance parameters and proposes recommendations. This chapter concludes by examining the timeline of the detection of the Cassandra Comet. Table 3-5 gathers the main detection and characterization systems for comparison.

Table 3-5 Detection and Monitoring System Comparison

System	Limiting Magnitude	Hourly Coverage (deg^2/hr)	Implementation/ Operational Cost	Status and Mission - Comments
LINEAR	19	1200	0 / +	Ground-based Detection dedicated Operational
NEAT (x2)	21 / 19	308 / 174		
LONEOS	19.3	390		
Spacewatch (x2)	21.7 / 23.3	43.5 / -		
Catalina (x3)	22	366 / 83 / 18		
Amateurs	14	good potential	≈ 0	Operational – to be coordinated
NEOSAT	20.5	295	++ / --	Space based – Detection dedicated – planned for the end of 2008
PanSTARRS	24	900	++ / +	Planned ground based Detection dedicated Looking for funding
LSST	24	1200	++ / +	
LMT Earth-based (per unit)	25 (expected)	Depends on the system	-- / +	Proposal – detection dedicated – Can be a network composed of several units
LMT Moon-based (per unit)	25 (expected)	Depends on the system	+++/++	
Worldwide Observatories	16-18	High potential (>280 units))	--/-	Available – Proposal: Part of their time to be dedicated for NEOs detection and monitoring
LEO (x2) + L4 or L5 telescope	25	500	++/+	Space based proposal Dedicated to detection and monitoring
		300	+++/++	

The limiting magnitude of current systems remains limited to approximately 19-20, though a few systems reach higher magnitude. The overall hourly sky coverage remains very low at these higher magnitudes, limiting detection efficiency as seen in Figure 3-10. As a consequence, there is a shortfall in the detection of high magnitude NEOs for efficient protection of the Earth.

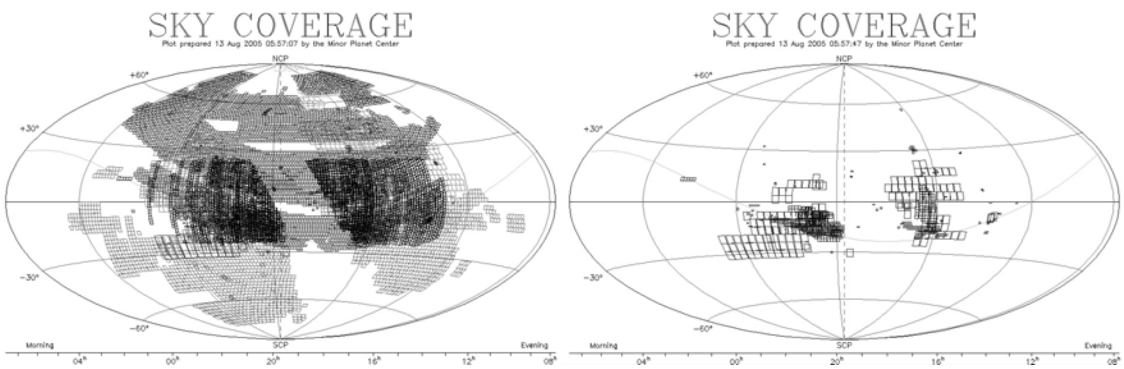


Figure 3-10 Sky Coverage: Magnitude 18 (Left) Magnitude 20 (Right) (MPC, 2005a)

Future planned systems, such as PanSTARRS and LSST will improve the situation, but they are still searching for funding and their costs remain high. Coordination of amateur astronomers could increase sky coverage at lower magnitudes, while the proposed ground-based LMT could increase high magnitude coverage. As a more accessible technology, the LMT could be selected by various countries, including in the Southern Hemisphere, for their contribution to the Earth protection strategy. Additionally, the space-based proposal can strongly improve both magnitude and sky coverage with the advantage of operating continuously above the effects of the atmosphere. However, this solution remains expensive. Other existing missions or spacecraft (such as SOHO, Spitzer, SWIFT and GAIA) could be used for NEO detection after the completion of their original missions. Future science missions or spacecraft could even be designed as dual use for relatively low additional cost. The problem of false detection, especially for high magnitude detection systems, has still to be worked out through technological improvements including software development.

Based on the previous conclusions, this report recommends:

- To institute measures to motivate and coordinate astronomers, both amateurs and professionals, to increase the efficiency for detecting and monitoring high inclination NEOs
- To increase funding to the MPC and Spaceguard Foundation and to extend their mission to focus on coordination of detection and monitoring systems, improve software, and initiate system studies
- To promote the use of current and future spacecraft, that have completed their primary mission, in detecting and/or tracking NEOs
- To promote new methods, including software and modeling developments, to reduce false detections
- To promote the development of high magnitude detection systems in order to increase the time available between the detection and a possible impact of a high inclination NEO
- To promote international cooperation in order to share the costs and optimize worldwide capabilities
- To develop Southern Hemisphere-based detection systems to increase overall sky coverage
- To utilize observatories that focus on other scientific mission by devoting a small percentage of each telescopes' time to NEO detection and tracking.

3.5 The Cassandra Scenario

A comet was found and identified as a high likelihood of collision with the Earth within 240 days.

Additional assumptions include:

- At the date of the Cassandra Comet event, future planned systems are in operation (LSST, PanStarrs, NEOSSat), allowing detection up to a visible limiting magnitude of 24-25
- Comet is spherical in shape
- Comet is fluorescing purely on the reflected and absorbed flux from the Sun
- Comet interaction with solar wind is minimal and thus it does not have a plasma tail
- Comet is not close enough to the Sun to be radiating significantly in the infrared region

Based on these assumptions and the orbital parameters of Cassandra, it is possible to graph the brightness of the comet against the time to impact as shown below in Figure 3-11.

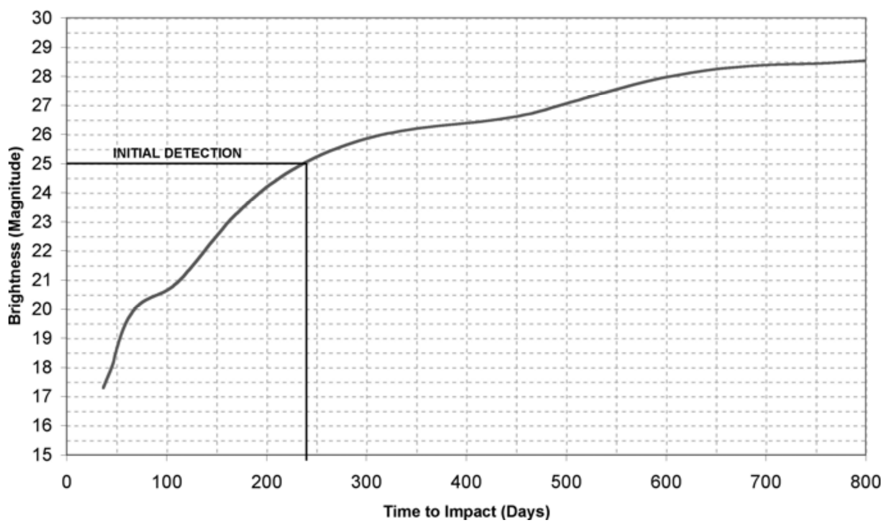


Figure 3-11 Graph of Brightness vs Time to Impact for the Cassandra Comet

Based on the limiting magnitude of the LSST and the above graph, Cassandra would be initially detected 240 days prior to a possible impact with the Earth at a distance of roughly 4 AU. If the comet was not occluded by the Sun, it would be visible by amateur astronomers within approximately 60 days of impact. It would become visible with the naked eye only a few days prior its collision with the Earth.

From the moment it is detected, astronomers would begin characterization and monitoring in order to specify and/or enhance measurements of: NEO class and identification, size and shape, albedo, average diameter, spin rate, surface roughness, emission of dust, etc. They would use available techniques such as photometry and spectroscopy using radar, optical and infrared telescopes. Within three to seven days, the calculations will show more precisely that the orbit of the comet presents a distinct threat to the Earth. Ongoing monitoring of the comet is required until the last minute as different effects, such as comet outgassing and comet break-up, could alter the comet's orbit. This could change the likelihood of a hit or alter the mitigation strategy.

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Chapter 4
Mitigation

After a threatening NEO has been detected, a mitigation strategy must be implemented to avert the threat. Two approaches are possible: deflect the incoming object, by changing its orbit, or disrupt it, by fragmenting it into pieces too small to pose a significant threat. Within these two strategies, various methods may be used.

This section provides an analysis of the deflection and disruption strategies, followed by a description and comparison of the different approaches. After the baseline method is selected, a sample mission design based on the Cassandra scenario is studied in its technical and operational aspects.

4.1 Deflection

Deflection methods rely on changing an object's orbital motion so that a threatening NEO and the Earth are no longer in the same absolute position at the same time. This is done by changing the object's orbital velocity vector with a velocity impulse (ΔV). If the impulse is large enough, the consequent change in the orbit results in the NEO missing the Earth. Since the energy to be used in the process depends upon the magnitude of the ΔV (as will be shown in the next section) and the mass of the NEO, there are definite limits to the applicability of this strategy: as soon as the object becomes too large, a deflection strategy starts to be impractical.

4.1.1 Deflection Mechanics

To deflect an object in orbit, a ΔV is needed. Once the velocity change is applied, the six Keplerian elements (a, the semimajor axis; e, the eccentricity; i, the inclination, ω, the argument of perihelion; Ω, the longitude of the ascending node and θ, the true anomaly) change and the orbit is altered.

A generic velocity change can be broken into three components, any of which has a specific effect on the orbital elements, as illustrated in Table 4-1.

Table 4-1 Effects of Different Types of ΔV on the Orbital Motion of a NEO

Orientation	Effect
Parallel	Semimajor axis (a), eccentricity (e), and argument of periapsis (ω) change
Radial	Semimajor axis (a), eccentricity (e), inclination (i) and argument of periapsis (ω) change
Out of plane	Inclination (i) changes

A compound impulse will change all six orbital elements. The ensuing displacement from the original motion consists of an oscillatory component and a secular drift growing with each successive orbit. The latter is the basis for the deflection of a NEO, applied years before the impact.

Determination of ΔV

The calculation of the orbit perturbations, as a result of the application of a ΔV at a certain position in space, can be accomplished through the procedure illustrated in Figure 4-1. The method has a few fundamental assumptions:

- All orbits considered are elliptical; parabolic (e=1) or hyperbolic (e>1) orbits invalidate the method
- Earth has a circular orbit around the Sun
- The centers of Cassandra and Earth coincide on June 20, 2015
- A minimum miss distance of 14000 km (two Earth radii plus margin) is assumed

It is further assumed that the Keplerian elements of the NEO are given or defined. The Cassandra scenario specifies some of the orbital parameters (*a*, *e* and *i*); the remaining ones (Ω, ω and θ at time of impact) are determined by the crossing of Earth's and Cassandra's orbits.

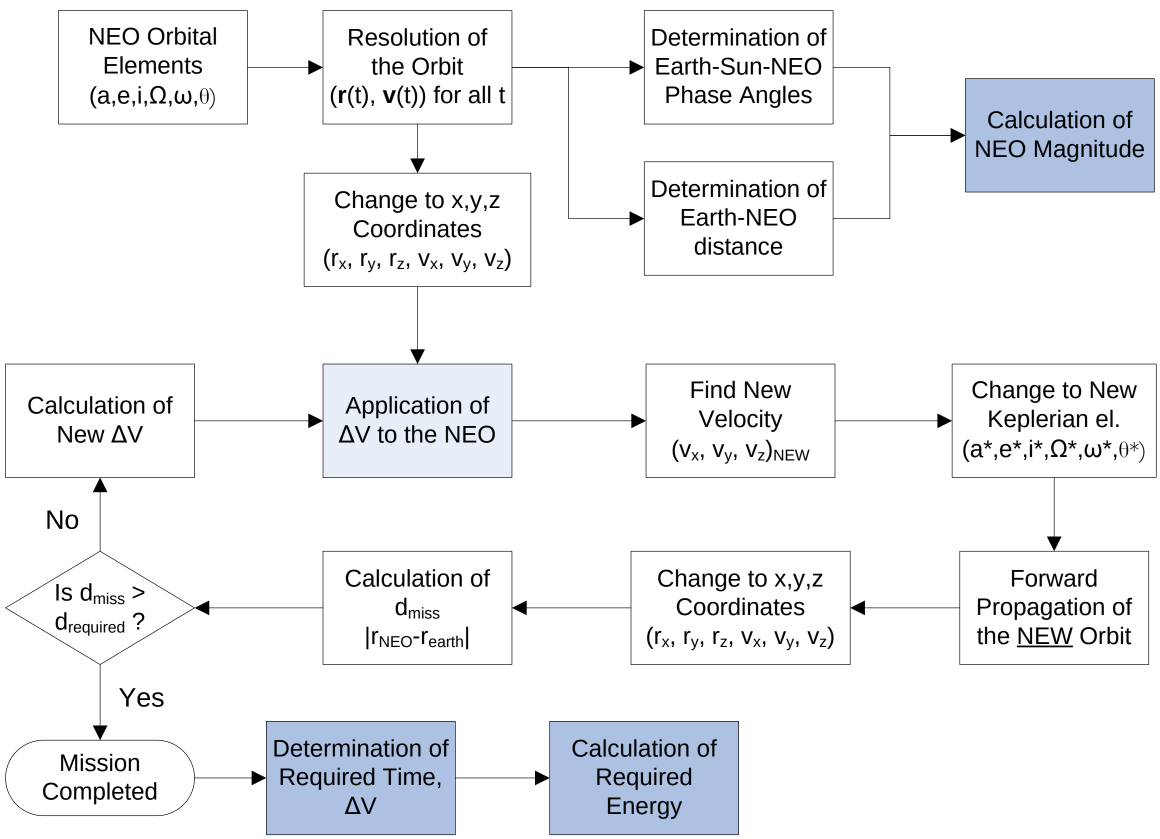

Figure 4-1 Orbit Analysis Procedure Flowchart

The first step of the analysis is the orbit resolution, to determine position and velocity of the object at any given time. The use of the Lambert's equation, which provides a relation between two positions of a planet in an elliptical orbit and the time necessary to traverse them, allows the problem to be solved (Weisstein 2005a). The additional calculation of Earth's position can be used to calculate distances and phase angles (necessary to calculate the visual magnitudes and occlusion angles).

The next step is the transformation of the coordinates into a Cartesian reference frame (Chobotov 2002, pp 62-65), to obtain a precise position vector at any time along the NEO orbit; time that can be expressed as t_{EI} or time before Earth Impact (EI).

By applying a generic ΔV to the velocity vector, we obtain the new velocity in Cartesian coordinates that we can transform to Keplerian elements and use to derive the new orbit (Chobotov 2002, pp. 66). For each one of the new orbits (one for every hypothetical deflection point) we can use a modified Laguerre polynomial method to solve Kepler's equation (Chobotov 2002, pp. 40-55) and propagate the orbit for a time t_{EI} (if no deflection was applied, at that time there would have been an impact).

We repeat the change to Cartesian coordinates and calculate the distance between Cassandra and Earth. If the value is acceptable, we have a successful deflection. If not, we change the ΔV and repeat the procedure. Some of the details and the references of the procedure are in the Appendix.

Each of the different possible maneuvers has a slightly different effect on the deflection distance of the NEO. Figure 4-2 shows the deflection distance as a function of the different orientation of the ΔV.

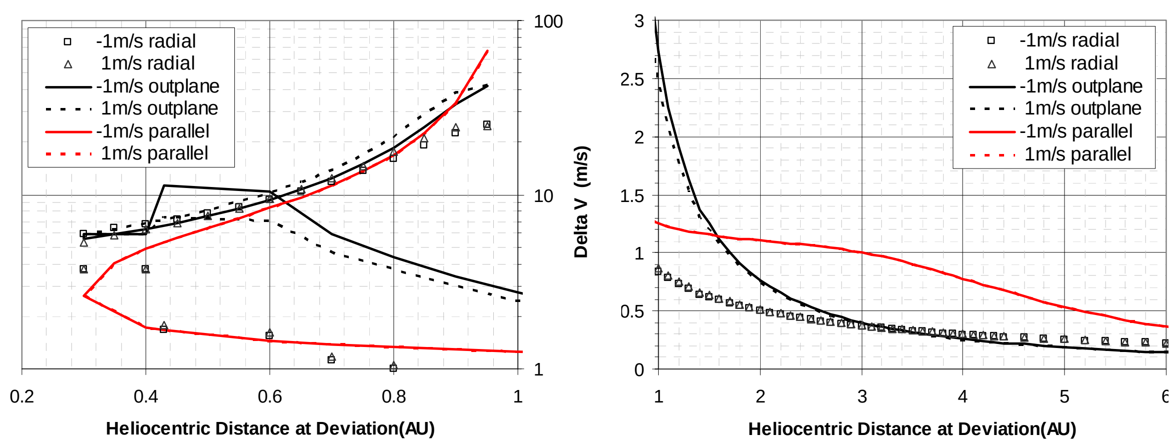

Figure 4-2 Deflection ΔV, as a Function of Different Orientations of the Impulse

It can be seen in Figure 4-2 that a ΔV aligned with the velocity vector is the most efficient way to operate only in a short range of distances at less than 0.7 AU from the Sun. At greater distances from the Sun (on the left of the figure), a radial or even an out-of-plane ΔV has a far better efficiency. In the region between 2 and 4 AU, the ratio is more than two.

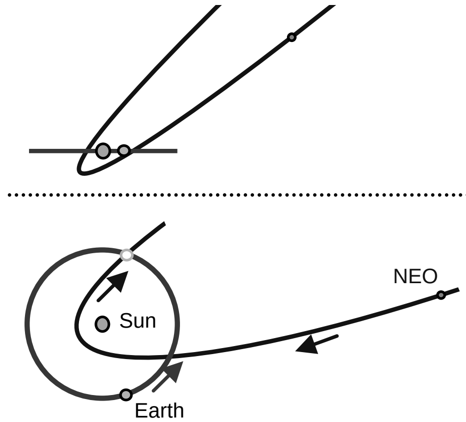

Figure 4-3 Orbits of the Cassandra Comet and Earth

4.1.2 Application to the Cassandra Scenario

The orbital parameters and mass of the Cassandra comet, as defined in the previous chapters, have been used to calculate the energies needed for a proper deflection. As a by product, the method can create information over the relative position and orientation of the Earth, the Sun and the comet. Figure 4-4 for example can be used to calculate the visual magnitude of the incoming body and the occultation periods: for a -20° - +20° Sun-comet angle, the occultation period would last from 50 to 30 days before impact.

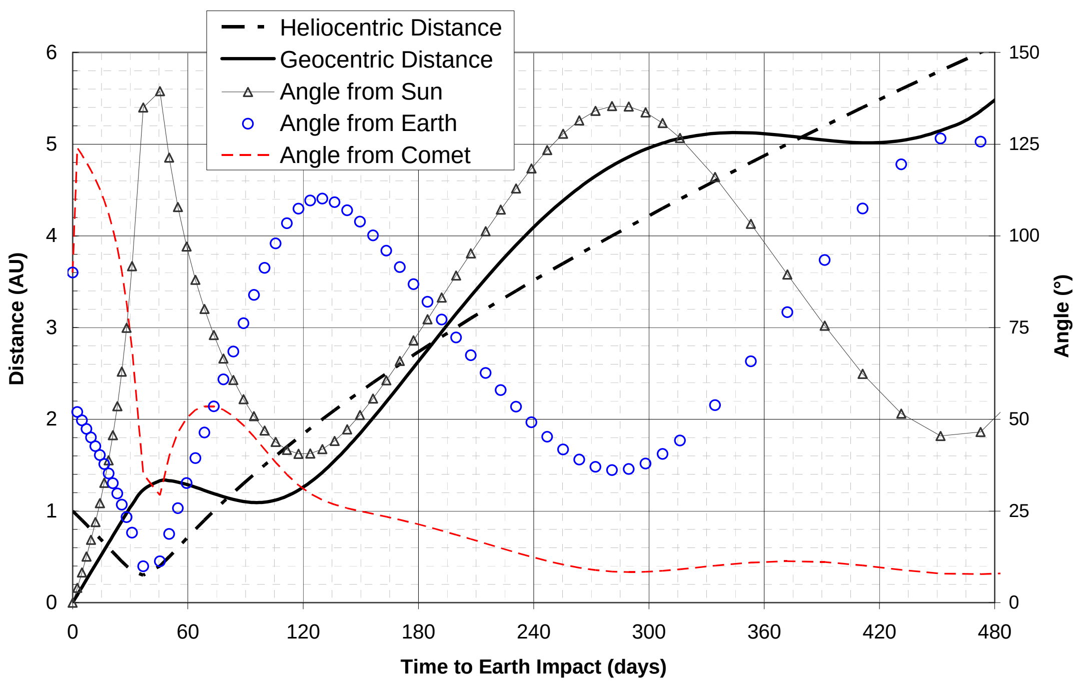

Figure 4-4 Positions and Angles of the Cassandra Comet with Respect to Earth and Sun

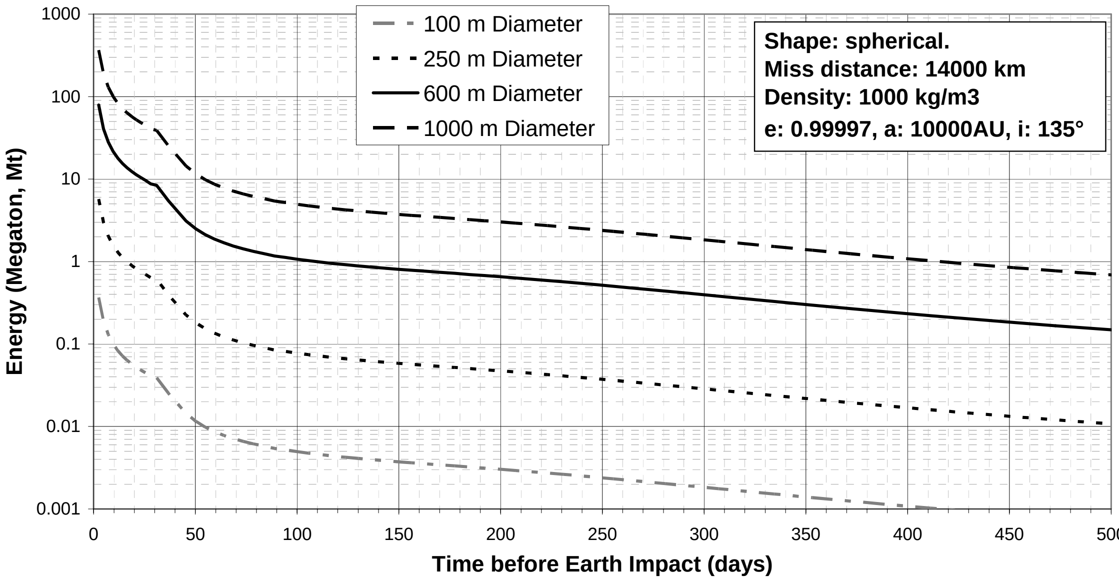

Figure 4-5 Minimum Deflection Energy vs Time before Earth Impact

As it can be seen in Figure 4-5, the deflection ΔV is heavily dependent on the time available. The farther away from Earth a mitigation action is implemented, the more time there is for the orbit perturbation to have an effect and thus less ΔV is required. However, since the energy depends on the original velocity, and a far away object is slower than a close one, required energy decreases substantially with distance.

As evident from the graph, for a long-term response time, the energy is relatively low. However, as the time allocated for mitigation response reduces, the energy increases significantly. It becomes fairly difficult, if not impossible, to deflect an incoming NEO when the time goes below certain values. It should be noted that the values of energy presented in Figure 4-5 are for the kinetic energy delivered to the object. For the time being, no assumptions are made on how this energy is transmitted.

4.1.3 Feasibility of the Strategy

While most of the methods for mitigation are inherently complex, deflection represents perhaps one of the most challenging methods for implementation. Most of the methods currently available for deflection rely on technologies that are still fairly primitive. Options such as solar-induced effects using solar sails, tugging the NEO using a high performance engine like the Variable-Specific-Impulse Magnetoplasma Rocket (VASMIR), and using mirror or laser systems to cause thermal ablative effects all utilize technologies that have not yet even been demonstrated in basic space applications. It is recommended that efforts be focused on developing the technologies that can be used for mitigation applications instead of primarily focusing on developing feasible mitigation strategies alone. This approach will provide a more practical framework for further developments and may gain further acceptance by the general public, especially if funds are allocated to research that may also have broad applications in other areas.

The high inclination of the Cassandra comet poses a difficult challenge for any type of deflection strategy because of the plane change that is required by an intercepting spacecraft. This limits the available launch window and presents an astrodynamics challenge in providing enough energy to perform the necessary plane change maneuvers to rendezvous with the NEO object. It may be possible to perform a gravity assist maneuver to provide the required plane change, but considering the short response time for such objects, it is not a realistic option.

Deflection of high inclination comets may prove to be unfeasible regardless of the situation. An adequate strategy takes significant time to implement (perhaps on the order of 1-2 years), which may not be enough time for a successful response. In reality, deflection is perhaps more suited to asteroids than comets, since most asteroids can be detected far in advance and have more accessible orbits, allowing for more numerous and easier mitigation opportunities.

Any long term plan for developing deflection capabilities requires several demonstration missions to prove that such a method is feasible. For the risk inherent in a potential comet impact, utilizing a technique which is untested and unproven presents an unacceptable risk. Missions such as NASA's Deep Impact and the proposed ESA Don Quijote mission form a good basis for furthering knowledge of mitigation strategies and their effectiveness, but more missions and technology demonstrations are required to ensure that the problem is well understood.

4.2 Disruption

4.2.1 Disruption Mechanisms

Instead of moving the NEO, an alternative way to reduce impact damages to the Earth is to disrupt it. In this context, "disruption" means a violent injection of energy into the mass of the incoming body that results in its fragmentation into smaller pieces. The disruption or dispersion of an object by an impact is generally measured by the amount of energy injected, averaged over the entire mass of the object. When an object is accelerated by a very brief impulse, energy is transferred into the object by a shock wave. The analysis of these methods relies primarily on the data and estimates accumulated for cratering and disrupting of terrestrial materials, which varies with its composition and mass. Porosity also has a marked effect on some of these methods (Gennery 2004). If the object is dispersed, the velocity of the center of mass of the fragments follows the conservation of momentum principle. Ideally, the fragments should disperse widely and at a lower speed than the escape velocity of the original object. Figure 4-6 show the worst case possible for a three-dimensional Gaussian distribution of the fragments, which was computed by integrating over the area of a circle represented by the projected outline of the Earth. The center of the distribution is represented by the cross and is situated at three Earth radii from the center of the Earth (which is outlined by the circle). Ideally, the fragments would be small enough to burn up and disintegrate in the atmosphere becoming then harmless.

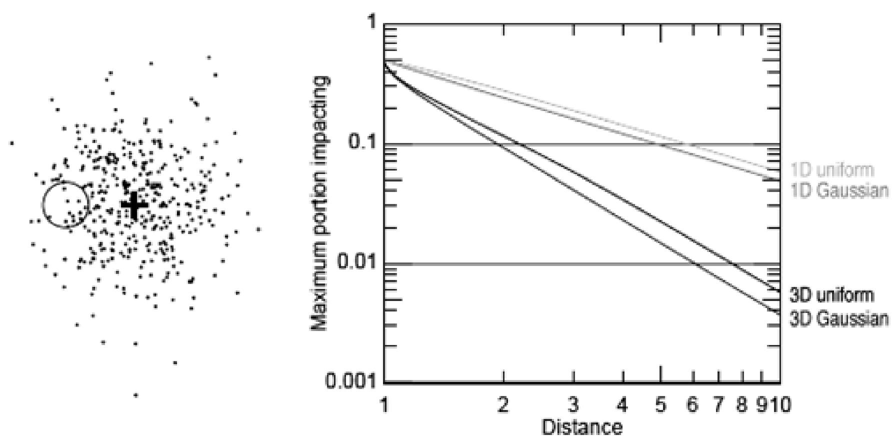

Figure 4-6 Distribution of Fragments Impacting Earth vs Amplitude (Gennery 2004)

Gennery (2004) developed analytical expressions of 3D and 1D distributions to determine the maximum portion of fragments η expected to hit Earth as a function of the distance *s,* in Earth radii.

For the various distributions the results are shown in Figure 4-6 on the right, while the equation applicable for the 3D distribution is shown below:

$$\eta = \frac{1}{e \cdot s^2} \qquad s >> 1$$

If enough energy is used, a complete annihilation can be assumed (by pulverization or vaporization). For a reduced level of energy the separated fragments will retain a significant fraction of the mass of the body. A disruption can be considered successful either when the greatest fragment cannot survive Earth atmospheric entry (no impact) or when the fragments are so dispersed that none of them impact Earth.

Because of the unknown nature of the internal structure of comets, only general assumptions on the amount of energy that keeps a body together (binding energy) can be made. If the target body has a feeble internal structure (rubble pile or dirty snowball models), only gravity keeps it together. In other terms, to subtract mass from the body, particles from its surface must be accelerated to the escape velocity. The energy needed is then given by the kinetic energy of all the particles present in the NEO. Since escape velocity depends only on characteristics we know, we can calculate the gravitational binding energy. Comparing this energy (constant at any distance) with the energy needed to deflect the object from its orbit (see section 4.1.2), it is possible to establish the distance at which disruption is more convenient than deflection, for a given mass. The result, shown in Figure 4-7, is clear: for small objects, considering that they are very difficult to detect (and then will be detected late), disruption is by far the best choice.

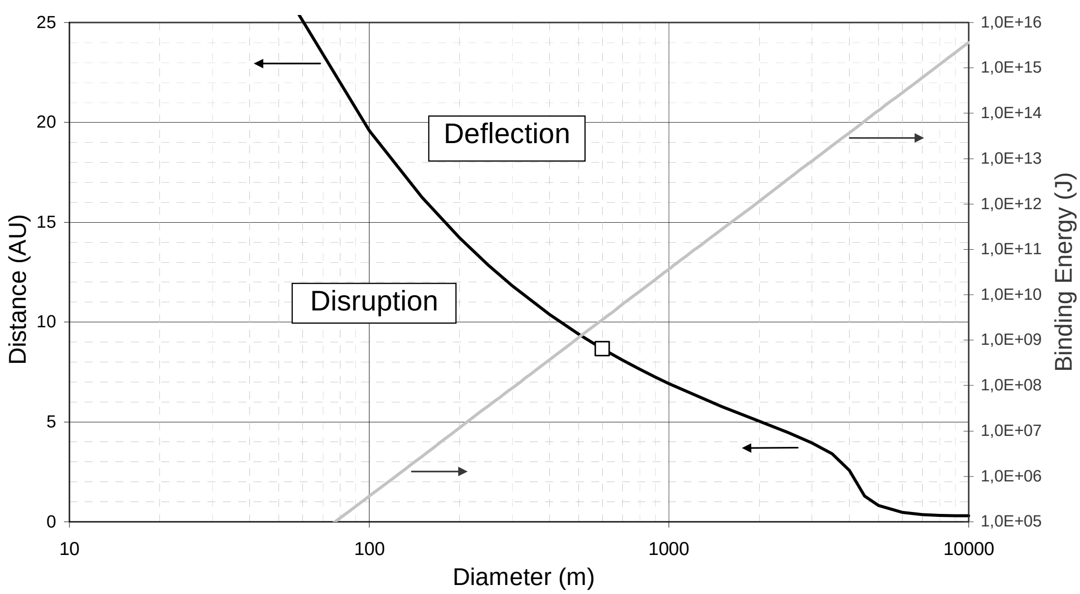

Figure 4-7 Heliocentric Distance where NEO Escape Velocity Equals Deflection ΔV

The results in Figure 4-7 are no longer valid if the NEO internal structure is more cohesive than a rubble pile type. For differentiated asteroids made of solid rock or metals, the required disruption energy might be increased by several orders of magnitude.

Two major methods are available for NEO disruption: kinetic energy and nuclear explosives. The first method, which technologically is the simplest one, relies on the energy transmitted to the NEO by colliding it with a projectile. The impacting process results in an ejection of crater material (Ahrens et al. 1992). The second one relies purely on the energy from the explosion of a nuclear device to cause stresses and mass ejections in the comet and to break it.

4.2.2 Disruption Considerations

The purpose of disruption is not to modify the trajectory parameters of the NEO, but rather to fracture the NEO. The amount of material that reaches the atmosphere from an object that is pulverized and dispersed is comparable to the amount of material thrown out during the eruption of medium sized volcano, and the average density of particles flow is around 10^{-7} to 10^{-6} g/cm^3, if the explosion takes place at a distance of about 0.01 AU [Simonenko et al., 1994].

Disrupting the NEO into multiple fragments is an issue for concern since the fragments could still be on collision course with the Earth and cause widespread regional damage ("buckshot effect"). Also, these fragments will likely be surrounded by a cloud of smaller fragments, which will make it more difficult for a second spacecraft to move near enough to place another explosive. Additionally, there is no guarantee the resulting fragments would be small enough to be harmless. Even if these fragments have a higher probability to burn up when entering the Earth's atmosphere, they can be large enough to cause damage. It is noted that objects smaller than 270 m pose little threat because they burn up in the Earth's atmosphere (see section 2.2.1). Moreover, multiple smaller impacts causing local or regional damage may prove to be less destructive than a single global disaster.

It should not be ignored that, even when there is no damage on the surface of the Earth, extreme damage (at very high cost) could be caused to space-based assets.

4.3 Methods Description, Analysis, and Selection

4.3.1 Description of Mitigation Methods

This section will describe eight mitigation methods, which vary in technical, social, and international feasibility. They differ in the amount of research and development time required because of the diverse complexity of the technology. Each mitigation method will be better suited for different scenarios, though few are suitable for high inclination NEOs. These differences are summarized in a trade matrix at the end of this section.

Tugboat Method

The tugboat method requires a spacecraft to land on a NEO, be attached to it and use its onboard propulsion to change its orbit. As a result the NEO misses the Earth. This method requires major technological advancements in three areas: propulsion, power and attachment system. For propulsion, the Variable-Specific-Impulse Magnetoplasma Rocket (VASIMR) engine is under study at NASA and has the potential to provide varying levels of thrust and specific impulse. It operates by using magnetic fields to accelerate ionized gas or plasma to extremely high exhaust velocities (Wikipedia 2005b). VASIMR can operate in a high thrust, low specific impulse mode, or a low-thrust, high-specific impulse mode. This method also requires further development of nuclear power in order to meet the demands of the propulsion system and the length of the mission. Nuclear reactors like the SAFE-100 could provide the necessary power (Ring et al. 2002). Lastly, a system to attach the spacecraft to the NEO needs to be developed. The attachment system needs to take into account the uncertainties in the structure of comets and asteroids and also the potential rotation of the body.

One of the advantages of this method is the direct control over the direction of the NEO as it is deflected. Another is that if the NEO is a fragmented body that is loosely held together, then the long-term application of low thrust will not affect its structural integrity. This is especially true if the attachment system is designed to be as wide as possible to maximize the force distribution (Schweickart et al. 2003). The disadvantage of this method is that the NEO needs to be detected approximately ten years in advance. Since this method is low thrust, the time required to change the NEOs velocity is significant and not suitable for high inclination bodies.

Kinetic Energy Impact

Kinetic energy systems rely on the energy liberated by the impact between the target NEO and a projectile traveling at a high velocity (see Figure 4-8b for an artist's impression of the concept). The impact of the projectile on the surface of the body delivers a ΔV that alters the NEO's trajectory. A recent example is the Deep Impact mission that used a projectile to cause small and localized damage to comet Tempel-1. It should be noted that this small impact was not designed to substantially alter the comet orbit, but a significant amount of scientific data on the composition and structure of the comet has been produced, providing invaluable background information to understand the feasibility of such an operation as a deflection method. This method is also the basis for ESA's Don Quijote mission that aims to provide the missing link between threat identification and threat mitigation by demonstrating the ability of altering the orbit of an asteroid (NEOMAP 2004).

The main advantage of this method is that there is only local damage to the NEO, and no fragments should be produced. The main disadvantage of this method is that it requires a large projectile mass and/or high projectile velocity to provide sufficient energy. This is a concern because of launch mass limitations. In addition, for this mitigation method, a new generation of heavy-lift launch vehicles may be required because of the heavy mass needed to impart enough energy. Due to the high response time, this method is not suitable for high inclination NEOs

.

Mirror and Laser Systems

The mirror and laser deflection strategies are similar. Both rely on the vaporization of surface material from the comet to create multiple jets of gas, which, given enough time, cause the NEO orbit to change, in a way similar to the effect that the Sun has on comets once they are near it. To direct energy toward the NEO surface either a parabolic mirror can be used (mirror strategy), to concentrate the rays of the Sun, or a pulsed laser can be used, to direct energy in a more precise way (see Figure 4-8d for an artist's impression).

This mitigation method is relatively complex. Especially for an Earth-based laser, major technological advancements are needed in order to create a beam strong and accurate enough to reach an object several AU away. A space-based laser would have to be compact and lightweight. In the case of the mirror, a precise attitude control system and a big deployable mirror would be necessary. This method has the advantage of being very flexible. Multiple mirrors and lasers can be set up in a variety of locations. One of the disadvantages of this method is that it cannot be used on a rotating NEO because the energy always needs to be concentrated on the same surface area. In addition, considerable time is required to complete the mission, and therefore, this method is not suitable for high inclination NEOs.

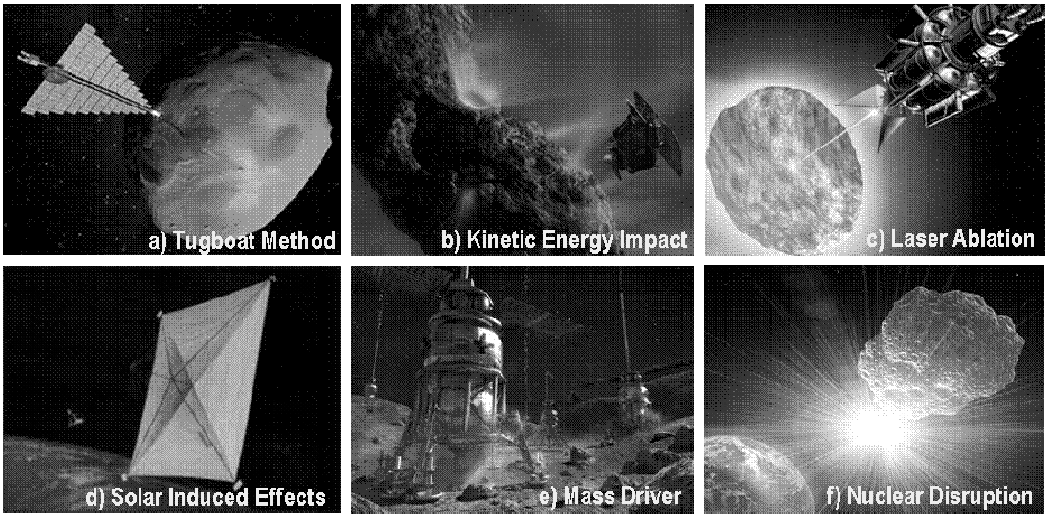

Figure 4-8 Artist's Depictions of Six Different Mitigation Methods

Solar Induced Effects

The Solar Induced Effects method relies on a solar sail attached to the NEO that use pressure from the solar radiation to push the NEO into a different orbit (see Figure 4-8e for an artist's impression). The solar sail would have to be a reflective material on the order of tens of kilometers wide in order to provide the necessary thrust to move a NEO from its original orbit. A deployable structure of that size would have to be developed. The sail would also have to be steerable in order to harness the solar radiation. In addition, an attachment system capable of handling the long-term stress would have to be developed. A functionally analogous alternative to the sail is a giant silvery balloon, which is thought to be easier to deploy than a sail (Gritzner 2001). The solar sail has the advantage that it is a nondestructive method to eliminate the threat. The disadvantage is that the successful development of deployable structure of this size is a serious technological and economic barrier. In addition, since this method is low thrust, more time is needed to move the NEO. As in the case of the tugboat method, the NEO would have to be discovered approximately ten years in advance.

Yarkovsky Effect

The Yarkovsky effect results from the fact that the Sun heats a celestial body's surface during the day and then the body cools off during the night. This causes the body to emit more heat from its afternoon side, creating a thermal radiation imbalance that produces a small acceleration. Applied over very long periods, the acceleration can have a sizeable effect (NASA 2003). The strength of the shift depends on the thermal and rotational properties of the object. This effect could be implemented by changing the thermal absorption properties of the object to enhance thermal radiation, thus allowing the emitted radiation to change the object's orbit slowly and gradually (Wikipedia 2005a). The method is not applicable to non-rotating bodies. Since the characteristics of an incoming object will be known very late, this method cannot be taken into consideration.

Mass Drivers

Setting up mass drivers on the NEO is possible using a variety of architectures. The most popular architecture is the "swarm" architecture (as can be seen in Figure 4-8c). A constellation of small spacecraft are installed on the NEO surface (Olds et al. 2004). Each spacecraft takes a small amount of mass from the NEO and induces a small acceleration away from the comet's gravitational field, slowly pushing the NEO in the opposite direction (D'Abramo 2001). This option is particularly desirable, since small spacecraft can be built using existing technology and mass drivers can be modular, allowing for easier and faster production. The mass drivers also have the advantage to be scaleable, allowing easy modifications for responses to different threats. The "swarm" architecture also provides greater reliability, since the loss of part of the swarm will not compromise the mission. The main disadvantage is that achieving the required impulse to direct the object depends strongly on the warning time. Considering kinetic energy scales with the square of the velocity, it is clear how strongly time-dependent these methods are. This technology is also at its early stages of development and can only be considered as a long-term strategy.

Nuclear Explosive Devices

Employing nuclear explosives is one of the most viable solutions for a planetary defense system against NEO threats, especially if the timeframe for devising a mitigation strategy is relatively short. Nuclear explosions could be used in different ways to fragment the NEO (exploding at different distances from the surface of the object), with the choice relying on different parameters, some of which are potential of fragmentation, required yield, device mass, targeting and detonation accuracy, and fraction of NEO deflection vs disruption (nuclear explosives can generate both consequences).

The main advantage of this method is that it is the only available mean our civilization has to provide considerable quantities of energy (see Table 4-3) in a very short time, since, on one side, nuclear explosives have a higher specific energy content than all other technologies known to man, and on the other, do not need much time to be effective. A very short time after the encounter with the NEO (seconds for disruption, a few days for deflection), mission success can be confirmed. Historically, this has always been considered the most appropriate mitigation method for sudden threats.

The disadvantages to this method include the international and political barriers. International treaties and UN resolutions limit the use of nuclear devices in space (see Chapter 5). Therefore, the issue of utilizing such a device in view of protecting the Earth and its inhabitants will have to be addressed before it can be envisaged to be tested or used for actual mitigation. In addition to international and political concerns, there are also technical and safety concerns. A mission needs to be planned, designed and tested, including a spacecraft (In-Space Transfer Stage, ISTS) to deliver the nuclear warhead and communicate with the Earth. Failure of the launch vehicle during launch has a potential for serious safety issues.

Kinetic Energy Impact

Kinetic energy systems can be used for deflection, as previously discussed, but also as disrupters. By colliding an impactor with kinetic energy higher than the NEO's binding energy, stresses would be produced in its internal structure. The impact of the projectile fragments the NEO into pieces as described in Section 4.2.1. The main advantage of this method is that, like the nuclear method, it has a fast response time. The disadvantages include the possibility of residual risk from fragments impacting the Earth and the high ΔV necessary to put the impactor on an intercepting orbit, if the warning time is too short. Except for the latter, these are issues also for the previous method.

4.3.2 Trade Matrix

The trade matrix (in Table 4-2) is a tool to compare eight different mitigation methods based on nine different criteria. The Timeframe criterion is the time that is required before the NEO is no longer a threat. This time does not include preparation, launch, or transit time. The Technology Readiness Level (TRL) rating is a NASA scale used to indicate how close to operational the technology is (Mankins 1995). Figure 4-9 below gives a description of how different numbers relate to technological readiness. The Residual Issues criterion addresses any consequences or any remaining risks after the mitigation method is successfully implemented. The Human Input criterion describes how actively humans need to be involved once the mission has been started. This includes any in-space or ground activity that might be required for the proper operation of the mission (EVA, prolonged ground operations, maintenance). The Scenario Effectiveness parameter describes how effective the method is at mitigating the Cassandra comet threat. This is the only column that specifically addresses the Cassandra comet scenario and that cannot be applied generally to any NEO threat.

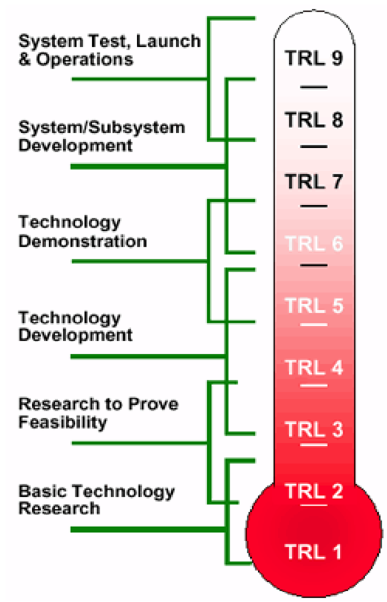

Figure 4-9 NASA's TRL Scale (from NASA 2005)

Table 4-2 Evaluation of Mitigation Methods

Method/ Criteria	Time-Frame	Technology Development Requirement	Cost	TRL	Residual Issues	Human Input	Social Issues	International Issues	Scenario Effectiveness
Tugboat	Years	(1) VASMIR engine (2) Attachment mechanism (3) Nuclear power	$$	4	Nuclear reactor left on a celestial body	Low	Medium - Nuclear power reactor	Low	Low
Kinetic Energy Deflection	Days to weeks	(1) Heavy-lift vehicle (2) Research the feasibility and effect of an impact	$	3	Potential for unintended disruption	Low	Low	Low	Low
Mirror and Laser System	Years	(1) Small and lightweight but powerful laser generators (2) Large deployable mirror (3) Precise position and attitude control system	$$	3	None	High	Low	Medium – It is unknown if a laser would be considered a weapon of mass destruction	Low
Solar-induced Effects	Years	(1) Solar sail materials (2) Develop the sail deployment mechanism	$$	4	None	Medium	Low	Low	Low

Table 4-2 (continued)

Method/ Criteria	Time-Frame	Technology Development Requirement	Cost	TRL	Residual Issues	Human Input	Social Issues	International Issues	Scenario Effectiveness
Yarkovsky Effect	Years	(1) Large mirror (2) Precise position and attitude control system	$$	2	None	High	Low	Low	Low
Mass Driver	Years	(1) Attachment mechanism (2) Mass driver mechanism (3) Networking technology for swarm architecture	$$$$	2	Nuclear reactor is left on a celestial body	Medium	Medium - Nuclear power reactor	Low	High
Nuclear	Day	(1) Appropriate upper stage (2) Targeting technology (3) Precise detonation timing	$$$	5	Fragments may remain on original collision course with Earth	Low	High – Use of nuclear weapons in space	High – (1) Nuclear devices are limited in outer space (2) sensitivity	High
Kinetic Energy Disruption	Days to weeks	(1) Heavy-lift vehicle (2) Research the feasibility and effect of an impact	$$$$	3	If the center of mass of all the fragments still have the original trajectory, impact is unavoidable	Medium	Medium - Nuclear power reactor	Medium	Low

4.3.3 Selection of Mitigation Method

The trade matrix above is a useful tool for evaluating which mitigation method is the best choice to deal with the Cassandra scenario. However, it is designed to be flexible and general so that it can be applied to any NEO threat. Cassandra is detected only 240 days before impact, leaving very little time for a reaction. Considering that decisions have to be made and that, if the method requires hardware on the target, preparation, launch and travel time must be considered, the time between impact and mitigation event will be extremely short (in the order of 70 to 100 days). To have some effect, the mitigation method must have a fast response time. This eliminates all the deflection methods because they all require several years to move a NEO by the desired distance. Only the Nuclear Device Method and the Kinetic Energy Disruption Method are left open for consideration. The latter option is not feasible because of the lack of technology development. With a ranking of approximately 3 on the TRL scale, the technology will not be ready in the 2012-2015 timeframe for this scenario. As a result, the Nuclear Device Method, which has the best timeframe and TRL, is the most feasible option. However, as discussed in Chapters 5 and 6, there are many social and international issues that need to be addressed to facilitate the use of this mitigation measure.

4.3.4 Detailed Nuclear Method Description

Nuclear explosives offer the highest energy per unit mass and therefore are the most appropriate mitigation solution for a NEO of large dimension. Many experts believe employing nuclear explosives is the only viable solution as a planetary defense system against NEO threats, especially if the timeframe for devising a mitigation strategy is relatively short (Ahrens and Harris 1994). Nuclear explosives have the greatest concentration of energy compared to non-nuclear energy sources like chemical explosives and kinetic energy devices (see Table 4-3). However, non-nuclear-using strategies has much less geopolitical and environmental drawback than strategies employing nuclear explosives (Shafer et al. 1994).

Table 4-3 Specific Energy

Source	Specific Energy
Chemical Explosive	6 MJ/kg
Kinetic Energy	50 MJ/kg
Nuclear Explosive	4×10^6 MJ/kg

As shown in Table 4-4, the yield available from nuclear devices is enough to deal with small objects and the weight characteristics permit delivery by existing rockets. (Simonenko et al. 1994)

Table 4-4 Yield vs. Mass for Nuclear Explosives Devices

Yield	Mass
1 Mt	0.5 to 1×10^3 kg
10 Mt	3 to 4×10^3 kg
100 Mt	20 to 25×10^3 kg

If necessary, the power of the nuclear device can be increased by an order of magnitude, while preserving its specified characteristics, but the modification of such devices would require more testing. It is possible to apply several nuclear devices or a single device of optimum configuration, to maximize its impact on the targeted NEO. By selecting a suitable method of affecting the target, a proper model of the evolution of the nuclear explosion near the NEO's surface can be developed and investigated.

There are three types of nuclear blasts: near surface burst by a stand-off nuclear device, surface burst and subsurface burst.

Near Surface Burst

The simplest nuclear dispersion approach is an explosion of a nuclear payload above the surface of the NEO. The burst of the NEO during the explosion is primarily determined by the fraction of the explosion energy transferred directly to the ground near the surface. The heated material will then rapidly expand. The main part of the released energy from a nuclear charge will be radiated in the form of x-rays during a time period of several hundredths of microseconds and will create a very shallow and large crater within the surface of the object (Figure 4-10a).

An explosion in space has quite peculiar characteristics, associated with the absence of atmosphere, the commensurability of the target object's dimensions, the composition of the object, the complex shape of the target object, the relatively weak gravity, and the unknown composition of the target object (Holsapple 2004). Because of the absence of atmosphere, there is no convective heating around the object, only radioactive heating. Different options are possible within this tactic, for example, to cause the device to launch a dense plasma cloud toward the target (Dyson 2002), to optimize the nuclear explosion in case in which the NEO has a rubble pile-like structure.

Surface Burst

Explosion of a nuclear device on the surface of the NEO may require rendezvous, speed matching and landing (Figure 4-10b) and will be at least 35 times greater than a near-surface burst (ISU MSS 2002). In this case, the soil is blown upwards and outwards. As an alternative, extreme precision in the timing of the explosion is necessary (100 ns), to detonate the explosive device a few meters above the target's surface.

Subsurface Burst

A subsurface explosion may require not only landing on the NEO, but also using a drill or other penetrating equipment to bury the device (Figure 4-10c). However, detailed knowledge of the composition of the NEO is required before an explosive can be properly placed. The effects on an NEO could be substantially increased if the nuclear explosive could be buried below the surface, because a considerably larger amount of energy is transferred through the denser material. This subsurface explosion is the most effective and requires the least energy, but at the expenses of weight penalties and uncertainties of reliability of a penetrator device.

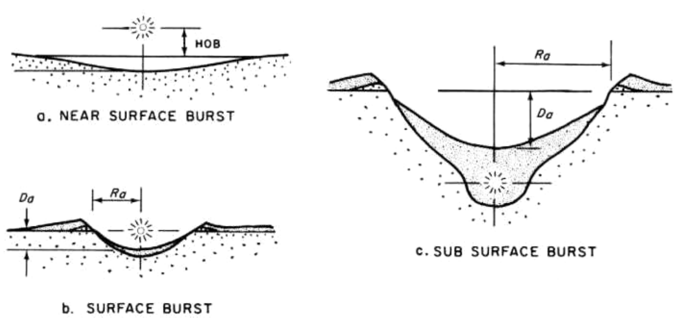

Figure 4-10 Burst Types (Sublette 2001)

Between these alternatives, a near surface blast should be used, since it is the most technologically feasible and tends to maximize the energy transfer and keep the object disruption at a somewhat reduced level.

4.4 Cassandra Mission Design

After having decided that the use of a nuclear stand-off explosion is the mitigation method of choice, this section will study a sample mission design consisting of a spacecraft carrying a nuclear payload to the Cassandra Comet. For this mission design, the baseline scenario previously described will be used, and will take into account the distance at which the NEO is detected, its orbit (and therefore the time available to implement a mitigation strategy), as well as the characteristics of the comet (composition, size, and mass).

4.4.1 Orbit and Trajectory

With the assumption that the proposed spacecraft mission will launch roughly 180 days before impact (allowing 60 days for a NEO mitigation system to be developed and built from the time of initial detection), an interception trajectory has been developed, whose characteristics are illustrated in Table 4-5). Figure 4-11 shows an illustration of the heliocentric transfer trajectory.

Table 4-5 Characteristics of the Interception Orbit

Parameter	Value
Launch Date	180 to EI
Flight Time to Encounter	~104 days
Heliocentric Distance At Encounter	1.1 AU
Eccentricity	0.33
Semimajor Axis	1.5
Inclination	45°

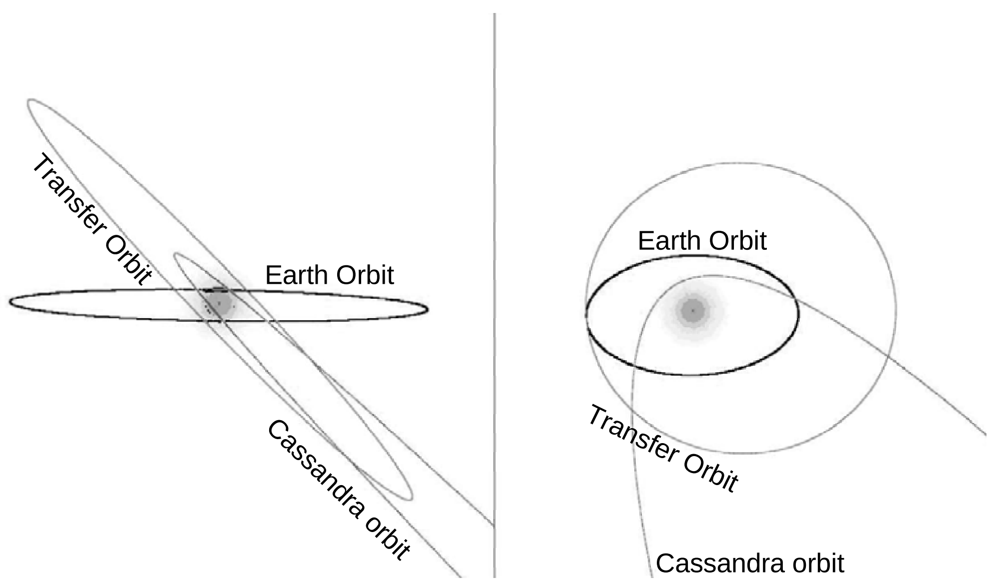

Figure 4-11 Cassandra Trajectory, Earth Orbit and Transfer Orbit of the Interceptor

The deciding parameter governing the choices made during the first part of the mission design is the short time available. On one side, detection capabilities limit the warning time to a bare 240 days, while the other, mission analysis requires a very early launch, since any delay would raise the energetic costs of the orbital transfer to prohibitive levels. In addition, time is needed to set up a mission, even with the assumption that everything is prepared and ready for launch.

As a consequence two main considerations have been made:

- Contrary to previous studies, (Smith et al. 2004) and considering that there is some risk of mission failure, only a single launch is planned. A second launch would either not arrive at the target in time or not at all
- The mission must be prepared in advance: components must be designed, developed and tested well before the necessity to use them arises. In the less than two months allocable for final mission preparation, no development is feasible.

4.4.2 Payload Selection

Figure 1-11 shows the amount of energy required to destroy the Cassandra object. As evident from the graph, at a heliocentric distance of approximately 1.1 AU, a nuclear payload of approximately 1 Mt is required to deflect or destroy the object. This distance from Earth corresponds to a launch date of our mission of about 104 days before the calculated impact date.

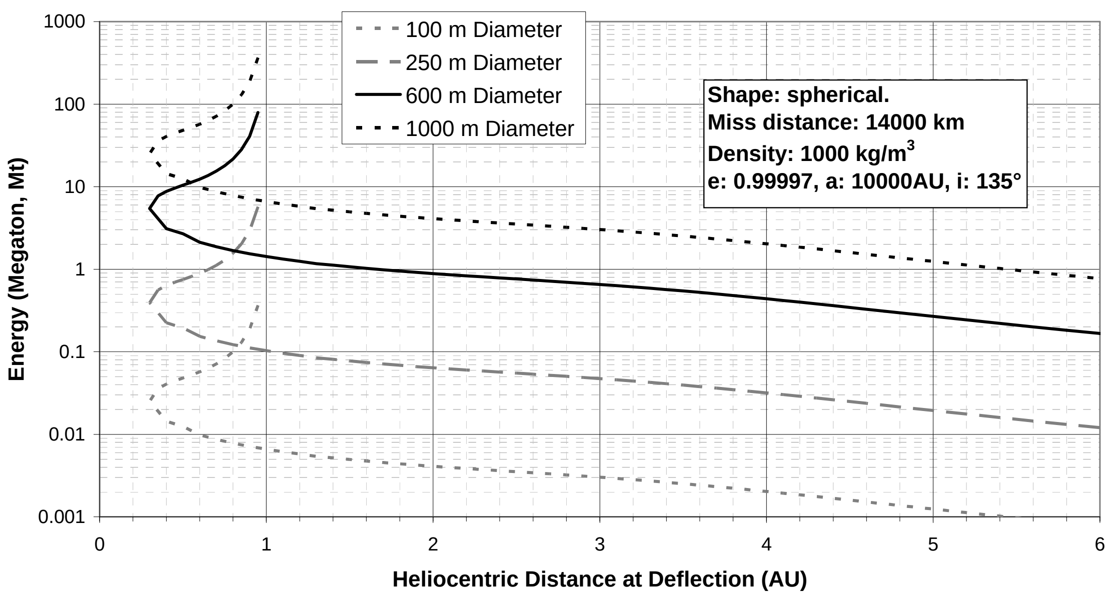

Figure 4-12 Deviation Energy as a Function of Distance of Cassandra from the Sun

To provide approximately 1 Mt energy to disrupt the Cassandra comet, several payload options are possible. These options are summarized in Table 4-6. The first is the B83 nuclear warhead, a variable-yield gravity warhead developed by the US, which has a maximum yield of 1.2 Mt. It is 3.7 m long, with a diameter of slightly less than 0.5 m (457 mm), and a mass of approximately 1100 kg. About 650 B83s were built, and remain in active service as part of the US "Enduring Stockpile". Another possibility in cases where a more powerful solution is required is the B53 nuclear warhead, with a yield of approximately 9 Mt. The B53 is 3.8 m long with a diameter of 1.27 m and a mass of approximately 4000 kg. There are currently 50 weapons in the Enduring Stockpile, but all these weapons are retained as part of the "Hedge" portion, meaning that the weapons are fully operational (or can be made so on short notice), but are not connected to delivery systems (Wikipedia 2005).

In case more time to develop a nuclear device is available, an explosive device could be built that could deliver energy in a fashion more useful to the purposes of deflecting or disrupting a NEO (as opposed to non-peaceful uses targeting living beings). Gennery (2004) states that a nuclear device could be built with the scaling relationships provided in Table 4-6 for an object optimized either for energy transfer through X-rays or through neutrons. Energy transmitted through neutrons is more effective in deflecting a NEO, even if neutron yield is usually lower, while energy delivered by X-rays can be significant for disruption purposes, since, by being absorbed superficially tends to induce shock waves in the body. Additionally X-rays are especially useful when the standoff distance is large.

Table 4-6 Nuclear Explosive Devices (Gennery 2004)

Case	Based on	Mass (kg)	Total Yield (Mt)	Energy of Neutrons (J)	Energy of X rays (J)	Availability
A	B83 warhead	1100	1.2	5.0×10^{13}	3.5×10^{15}	Currently in service
B	B53 warhead	4000	9	3.8×10^{14}	2.6×10^{16}	Possibility still in storage
C	Optimum for neutrons	840 $Y^{0.85}$	Y	$4.2 \times 10^{14} Y$	$2.7 \times 10^{15} Y$	Assumed custom design
D	Optimum for X-rays	460 $Y^{0.85}$	Y	$4.2 \times 10^{13} Y$	$2.9 \times 10^{15} Y$	Assumed custom design

Since it is unlikely that the Cassandra threat will provide sufficient time for an elaborate response, the most feasible option for the nuclear payload is the B83 nuclear device. At this point in time, it can provide the necessary energy for destruction of the Cassandra comet, and does not require any refurbishment or new development to ready the payload for the mission.

To ensure the transfer of the maximum amount of energy and considering the uncertainties related to the efficiency of such a transfer, the use of one nuclear device, which must be detonated as close as possible to the comet, may not be sufficient, unless the target body is very small (leaving a very large margin of error). The only way to achieve enough energy for such a deflection will be the launch and use of multiple such devices. Alternatively, the B53 model could be used, but this would require that the payload be readied for launch as soon as possible, which may or may not be possible depending on the state of the nuclear explosives. Moreover, a space system must be designed around the significantly heavier B53 payload, since the device has a mass approximately 4000 kg.

4.4.3 Spacecraft Design

Using standard spacecraft mass and power estimating relationships based on payload mass and power, a rough estimate of the spacecraft mass and power has been provided in Table 4-7. Both designs assume a configuration whereby the cruise stage and interceptor travel as a single unit until the vicinity of the comet, when the interceptor (with the nuclear payload) is released to impact with the comet, while the cruise stage continues in its trajectory at some safe distance away, to verify the success of the mission or announce its failure. This configuration is similar to that used by the Deep Impact mission.

Since this kind of spacecraft design has already been extensively explored, the reader is encouraged to consult some of the NEO interceptor designs produced in the recent past, an excellent example of which is given in Smith et al. (2004). The design, shown in Figure 4-13, has two separated parts: one impactor, with the nuclear payload and a cruise stage, with monitoring and attitude control functions.

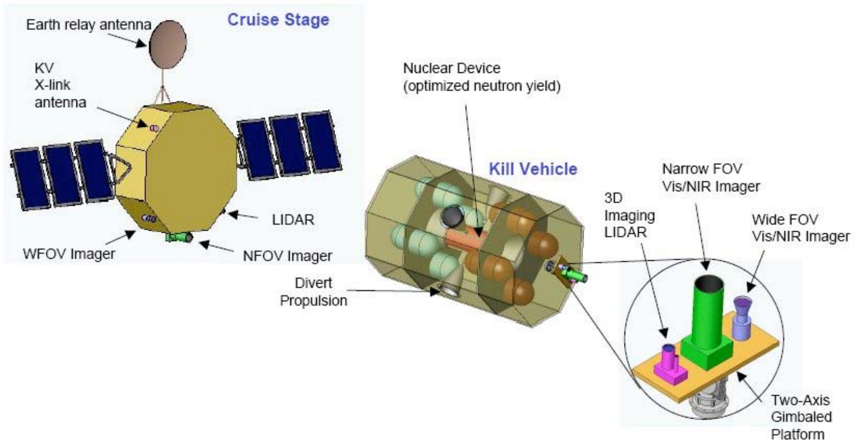

Figure 4-13 Example of Interceptor Spacecraft Design (from Smith et al. 2004)

Table 4-7 Mass and Power Budget for Spacecraft Designs

Subsystem	Mass (kg)	Power (W)	Mass (kg)	Power (W)
	B83 Payload (~4000 kg)		B51 Payload (~1100 kg)	
Payload				
Nuclear	3615	-	1089	-
Instruments	50	100	50	100
Attitude Control	22	58	20	58
Adapter to Warhead	45	-	18	-
Adapter to Launch Vehicle	115	-	35	-
Command and Data Handling	11	24	7	24
Communication	41	72	35	72
Power	430	109	192	109
Structure	931	0	311	0
Propulsion System	107	18	36	18
Propellant	965	-	322	-
Thermal Control	124	18	42	18
Margin	717	100	240	100
Total	**7175**	**500**	**2396**	**500**

The proposed spacecraft design will be fairly simplistic in its design. This will be accomplished utilizing flight tested, standard Commercial Off-The-Shelf (COTS) components where possible, all with a TRL as close to 9 as possible. This can ensure that the spacecraft will be developed in the shortest time possible, and will be fairly reliable during its mission. Table 4-8 provides a brief description of each of the spacecraft subsystems.

Table 4-8 Description of Spacecraft Subsystems

Spacecraft Subsystem	Components	Rationale
ADCS	Star tracker	Precise attitude determination
	Lidar system	Range determination (from spacecraft to Cassandra comet)
Propulsion	Bi-propellant propulsion system	Mid-course corrections Provide quick changes during the final approach to comet Maneuvering capabilities of main bus from the impactor
Power	High-performance solar arrays (GaAs)	Power production for main spacecraft
	Batteries (impactor)	Power source for impactor probe
Command and Data Handling	Standard processor and data storage system	Spacecraft processing and data storage
Communications	X-band transponder	High data rate communications
Structure and Mechanisms	Spacecraft bus (aluminum)	Reduced mass structure
Thermal	Passive thermal control system (blankets, surface radiators, finishes, Multi-layer Insulation)	Keep spacecraft within prescribed temperature range
Payload	Nuclear explosive device	Comet deflection
	Wide and narrow FOV cameras	Impact verification from primary bus

4.4.4 Launch Systems

One of the major constraints posed by the Cassandra mission is the hyperbolic excess velocity required. If the launch is done six months before impact, a 45° plane change is needed and a spacecraft must obtain approximately 25-27 km/s of hyperbolic excess velocity to be sent on the proper trajectory towards the comet. This amount of hyperbolic excess velocity (and the corresponding C3 launch energy of 600-700 km^2/s^2) is outside the capabilities of current launch systems. Launch systems today, even with an upper stage can provide, at most, a C3 slightly higher than 100 km^2/s^2 (assuming a kick stage is used), as shown in Figure 4-14.

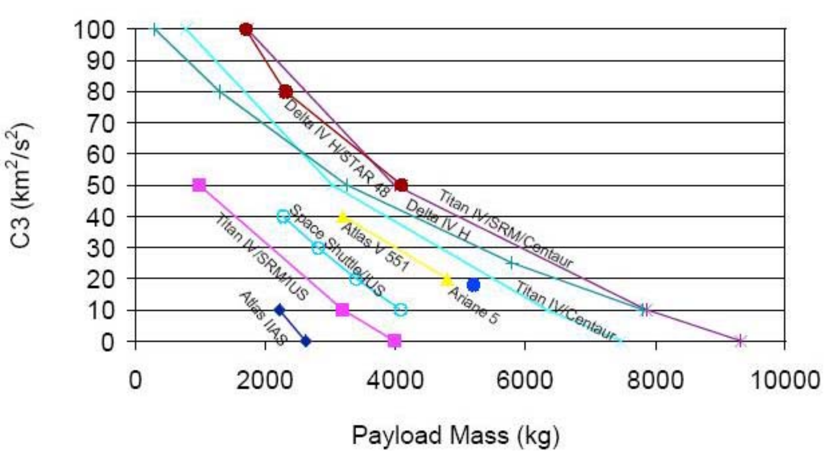

Figure 4-14 C3 Launch Energy vs Payload for Different Launchers (Smith et al. 2004)

Note that, in a different situation, with more time (in the order of few years), gravity assists may provide additional boosts, but this is not the case for this mission.

While difficult, it is possible that a new launch vehicle could be constructed using expendable launch vehicle technologies from various space-faring countries. This, of course, is a stretch by any means, as it would require a significant development effort for the launch vehicle, launch facilities, and ground processing facilities. Cost and development time are also significant issues.

In the mid and far term, there may be several technologies which may be able to accelerate a spacecraft fast enough to reach such high hyperbolic excess velocities. Technologies such as laser propelled solar sails, magnetic sails, and nuclear rockets are all possibilities in the future. Significant development must take place to advance these immature technologies, but they are not outside the realm of tomorrow's reality.

4.4.5 Recommendations

While a feasible solution for the Cassandra scenario seems to be exceedingly difficult, this does not necessarily imply that all high inclination comet threats lack a clear solution. Rather, it should be reiterated that improved efforts must be focused on detection, because improved detection efforts will provide additional time for a mitigation response. In reality, a six month response time does not allow a response regardless of the threat. The time required for building a space system, the energy required on specific transfer trajectories, and the amount of energy required by a nuclear payload all significantly complicate the problem.

It should also be noted that the Cassandra threat is unique in the sense that is a very challenging NEO threat. The high inclination of the comet (135°) makes it almost impossible to reach using current launch systems, and the time for response eliminates almost any possibility of a using a planetary gravity assist.

4.5 Conclusions and Recommendations

The first step in mitigating a hazard is to understand it. The comprehension of the internal structure of a high inclination NEO is a critical step in designing and developing viable mitigation measures. The second step is to be aware of it. To maximize and use effectively the warning time, the detection systems need to be improved in order to maximize response time and mitigation method selection possibilities. The third step is to be able do something about it. A major improvement in the propulsion technologies is needed to be able to reach high inclination orbits in a short period of time. In addition, time restrictions do not allow for a mission design and development after the threat has been found. Therefore, a multi-role, adaptable mission needs to be designed and prepared in advance.

Present deflection methods use a small but constant force to move the NEO into a trajectory that avoids Earth. The force is so small that these methods need several years to complete the mission; they, however, have few disadvantages. Disruption methods need less time since they impart a significant amount of energy to the NEO in a very short time. Disruption, however, has the residual risk that the fragments may reenter Earth's atmosphere, causing widespread damage. In addition, methods that employ nuclear devices have significant social, political and legal issues.

With current technology, the only viable solution is to launch a nuclear device and detonate it in a near-surface burst. To increase the options, research, development, and testing must be conducted. This can be done through several technology demonstrations and validation missions. Missions like Don Quijote and Rosetta are necessary validation tools. When looking at the big picture, however, these are only tentative first steps that need to be followed by more significant missions.

In order to be able to use the mitigation method, a rapid response capability must be developed. These capabilities include the development of a new heavy-lift launch vehicle, capable of delivering massive payload in orbit and the arrangement of an immediate launch capability. In addition, propulsion technology must be greatly improved in order to reduce fuel mass consumed during launch and plane change maneuvers.

For the future, the major recommendations are:

- Substantial increase of detection capabilities, to elevate warning time
- Promotion of scientific characterization of Near Earth Objects, with special emphasis on their structure at superficial and deep level
- Improvement in propulsion technologies
- Development of a heavy-lift launch vehicle
- Creation of a rapid response capability

4.5.1 Cassandra Scenario

In order to mitigate the Cassandra threat, the mission must employ the most effective mitigation method, a trajectory that can meet the time constraints, and a launch system capable of launching and delivering the spacecraft to the target.

The baseline mitigation method is to utilize a nuclear explosive device, capable of disrupting the Cassandra comet. The payload selected is B83 US nuclear warhead, with a yield of 1.2 Mt, a mass of 1100 kg and is currently in active US service.

The spacecraft design assumes a configuration with a late separation shortly before impact into cruise stage and impactor (analogous to Deep Impact).

With the assumption that the launch will be 180 days before impact, the spacecraft will take approximately 104 days to rendezvous with the Cassandra comet, using the transfer orbit detailed in Table 4-5.

The launch system is the current major limitation of the mitigation strategy, while all other elements of the mitigation strategy investigated are feasible.

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Chapter 5

International Cooperation

Detection, characterization, and mitigation of NEO threats are global issues. Regardless of where the impact may occur - or even if it will occur - the entire Earth is involved. Certainly a NEO threat cannot be dealt with from a local, or even regional, perspective. As mentioned in previous sections, the detection, characterization and mitigation of NEOs will be a highly orchestrated process with many trade-offs considered along the way. This chapter details the international involvement and cooperation necessary for a successful approach to the issues discussed in this report.

International aspects concern the policy involved in cooperation, a C&C structure, the national and international legal framework, and funding. A new international organization will be proposed to lead the effort and establish plans and structure for the C&C effort. Potential funding resources and strategies will be discussed last.

5.1 Policy

Although the international community has increasingly recognized the possible consequences of NEO impacts, both scientifically and politically, only a few initiatives involving financial commitments have been undertaken by state authorities. The AIAA (American Institute of Aeronautics and Astronautics) has been publishing on the subject of NEO as a threat to Earth since 1990. They suggest an integrated, systematic, and multi-disciplinary approach to be carried out by an interagency governmental body, focused on planetary defense (AIAA 1995). In 2000, the United Kingdom Task Group on Potentially Hazardous Near Earth Objects released its recommendation that the British Government urgently seek, along with other governments and international bodies (in particular the IAU), to establish a forum for open discussion of the scientific aspects of NEOs, and a forum for international action (UK Government Task Force 2000). More recently, in 2005, the Natural Hazard Working Group submitted its report to the UK Government, including NEOs in the list of global physical natural hazards, and called again for an international effort on the subject (UK Government Task Force 2005). ESA presented in December 2004 its future programs and activities in NEOs at the UNCOPUOS Scientific and Technical Subcommittee, as "a preparatory step for a framework of international cooperation to be established" (Secretariat of the UN General Assembly 2005). Nevertheless, at this point in time, an international framework to address detection and possible responses to a NEO threat is still missing.

Detecting and monitoring NEOs requires setting up a continuous monitoring capability, able to observe different regions in space at short intervals of time. To reduce costs and share information, an international framework utilizing already existing observation points and national programs is strongly recommended. The following sections analyze existing forms of international cooperation, weighing their advantages and drawbacks against identified requirements. An international framework to regulate and facilitate cooperation on NEOs is proposed. An international organization offers many advantages, largely recognized by the global political and scientific community. Specifically for a NEO threat, the advantages could:

- Enhance international cooperation at all levels
- Foster a general level of confidence between States
- Promote international leadership and political prestige
- Instill moral obligations through both political and/or public pressure
- Increase worldwide safety by joining efforts and resources against a global threat
- Utilize existing infrastructure (observatories, launch pads, information)
- Improve overall efficiency of detection, characterization, and mitigation
- Promote technology gains and cost sharing

In particular, detection of a NEO on a collision path with the Earth constitutes a global threat. The current detection systems would not allow identification of the possible impact zone until the object is very close to Earth, approximately ten days before impact. Therefore, all States are equally at risk at the time a mitigation strategy is to be undertaken.

5.1.1 Forms of International Cooperation

Different forms of international cooperation are analyzed considering their advantages and disadvantages (ISU 2001). For the purpose of this study and for a proposed cooperation to address NEOs, the following types of international cooperation are analyzed:

- Inter-Governmental Organizations (IGOs)
- Inter-Governmental Agreements (IGAs)
- Memoranda of Understanding (MoU)

Inter-Governmental Organizations

Table 5-1 outlines the advantages and disadvantages of international cooperation within an IGO.

Table 5-1 Inter-Governmental Organizations' Advantages versus Disadvantages

Advantages	Disadvantages
Promotes regulatory stability	Large institutional framework
Generates high policy consensus	Lack of flexibility
Reduces risk of proliferation of sensible technology (missile, arms, and potential dual-use technology) due to implementation of precise rules	Non-compatibility with existing State policies and regulations, especially US export control (IGO are independent from national laws and policies, and very binding at the same time)
Supports technology integration/flow	Participant withdrawal difficult
Domestic responsibility (each State responsible for implementing regulations agreed upon in the MOU on a voluntary and independent basis)	Long negotiation time to reach stable agreement
Highly effective, once established	

Examples of this form of cooperation are UNCOPUOS and the International Strategy for Disaster Reduction (ISDR).

UNCOPUOS aims to review the scope of international cooperation in peaceful uses of outer space, to devise programs in this field to be undertaken under UN auspices, to encourage continued research and the dissemination of information on outer space matters, and to study legal problems arising from the exploration of outer space. The committee and its two subcommittees meet annually to consider questions put before them by the UN General Assembly, to review reports submitted to them, and to address issues raised by member States. They work on the basis of consensus and make recommendations to the General Assembly. (Office for Outer Space Affairs 2005).

The ISDR was conceived within the UN as a cooperative framework to promote and develop an international disaster reduction strategy. The ISDR vision is "to enable all societies to become resilient to natural hazards and related technological and environmental disasters in order to reduce environmental, human, economic and social losses" (United Nations International Strategy for Disaster Reduction 2001). ISDR is in charge of raising necessary funds; therefore, one of its tasks is to identify innovative funding involving both public and private sectors. (United Nations International Strategy for Disaster Reduction 2001).

Inter-Governmental Agreements

Table 5-2 outlines the advantages and disadvantages of international cooperation within an IGA.

Table 5-2 Inter-Governmental Agreements' Advantages versus Disadvantages

Advantages	Disadvantages
Facilitates integration of global scientific/engineering	Limited policy consensus (opposition from excluded parties possible)
Single agreement	Technology transfer problems not always addressed; reduction of risk of proliferation of sensible technologies difficult to enforce
Government participation	Limited regulatory stability
Withdrawal limited to certain binding aspects only	Domestic responsibility (each State responsible for implementing regulations agreed upon in the MOU on a voluntary and independent basis)
Compatible with existing policies and regulations	Difficult to negotiate
Effective	

Examples of this form of cooperation are the ISS and the Inter-Agency Space Debris Coordination Committee (IADC).

The ISS is a cooperative program for the joint development, operation, and utilization of a permanently inhabited station in low Earth orbit. The legal framework defines the rights and obligations of each State and their jurisdiction and control with respect to their ISS elements. The ISS legal framework is built on three levels of international cooperation agreements. The first level is an inter-governmental agreement (IGA) signed on January 29, 1998 by the 15 governments involved in the ISS project. The two additional levels are discussed in the following section on Memoranda of Understandings. (European Space Agency 2001).

The IADC is an international governmental forum for the worldwide coordination of activities related to the issues of man-made and natural debris in space. The primary purposes of the

IADC are to exchange information on space debris research activities between member space agencies, to facilitate opportunities for cooperation on space debris research, to review the progress of ongoing cooperative activities, and to identify debris mitigation options. It is composed of a steering group and four specialized working groups. (Inter-Agency Space Debris Coordination Committee 2005).

Memoranda of Understanding

Table 5-3 outlines the advantages and disadvantages of international cooperation within an MoU.

Table 5-3 Memoranda of Understandings' Advantages versus Disadvantages

Advantages	Disadvantages
Negotiation/set-up time is shorter than other forms of int. cooperation	Technology transfer problems (duplication of efforts from members could be a major consequence of non-technology-sharing policy generally followed under MoU)
Compatible with existing policies and regulations	Unstable, since not very much binding for the members
	Domestic responsibility (each State is responsible of implementing the regulations agreed upon in the MOU on a voluntary and independent basis)
	Limited policy consensus

The ISS program also demonstrates examples of this form of cooperation. The second level of the ISS framework includes four MoUs between NASA and cooperating space agencies that describe in detail the roles and responsibilities of the design, development, operation, and utilization of the ISS. The agreements serve to establish the management structure and interfaces necessary to ensure effective utilization of the ISS. The third level includes various bilateral implementing arrangements between space agencies. The arrangements distribute concrete guidelines and tasks among the national agencies. (European Space Agency 2001).

Trade Matrix for International Cooperation on Potential NEO Threats

Possible forms of international cooperation have been evaluated based on certain criteria within Table 5-4 below. Factors with potentially greater impact on the effectiveness of international cooperation, according to the analysis in the previous chapters, have been selected as criteria. The criteria have an associated weight to establish their relevance to the NEO subject in particular. A ranking from 1 to 5 has been used, to assess the effectiveness of the form of cooperation with respect to the weighted criteria. The line "total" shows the results of the trade after the weighting.

Table 5-4 Trade Matrix for International Forms of Cooperation

Criteria	Weights	Proposals		
		Inter-Government Organization	Inter-Government Agreement	Memoranda of Understanding
Policy Consensus & Stability	10%	5	2	1
Regulatory Stability	10%	5	2	1
System Flexibility	10%	1	3	5
Technology Transfer	5%	4	3	1
Implementation Timeframe and Cost	15%	1	3	5
Compatibility with existing Policies and Regulations	20%	1	5	5
Domestic Responsibility	10%	5	2	1
Effectiveness (Scientific Data Management & Resources Mobilization Capability)	20%	5	5	1
TOTAL	100%	315	350	280

Based on the trade matrix, the best form for international cooperation on NEOs is the IGA.

5.1.2 Proposal for a New Organization

As a first step, the coordination of efforts related to NEO detection, characterization, and mitigation would be based on a limited voluntary cooperation that will not supersede current or potential agreements among members. However, the organization should be flexible enough and prepared to evolve into a more integrated and consolidated structure as experience is gained. This paper proposes the foundation and layout of the International Near Earth Object Committee (INEOC).

The INEOC Scope

The INEOC would provide a comprehensive cooperative framework to coordinate members' existing and future programs related to NEO detection, characterization, and mitigation and to share their benefits.

The INEOC will:

- Review all ongoing NEO research activities and programs
- Recommend new opportunities for research and study
- Plan and implement possible cooperative opportunities of mutual interest and benefit
- Coordinate the members' programs to utilize capabilities and promote a complementary approach to optimize current assets and means
- Serve as the primary platform for exchanging information and plans regarding current and future activities connected with NEO

- Promote dialogue among the members, NEO-interested communities, and other organizations
- Propose an overall strategy and appropriate C&C plan
- Promote all aspects of strategy implementation among involved actors, in particular State governments and policy makers
- Identify additional funding sources
- Identify requirements to strengthen its institutional capacity to develop an integrated and coherent response to a NEO threat
- Increase public awareness of potential NEO threats

Membership

INEOC principle members are international or national governmental organizations carrying out programs or activities related to the detection, tracking, characterization, mitigation, or study of NEOs. States with current programs include Australia, Canada, China, European Union, Japan, the US, and the UK.

Associate members take part, on an ad hoc basis, in the activities and discussions of the working groups. Their expressed opinions are included in all reports. Approval by the associate members is not required to establish consensus for proposals. The following organizations may be invited to participate through the status of associate member:

- Governmental organizations that are international or national in nature and have a civil space segment activity that supports INEOC objectives
- Other non-governmental organizations that currently have a significant activity that supports INEOC objectives (e.g. IAU, Spaceguard Foundation, SETI, academic and research institutes, etc.)

Individual members contribute to INEOC's goals on a voluntary basis and will use their best efforts to implement INEOC recommendations in their respective programs.

Organizational Structure

INEOC is comprised of the Steering Committee, four specialized working groups, and a Threat Response Team as shown in Figure 5-1 below.

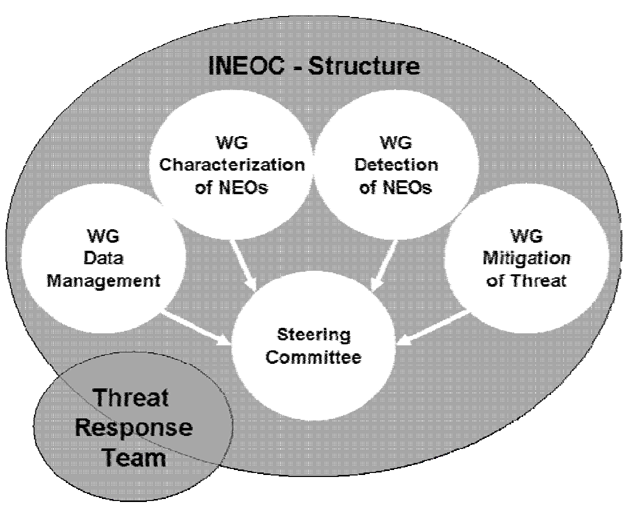

Figure 5-1 The INEOC Structure

The Steering Committee is composed of delegates of the working groups and is in charge of the overall guidance and management of INEOC's activities. The chairmanship of the INEOC Steering Committee will rotate among its members, on a yearly basis.

The Steering Committee's activities include:

- Organization of INEOC's activities and support of general administrative requirements
- Definition of annual program and new areas of activity
- Definition, coordination, and monitoring of the working groups' activities
- Appointment of new members by consensus decision
- Representation of INEOC in other organizations
- Coordination with other organizations on issues related to NEOs

The Steering Committee would develop an appropriate C&C chain and procedures extending from initial detection to response to a NEO threat. The C&C framework would be approved by the INEOC members.

As an output of the C&C plan, a Threat Response Team would be established. This Team would be comprised of both the members of the Steering Committee and the authorities involved in the C&C chain, including State governments and military personnel.

Four specialized working groups are proposed in Table 5-5 and are monitored by the Steering Committee. Members of the working groups are experts in the associated field of investigation and are appointed by consensus decision of INEOC members. Each working group chooses a chairperson to organize and guide its activities. The chairperson reports to the Steering Committee. Each working group establishes its own agenda and may receive tasks from the Steering Committee. The Steering Committee, when deemed appropriate, would establish new standing or temporary working groups.

Table 5-5 The INEOC Working Groups' Definition

Working Group	Scope
Detection of NEOs	• Review existing detection methods • Assess new technological developments • Promote cooperation among members for the development of new detection programs and infrastructure • Promote and provide incentives for detection of objects by amateur astronomers
Characterization of NEOs	• Review current and new characterization methods • Promote and provide incentives for characterization of objects by amateur astronomers
Mitigation of Threat	• Review potential mitigation methods • Propose an adaptive solution for each type of threat • Assess new technological developments
Data Management	• Coordinate detection data acquisition, characterization, and storage • Promote standardization of data collection, archiving, and distribution • Ensure electronic access by necessary personnel • Ensure secure data distribution in case of detection of threat

An analysis of existing forms of international cooperation shows that an inter-governmental agreement would be the most suitable, to establish and strengthen cooperative relationships among States with space capabilities and programs dealing with the NEO issue. It is equally important to include established non-governmental actors such as the scientific community and research institutions in this cooperation, as they already have a wealth of knowledge on NEOs.

This form of cooperation would enhance:

- Coordination of space agencies' short and medium term programs, for detection and mitigation strategies, to understand and prevent the NEO threat;
- Sustainability of a program to collect and exchange information on observed NEO, like the already-existing Minor Planet Center (MPC) of the International Astronomical Union (IAU)
- International awareness of the NEO threat, both at public and political level

It will especially allow introducing a chain of C&C capable of reaching the decisional government level in an expedient manner, whenever this might be needed.

5.2 Command & Control

An international body that deals with a NEO threat must include a clear C&C structure that defines the key players, how they communicate and the timeframe in which actions are taken. Currently, no such international C&C structure exists. Amateur and professional astronomers and astrophysicists communicate via informal channels including telephone, e-mail and Internet chat rooms, but there are no formal protocols to be followed when a threatening object is detected. The MPC in Cambridge, Massachusetts collects and analyzes astronomical images from observatories around the world and posts results on their public website, which allows access by the astronomical community for further analysis. However, once observers find an object that appears to be on a collision course with the Earth, there must be a well-defined procedure in place to deal with it. An event of international importance should be dealt with internationally within a clear, well-defined international structure. The need for such a structure is illustrated by the series of events that took place following the institutional discovery of a NEO in early 2004.

5.2.1 Near Earth Object AL00667

The following summarizes the events surrounding the discovery of object AL00667 and the activities that followed (Chapman 2004).

On the evening of January 12, 2004, object AL00667 was detected by the LINEAR observatories in New Mexico. As is customary, the data were sent to the MPC approximately 12 hours later. Preliminary trajectory calculations were performed at the MPC based on the four data points obtained from LINEAR and the results posted on the NEO Confirmation Page (NEOCP) for amateur astronomers and astrodynamicists, in order for them to verify the calculations. Once the MPC staff had posted the information on the website, they left for the night.

Not long after the information had been posted, an amateur astronomer visiting the website noticed the new information and realized that the calculations predicted that the object would be 40 times brighter and therefore six times closer to the Earth in just one day. He posted his findings to Yahoo!'s Minor Planet Mailing List (MPML) chat room. A professional researcher who happened to be monitoring the chat room at the time determined that based on these results, the object had a high probability of impacting the Earth the next day. He then informed several scientists at NASA and JPL who attempted to contact the MPC. Approximately half an hour later, they reach the MPC director, who immediately changed the information on the webpage to show a new trajectory that also matched the data but did not predict an impact. An hour later, the MPC staff member who had originally posted the data predicting an impact, replaced the director's new posting with another one that showed the object narrowly missing the Earth. Neither of these two later postings was made using any new data; rather, they were attempts at political correctness.

Over the following several hours, amateurs and professionals from around the world discussed the situation by telephone, e-mail and in Internet chat rooms to determine what should be done. An astronomer in the UK was able to search the area of the sky where the object was predicted to be located and did not find the object. Several similar reports were sent to the MPC and later that night, LINEAR obtained additional data on AL00667 and sent these data to the MPC, but because no one was working at the MPC that night, the additional measurements were not analyzed until the next morning.

Once the analysis of the new data had been performed the next morning, the results were again posted to the NEOCP website. The trajectory calculations were revisited, and analysis determined that the object would not, in fact, impact the Earth. Scientists had originally estimated the size of the object to be about 30 m across, which would have an impact effect of 1 to 2 Megatons of TNT. Depending on the location of impact, an object of this size could have disastrous effects. The actual NEO turned out to be much larger, but thankfully it passed by the Earth a couple of weeks later at a safe distance of several million kilometers.

In this situation, it was not clear what should be done, as this was the first time a threatening object had been discovered with such a short predicted time to impact. It was unclear which institutions and authorities should have been informed and involved.

This recent case highlights the need for implementation of a clear command and control mechanism to prepare for and respond to NEO threats in a serious way. Procedures and clear communication protocols must be defined in order to react appropriately. The response time in such situations is critical. Data must be received and analyzed quickly and the processed information disseminated to all relevant institutions, which must be known in advance and able to be contacted at all times, 24 hours a day and seven days a week. Amateur astronomers are a great asset for providing additional observation data and calculations of the size and trajectory of objects, which shows the importance of including this large group in order to enhance the technical data. Involving scientists and qualified amateur astronomers from different institutions and countries with their varying expertise and experiences can yield results in a timely manner. Again, time is of the essence in such situations, and therefore, despite uncertainties, it is necessary to inform national governments as soon as a potential threat is validated and eventually to inform the public.

5.2.2 Proposed C&C Structure

Figure 5-2 shows a proposed C&C structure for effectively dealing with NEO threats. Rectangles indicate institutions while arrows indicate the flow of information between those institutions. Ovals indicate the actions generating an information flow between institutions. The previously proposed INEOC Steering Committee would refine the following process to include detailed participation of States and key contributing organizations.

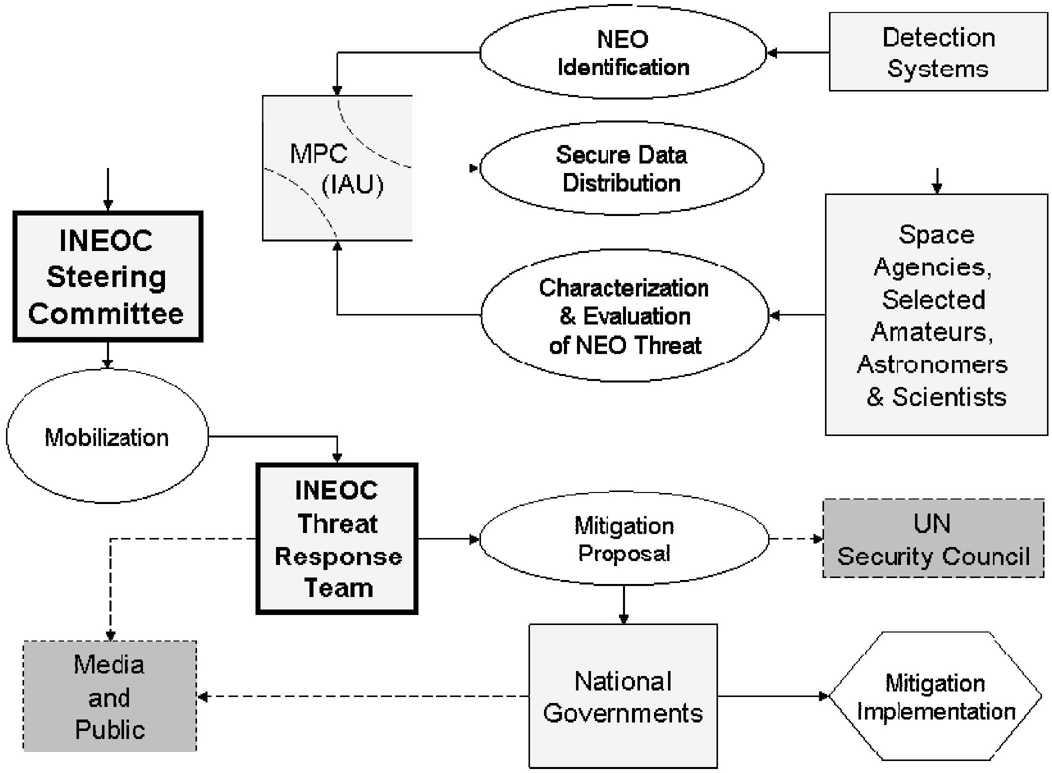

Figure 5-2 Proposed NEO Threat Command & Control Structure

The process begins with the detection of a NEO by a ground-based and/or space-based observatory. The data is sent to the MPC for preliminary analysis. The MPC is staffed around the clock by either on-site personnel or people connected remotely via the Internet. The results of the analysis are reviewed by senior MPC staff to determine if a potential threat exists, after which the results are posted to a secure web site. If the MPC identifies a potential threat during its preliminary analysis, it immediately contacts the reviewing parties and requests they review the preliminary data posted on the website. These parties rapidly perform additional analyses to evaluate the preliminary results. The parties communicate with each other via direct means (telephone or e-mail but not public Internet chat rooms) to compare results and determine if more information, such as additional observations, are needed. The evaluators then post their results back to the MPC's secure website.

A secure website is used because the information is still preliminary at this stage and thus is subject to change. It is important to prevent the general public from becoming alarmed about a premature impact prediction that may, in fact, prove to be inaccurate after further confirmation. This is highlighted by recent examples, including the one identified in the previous section, as well as the situations surrounding the discoveries of asteroids 2002 NT7 and 2003 QQ47, with impacts originally predicted in 2019 and 2014, respectively. These cases underscore the need for validation of the threat prior to mass dissemination of information. In all three of these cases, original calculations predicting an impact were shown to be inaccurate once additional data were obtained. In the latter two examples, the media sensationalized the stories and alarmed the public unnecessarily. As discussed further in chapter 6, this also has the undesirable effect, after repeated instances of such false alarms, of creating public distrust of the scientific community and desensitization of the public to the NEO threat.

Individuals allowed to access the secure website include selected amateur and professional astronomers and astrophysicists, along with space agencies (e.g. the NASA NEO Program Office at JPL). These individuals would agree not to disseminate information to the media or to the public about potential threats. The responsibility for communication with the public lies with the INEOC and national governments.

The MPC reviews the additional information from the scientific community to determine if a credible threat exists (i.e., greater than a 1% chance of impact). If a credible threat is confirmed, the MPC immediately informs the INEOC Steering Committee of its findings. The members of the steering committee then mobilize the INEOC Threat Response Team, composed of the steering committee as well as space agencies and State governments. The threat response team reviews the information provided by the MPC, obtains further data if deemed necessary, and begins formulating a strategy to mitigate the NEO threat. The team considers all possible options and their respective effectiveness on the object, which depends on the object's size, composition, velocity, and distance from the Earth. They create a mitigation trade matrix similar to the one found in Chapter 4 to evaluate the different methods available at the time. A preferred mitigation strategy is selected and the threat response team informs State governments and the UNSC of its proposal for mitigation. At this stage, a news conference is held to inform the public. The appropriate parties then set out to realize the proposed mitigation strategy.

Depending on the strategy selected, military resources may become involved. For example, if nuclear or certain types of kinetic energy devices were selected, military personnel would likely be responsible for implementing the mitigation strategy (in the case of the United States, the U.S. Air Force). The space and military agencies would likely conduct the mission design and provide the launch vehicle.

The timeframe for these activities is heavily dependent on the amount of time between the detection of a potentially threatening NEO and the predicted time to impact on the Earth. For an extremely short-term scenario (on the order of days, months or a few years), the time between initial detection and verification of the threat would be on the order of 1-2 days. Mobilization of the threat response team and selection of a mitigation strategy (if mitigation is deemed possible) would have to occur quickly. State governments, the UN Security Council and the public would be informed as soon as possible. However, in the case of a longer-term threat (on the order of several years or decades), these events would not be as urgent and more time could be spent characterizing the object and considering mitigation options.

5.2.3 Participation of States

State governments can contribute various forms of technology and resources to assist in the execution of the proposed C&C plan. These contributors include both space-faring and non-space-faring States. This section will focus on contributions from States other than those with advanced space programs and launch capabilities. The core space-faring contributors would be the United States, European Union, Russia, China, Japan, and Canada. Other States with strong scientific expertise could contribute to further research and development of detection, characterization, and mitigation strategies. Democratic states are of particular interest because their political regimes enable the international cooperation proposed in this report.

Brazil, India, Israel, and Ukraine possess strong scientific expertise and could contribute to a global effort in response to a NEO threat. Ukraine, for example, possesses significant expertise in launch technology. The others host capable observatories and a well-educated scientific community. These States could team with core States to help develop specific space-based technologies.

Participants with potential ground-based detection technology and resources are referenced in Table 5-6.

Table 5-6 Non-Core Participants and Associated Projects

Telescope Project	Non-Core Participants Involved
LSST	Chile, Mexico
Australia Telescope National Facility	Australia
Southern African Large Telescope	South Africa, New Zealand
Robotic Telescope for Thailand's Astronomy Research	Thailand
Taiwan Oscillation Network	Taiwan, Uzbekistan

Core space-faring States and other non-core States with scientific expertise will provide the base of the C&C structure. In addition to State government involvement, amateur astronomers could provide valuable help in day-to-day monitoring of the sky. This report, therefore, recommends this set of players be considered in the C&C structure. Figure 5-3 depicts the potential global cooperation in response to NEO detection and threats.

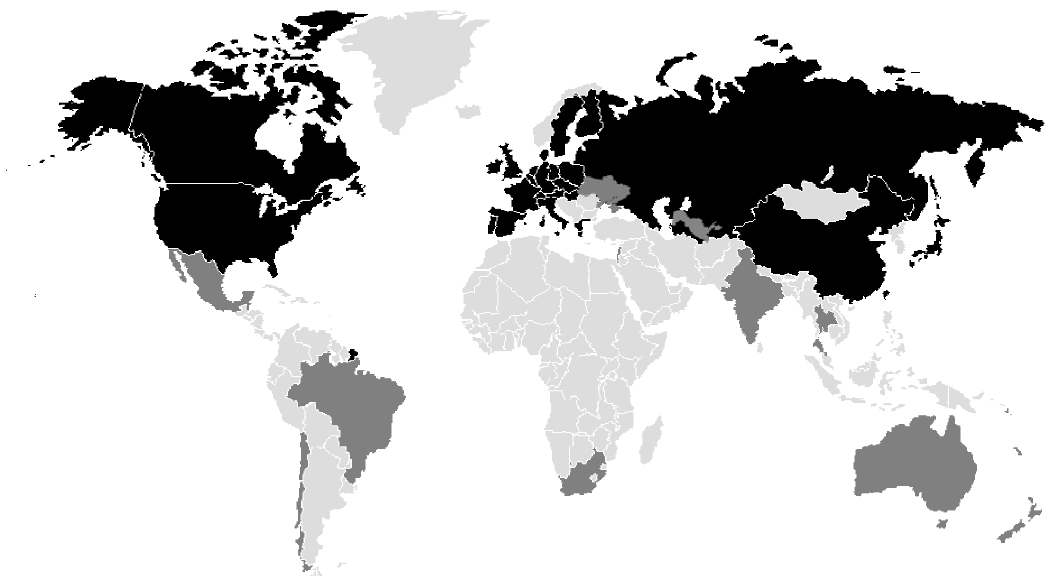

Figure 5-3 Potential International Cooperation and Involvement

5.3 Legal Issues Related to NEO Detection and Mitigation

Proposed detection and mitigation strategies are in line with the policy goals and the key treaties defining international space law. Indeed, each of the treaties lays great stress on the notion that the domain of outer space activities should be devoted to enhancing the well-being of all humanity. Each includes elements elaborating the common idea of promoting international cooperation in outer space activities. (OOSA 2001a).

Nevertheless, the detection and mitigation of a NEO threat might raise a number of legal issues. Although these laws do not specifically address the problems that could arise upon the discovery of a NEO impact threat, principles contained in the 1967 Outer Space Treaty (OOSA 2000) and the 1972 Liability Convention (OOSA 2001b) apply to any space-related activities, including

NEO detection and mitigation activities. Major issues are identified below that are likely to be raised when implementing the proposed strategies.

5.3.1 Liability Issues

State liability could be put at stake in case of deflection or disruption of a detected NEO that requires the launch of a mitigation device. The question is whether the States undertaking the proposed mitigation measures would be liable for the damages that could result from such maneuvers. At the moment, the liability regime in place under international treaties is geared toward the liability of a State whose "space object" has caused damages to another State.

Two types of damages could occur when conducting the proposed mitigation strategy: damage to the Earth or damage to other space objects. The Liability Convention establishes two levels of liability depending on whether the damages occur on Earth or in space. Articles II and III specify an absolute liability for damages caused on Earth by a launching State's space activities and fault-based liability when damages occur in space.

First, damage to the Earth might occur during launch. According to Article VII of the Outer Space Treaty, the liability is assessed on the launching State, which is defined as the State that launches or procures the launching of an object into outer space and from whose territory or facility an object is launched. Articles IV and V also provide that States are jointly and severally liable for damages caused by their cooperative space efforts. The current regime is rather strict in establishing an obligation to compensate, regardless of the circumstances in which the damages were caused. Indeed, the Liability Convention is considered to be a "victim-oriented" treaty that aims at protecting victims of damages by placing them in the most favorable legal position.

Second, damages to other space objects could be caused as a result of the mitigation strategy itself and under circumstances where the launching States would not have any form of control on the incidental or even massive damages that could result from a mission. Today, it is unclear whether or not the terms "damage caused by its space object" could also encompass indirect consequences such as damages caused by fragments of a disrupted NEO. One school of thought is that the fall of such fragments onto the Earth is too remote a possibility to qualify as damage caused by a State's space object, making the Liability Convention inapplicable. In such a case, could a State still be held liable under the general international law regime?

Other scholars consider the intentional disruption of a NEO and the expectation of collateral damages to have a sufficient causal connection to invoke the Liability Convention and hold liable the launching State. In that case, difficulties as to the definition of the launching State still arise because many States could be deemed to participate in "procuring the launch". Currently, neither the Liability Convention nor the Outer Space Treaty provide for any waiver of liability towards third-party damages. Further, the entire space liability regime, whether dealing with absolute or fault-based liability, relies on the assumption that the launching State is known. This highlights the need for either an explicit waiver of liability in the specific case of an attempt to destroy or defect a NEO, or a separate liability framework to provide for such a situation. In any case, the actual liability framework is not suitable in its application, as is, and would need to be addressed by the international community. A pragmatic solution to overcome this situation would be to have States agree on a mitigation proposal and agree to waive any liability that could be claimed against the launching States. However, it might be difficult to negotiate for waiver of liability since there are several different national liability regimes around the globe. For example, some domestic laws (e.g. Japan) do not permit unconditional waivers of liability because such waivers contradict established social norms.

Finally, one could argue a State that was liable for damages as a result of NEO mitigation maneuvers should have a defense that its intention was solely to protect the planet and used its best endeavors to do so. The State could invoke the right to self-defense, as codified under Article 51 of the UN Charter (1996-2002) and which is also part of customary law:

"Nothing in the present Charter shall impair the inherent right of individual or collective self-defense if an armed attack occurs against a Member of the United Nations, until the Security Council has taken measures necessary to maintain international peace and security."

This provision, although appealing, incorporates two substantial and independent limitations on the right to use force in self-defense. Such a right exists only (1) where there was an "armed attack" against the country and (2) "until" the Security Council has had time to take appropriate measures. Therefore, one may be cautious in invoking such a notion in the particular context of an offensive action against a celestial body, since this article has been written to provide for self-defense against another States, not against natural space objects. As another alternative, the Good Samaritan doctrine, a legal principle that prevents a rescuer who has voluntarily helped a victim in distress from being successfully sued for "wrongdoing", could also be invoked. However, this is not a concept accepted throughout the world.

5.3.2 Use of Nuclear Devices to Mitigate a NEO Threat

As concluded in Chapter 4, the one method that is both technologically feasible and has a fast response time for the mitigation of a high inclination comet is the use of a nuclear device. However, this option can only be considered as the preferred solution from a political and legal point of view if the international community acknowledges and acts upon the existing constraints.

Provisions forbidding or limiting the use of nuclear devices can be found in the Outer Space Treaty, which States, under its Article IV, that:

"States Parties to the Treaty undertake not to place in orbit around the earth any objects carrying nuclear weapons or any other kinds of weapons of mass destruction, install such weapons on celestial bodies, or station such weapons in outer space in any other manner." Further, the same Article forbids the establishment of military bases and the testing of any type of weapons on the Moon or other celestial bodies.

Although the conduct of military maneuvers on any celestial body (including NEOs themselves) as well as the testing of any nuclear device would be banned, the Outer Space Treaty does not expressly prohibit the testing of the same system in outer space, at least so long as the device is not "in orbit" or "installed" on celestial bodies or otherwise "stationed" in outer space. This would allow the launching of a nuclear device aimed at disrupting a high inclination comet.

As far as the use of weapons of mass destruction is concerned, there is currently a lack of consensus on a definition of such weapons. Nevertheless, it seems reasonable to argue that a device, nuclear or not, that would be powerful enough to move a large NEO such as a comet is likely to qualify as a potential weapon of mass destruction. As a result, any mitigation method that would require the orbiting, testing, installing or stationing of such a device would fall under the prohibition. Nevertheless, in case of an imminent NEO threat, calling for a fast response, it could probably be argued successfully that the rationale of the Treaty prohibition was to limit the testing or use of weapons in outer space intended to act against another State or its space assets. Using a nuclear device or any other weapon of mass destruction to destroy a NEO would likely be outside the intended scope of the 1967 Treaty. Legal specialists Gerrard and Barber (1997) advise: "The ban on placing such weapons in orbit, installing them on celestial bodies, or stationing them in outer space was intended to protect nations from space-based threats by other nations and did not anticipate threats originating in outer space".

Liability issues connected with the use of a nuclear device are also likely to arise. Under the Liability Convention regime (Article VI), exoneration from absolute liability is denied "in case where the damage has resulted from activities conducted by a launching State which are not in conformity with international law" (OOSA 2001b). In other words, if a nuclear device were to be placed into orbit by a State in order to mitigate a NEO, this would constitute a violation of international law. The launching States would then be subject to strict liability.

The international law principles do not prevent a State from launching a nuclear device from Earth in order to disrupt a NEO such as a high inclination comet, as long as the device is not placed into orbit. If the only way to effectively mitigate a NEO threat is to use a nuclear device in a way that is currently forbidden, the international community would have to take up the possibility of waiving such prohibitions of use of nuclear devices.

5.3.3 Domestic Regulations Issues

With international detection and mitigation strategies, several national laws and regulations will have to be taken into account in order to achieve a practical and efficient implementation of such strategies.

Export Control

Each State has unique sets of requirements to control, through licensing or broad regulatory exemptions, transactions that involve the export of certain goods or the transfer of certain technology. These technology export controls can render international cooperation difficult, especially if it involves sensitive technologies, such as nuclear weapons.

The proposed mitigation strategy of using a nuclear device could raise national issues for the contributing States with respect to their export policy regimes. Since 1999, the US has a complex and rigid set of rules to be satisfied before a transaction can lawfully be completed. Many of those rules can be found in the International Traffic in Arms Regulations (ITAR) provisions.

To date, there has been a prominent international effort for the non-proliferation of weapons through multi-national agreements such as the 1987 Missile Technology Control Regime (MTCR) and the 1996 Wassenaar Arrangement on Export Controls for Conventional Arms and Dual-Use Goods and Technologies. These agreements typically allow sharing of technology within parties to the agreement, but otherwise restrict the export of technologies that could be used to create weapons of mass destruction. Typically, space technologies are controlled under these agreements since they can often be used for both civilian purposes and as weapons. For the MTCR, each member to the agreement is responsible for implementing the guidelines and annexes contained therein in accordance with national legislation and practice. So far, such members include, *inter alia*, the Russian Federation, Japan, the UK, Canada, the US, and many European nations.

An imminent NEO threat could be considered by a State as a national security concern and would therefore override any export control limitations. Therefore, the above rules could potentially become secondary and do not pose significant risk to mission success.

Potential Claims by Nationals

There is a risk of legal claims by nationals of a State with regard to the testing and/or the destruction of a NEO. Some States allow national claims on international space activities under their national regime. For example, a Russian court ruled that an astrologer could proceed with a lawsuit against NASA for its bombardment of a comet. The Russian woman claimed that by slamming a probe into a comet, NASA's Deep Impact mission endangered the future of civilization. She is seeking damages totaling US$300 million for her "moral sufferings". Although her case was initially dismissed from a lower court because Russia has no jurisdiction over NASA, the ruling was overturned when she showed that the agency's office in the US Embassy in Moscow fell within Russian jurisdiction (Australian Broadcasting Corporation 2005). Although the outcome of this particular case is unknown at the time of writing, it is surely worth mentioning this might give a precedent to future similar claims following an attempt to destroy a NEO.

5.3.4 Recommendations

Domestic space policy with respect to NEOs already exists in many States and could easily evolve into multi-lateral agreements. Creating a multi-lateral agreement could be the most efficient way to establish a practical international framework to achieve collaboration on the detection and mitigation of NEOs without disregarding the space law regime.

Existing agreements connected with disaster response are of particular interest, as they carry provisions aimed at overcoming regulatory obstacles that could preclude a fast response. One example is the 1998 Tampere Convention on the Provision of Telecommunication Resources for Disaster Mitigation and Relief Operations that aims to facilitate prompt telecommunication aid to mitigate a disaster's impact (ITU 2005). Article 9 of the Convention deserves attention, as it calls on States to use their best efforts to reduce or remove regulatory barriers that could impede the ability of organizations to use telecommunication resources for disaster management. A similar cooperation among States interested in NEOs, with respect to waiver of liability, export controls, and other related legal issues, would be a sound step towards a successful implementation of proposed mitigation strategies.

It is doubtful any State, when facing a NEO threat, would raise the legal issues discussed above or would object to any of the proposed mitigation methods, including the testing of nuclear devices. However, objections could arise if such testing appeared to be a pretext to do what would otherwise be forbidden. Also, if the risks to the Earth would be unacceptable, the international community would certainly object. In any situation, it is fundamental an international structured response be implemented in order to avoid panic and chaos that could lead to the unfortunate destruction of our planet. The suggested approach of an IGA through INEOC, modeled on the Tampere Convention, could create a global detection system and encourage States as a unified whole in response to a NEO threat.

5.4 Funding NEO Detection and Mitigation

One of the most difficult aspects of dealing with the NEO threat is acquiring the funds to "defend" against, and to continue to defend against, a threat that, seemingly, never comes. As Park points out "societies will not sustain indefinitely a defense against an infrequent and unpredictable threat. Governments often respond quickly to a crisis, but are less well suited to remaining prepared for extended periods." (Park *et al.* 2004, p.1226) Politicians are eager to act when it is clear something must be done, such as after any natural disaster has occurred. Yet politicians are reluctant to spend precious resources on programs that are only valuable if something happens. This can plainly be seen when looking at the expenditure of the US Federal Emergency Management Agency (FEMA). Ganderton notes that between 1988 and 2001 US$28 billion was spent on recovery while only US$2.6 billion was allocated to mitigation, less than 10% of the amount on recovery (Ganderton forthcoming). Preemptive techniques to deal with disasters, such as detection and mitigation, receive desperately few funds even when these disasters regularly occur on an annual, or near-annual, basis. With this in mind, it is easy to see why the extremely remote chance of a threat of a NEO impact has so far failed to convince governments that funding must be allocated in order to detect and mitigate this threat.

Indeed, it is possible governments or agencies will not deign to allocate significant, or even sufficient, resources to NEO detection and mitigation until a future collision with a NEO is confirmed. However, the expected annual cost of NEO impacts, which lies within a broad range from $60 million to $1.1 billion, implies that it makes sense to spend up to at least $60 million per year, every year, on a program of detection and mitigation development of the large "global killer" objects. Of course, it is evident from the case of an impact from a high inclination long-period comet that, given our limited detection capabilities, by the time the threat is detected it would likely be too late, no matter how much money is thrown at the mitigation project. Given this dilemma, it is important to assure current funds allocated to NEO detection are optimally utilized and that there are coordinated national and international efforts to secure funds for detection, data management, and mitigation strategy development.

5.4.1 Why Should We Fund NEO Detection?

Early warning of a NEO impact could save lives and, thus, reduce the cost of an impact. Although mitigation programs could potentially provide a total reduction of costs, even detection by itself can provide substantial reduction in the economic cost of impact. Advanced detection and warning of a collision could provide enough time for threatened areas to be evacuated. This would reduce, if not eliminate, the loss of human life which is by far the most costly aspect of any potential impact disaster in economic and human terms. This is evident as seen in the Indian Ocean earthquake-tsunami discussion in Chapter 2. Even if an object is detected too late for any effective deflection or disruption mission to be implemented, a detection system can significantly reduce the cost of the impact. This highlights the significantly high cost savings a detection system represents in comparison to a mitigation program. Although a detection system does not reduce the costs of a "global killer" scenario, detection alone, combined with effective evacuation plans, is still a viable method of reducing the cost of the smaller consequence local/regional impacts which we are far more likely to encounter.

5.4.2 A Perspective on Funding for Natural Disaster Mitigation

It is not entirely clear to the public and policy makers that more funds should in fact be dedicated to NEO detection and mitigation given that there is already approximately US$5 million per year allocated through NASA's budget. For example, if we take the estimated annual cost of total NEO impacts to be around US$200 million per year (a compromise between the two cost estimates discussed in the cost section in the assessment chapter) then we find that detection and mitigation strategies allocations are about 2.5% of the expected disaster cost. Although this seems low, we must remember the mitigation expenditure for FEMA was only 9.3% of its expenditure on response and recovery. Furthermore, FEMA expenditure on recovery only represents a fraction of the total cost of the disasters. The most expensive U.S. natural disasters from 1988 to 1996 total in excess of US$100 billion (Anon 2005 and van der Vink et al. 1998). This means FEMA natural disaster mitigation expenditures are roughly the same percentage of the costs per natural disaster as NEO detection/mitigation expenditures are per the expected cost of a NEO impact, around 0.025. If the disaster costs up to 2001 are included, the percentage for FEMA would in fact be much lower. From this analysis, it is clear the detection and mitigation efforts geared towards a NEO threat are in fact reasonably well-funded in comparison to the mitigation funding for other natural disasters, and especially given their low probability of occurrence.

This does not suggest that funding for NEOs detection and mitigation should not be increased as clearly there is too little funding to do the job properly. What this analysis makes clear is the highly reactive way that humans deal with natural disasters. If we combine this with the low probability of an impact it is clear that, for better or for worse, the NEO community must come to terms with the fact that any significant increase in funding is extremely unlikely. The international NEO community must focus on maximizing the use of current limited resources and put off discussions of elaborate space based detection systems which, however desirable, will be economically impractical for many years to come.

5.4.3 Options for Future Funding

Funding to deal with the NEO threat may not be very likely to increase in the near future; however, old funding sources may dry up and new ones may need to be found. The following are potential options for funding sources for NEO detection programs.

The United Nations

Although the U.N. is occasionally effective in consolidating the global community's interest on a certain topic, it is less effective at making decisions or securing funding. Most nations are extremely hesitant to promise new funding to U.N. programs, as governments often believe that funding national programs better fulfills their goals. This, combined with the low probability of a NEO impact, means the U.N. is not likely to become an effective venue to lobby for increased NEO detection funding.

Private Investments

Philanthropy has long played an important role in the history of science. It is not inconceivable that a wealthy individual, or group of individuals, could be persuaded to devote some of their wealth or their estate to NEO detection and mitigation programs if they could be convinced that the endeavor was a valuable cause. However, the case for philanthropic NEO program endowments is a very difficult one to make since it competes with far more urgent issues such as famine, world poverty, disaster relief, education, and a host of other interests most people can relate to, or find far more pressing.

Private companies may be willing, if enticed with subsidies, to develop technology that could be used for NEO mitigation as this technology could potentially be utilized in any NEO resource extraction efforts. Although SpaceDev has indicated it intends to fund a private mission to a NEO, the age of asteroid mining is at least a few decades away from becoming economically viable. In the long term, privately developed technologies and competences may, in fact, eventually provide the backbone of a NEO mitigation mission. However, for the short term, NEO detection and mitigation will likely remain the purview of governments.

National Funding Based on a New IGA

All funding allocations for the NEO detection effort are currently done at the national level and it is likely to remain this way. Currently seven nations have programs of NEO detection, the U.S., U.K., Europe, Japan, China, Canada and Australia. In order to optimize the global detection effort, we propose that it would be beneficial to establish the INEOC, with nominal funding from the participants. In this framework, nations would still fund their own national programs; in turn, these programs would contribute a very nominal amount, in the order of a few thousand dollars, to help with the operation of the INEOC. The goal would not necessarily be to increase funding for NEO detection efforts but to better coordinate international efforts so the few funds that are allocated are spent in a way that best serve the global NEO community. The INEOC could also coordinate efforts for space missions to be used for NEO detection or mitigation tests if these efforts do not conflict with primary mission objects.

5.4.4 Implications for Future Efforts

It is clear the detection of all objects greater than 1 km, which threaten the entirety of human civilization, is an extremely valuable and potentially species saving exercise which must continue to be funded for both cataloguing and monitoring. If the cost of the event, such as the obliteration of humanity, is infinite, then it is sensible to spend what is necessary to ensure it does not happen. It is unclear; however, that pursuing a much more expensive program to catalogue the smaller NEOs is a practical or desirable endeavor. As the NEO size decreases, the cost of detection increases disproportionately to the economic damage caused by smaller impacts. This represents less than 10% of the expected damage despite their more frequent occurrences. It seems unnecessary to expend significant resources to catalogue and monitor the estimated 100,000 NEOs in the 50 to 200 meter range, as they pose no greater risk than any other major natural disasters that we have come to accept (Yeomans 2003). Expending vast amounts of resources to prevent a low probability natural disaster is, unfortunately, not a current practice. All discussion of NEO detection and mitigation programs, especially their funding, must bear in mind our heavily reactive human nature when dealing with natural hazards.

5.5 Conclusions and Recommendations

As previously discussed, there are many aspects to address in developing an international infrastructure for NEO detection and threat response. Policy, legal, and funding obstacles need to be dealt with for the successful implementation of a new IGA and C&C plan.

This chapter stresses two recommendations:

- The creation and implementation of INEOC
- The implementation of the proposed C&C plan

There is a chance to avoid global disaster, if the world is prepared, by having established the proper framework and systems for detection, characterization, and mitigation. Currently, there is a lack of coordinated international cooperation. To achieve a level of preparation and readiness, INEOC will coordinate the participating States in the planning and C&C phases of the ongoing process.

INEOC should be established to coordinate international cooperation with the following objectives:

- To coordinate current and future efforts to detect, characterize, mitigate, and manage NEO resources and data at an international level
- To optimize existing resources (expertise and facilities)
- To utilize a C&C protocol upon confirmation of a NEO threat

Funding priority should be given to detection systems for early warning of objects that pose a global threat. There should also be increased funding for the MPC to improve and extend its competencies.

By implementing the proposed C&C protocol, the international community is pre-arranged to address NEO threats. If the Threat Response Team needs to be mobilized due to a NEO threat, the general process, as well as policy and legal issues, are already addressed. The State governments and space agencies can then focus on the best possible mitigation strategy without the distraction of limitations or conflicts of interest.

5.6 The Cassandra Scenario

An assumption for the Cassandra Comet Scenario is that international cooperation is already established in the form of INEOC. Several interested States signed an IGA to define the coordination efforts pertaining to the Steering Committee and the four specialized working groups. A clear international C&C plan has been outlined by the Threat Response Team. The design and manufacturing of various systems to address such a NEO threat were performed

After initial detection of the object 280 days prior to EI and subsequent characterization of the NEO as potentially hazardous, the data is posted to the MPC's secure website for validation by professional and selected amateur astronomers and astrophysicists. The following two to three days focuses on using all available ground- and space-based assets to perform additional observations. Once the threat from Cassandra Comet is verified, the INEOC Threat Response Team is mobilized and their first order of business is to inform the UNSC, the national governments, media, and the public. Monitoring of the object continues and additional resources are employed as necessary to better define the NEO's characteristics. The Threat Response Team would review previously-planned (and ideally tested) mitigation responses to make the best possible selection of a mitigation strategy.

Given the short warning time in this case, the most likely response is a nuclear disruption strategy. Participating national governments are then informed of the proposal, as is the UNSC. In this scenario, it is assumed the national governments accept the proposed mitigation strategy, given the danger posed by the comet and the lack of other effective mitigation options. These governments set about resolving any further legal and policy issues that could hinder the implementation of the proposed strategy in a timely manner, keeping in mind the goal of protecting humanity from peril.

The national governments, with the assistance of the Threat Response Team, use all available resources to implement the accepted plan. They use technology and expertise from both the military (for use of nuclear devices) and the space agencies (for mission design). Due to the extremely tight timeframe involved, existing technology for the nuclear device, spacecraft, and launch vehicle are used. A round-the-clock effort is conducted to ready the mission for launch as soon as possible. Launch occurs a minimum of 180 days prior to EI, leaving only 60 days for mission design and launch preparation.

Once the mission is launched, the Threat Response Team monitors the mission's progress and evaluates the success of the mitigation device. They then determine what additional steps, if any, are required.

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Chapter 6

Social Implications

In order for governments and international organizations to allocate the resources needed to manage a NEO threat, public support is essential. This is more critical with high inclination objects because of the short warning time. As mentioned in previous chapters, the cost of developing, coordinating, and implementing programs is quite high. Governments must gain public support in order to release funding. This can be accomplished by informing and educating the public about the realities of a NEO threat. After analyzing the public's beliefs about or awareness of NEOs, appropriate educational approaches can be designed that take cultural influences into account. Scientific outreach programs, traditional or institutional education, and the use of media will be valuable tools in facilitating communication with the public.

In the development of any policy, governmental agencies must take into account public awareness of, and reactions to, the NEO threat. Effective communication between the scientific community and the public will be an essential component of any administrative strategy.

The media is the main player involved with proper dissemination of knowledge about high inclination NEOs and distribution of information for an impact warning. While the media is the key to communication and knowledge, it can be considered an obstacle as well as a facilitator.

Because of the complexities and breadth of the various social issues involved with the NEO threat, this chapter focuses on the current public awareness of NEOs, societal reactions to the above proposed detection and mitigation strategies, and the role of the media as a tool to inform the public of a NEO threat. Finally, the report offers an approach to use the media to help the scientific community and the public communicate effectively on these issues. Some suggestions to inform the public are presented below to help acquire and maintain public support in order to further efforts to protect the population from high inclination objects and to prepare populations for warnings of an impact.

6.1 Public Awareness

Before implementing any proposal designed to gain public support or deal with public reaction to a threat, the scientific community must understand the public's current knowledge and beliefs concerning comets. This step involves much more than simply measuring factual awareness. The personal, societal, and broad cultural meanings attached to this knowledge also are relevant. Only with this information can meaningful action be taken.

6.1.1 Representations of Cosmic Threats

Any understanding of reality, including the public understanding of a NEO threat, is partially based on representations, or mental objects created and modified by experience. These representations may have two interrelated dimensions: a subjective, individual dimension ("I think comets are aesthetic.") and a collective social and cultural dimension ("Comets are bad omens."). The latter has been studied in sciences such as history, archaeology, and paleontology.

Historical Representations of Celestial Bodies

The celestial environment has regulated the evolution and current pattern of life on Earth through its imprint on biology (solar and cosmic rays, lunar tides, human menstrual cycle) and societies (concepts of time). For example, the origin of life itself may lie in NEOs. An initial bombardment of asteroids and comets may have prevented the appearance of life, until a less intense rain of comets could bring life-supporting materials, such as water and/or amino-acids, to the surface of the Earth. Although archaeological records do not provide sufficient evidence, some mythological catastrophic events, such as the Biblical flood, might be related to destructions from volcanic eruptions, earthquakes, and celestial encounters (see Peiser et al. 1998 for the hypothesis of an impact during the Bronze Age).

One still can visually perceive the Sun, the Moon, the Milky Way, planets, stars, and comets appearing and disappearing in the sky. All these have been culturally represented since the dawn of our species, and often are related to supernatural powers (e.g. gods and their activities). Unusual events, such as eclipses, celestial conjunctions, or passing comets always have been perceived as particularly meaningful events. During the 5th century B.C., the Chinese Han Dynasty recorded the passage of comets and omens associated with them. Similarly, another comet led to the fall of the Aztec empire because Emperor Montezuma decided, under its auspices, not to oppose the arrival of Cortes.

With its period of approximately 75 years, the famous comet Halley has followed the history of mankind since 240 B.C. In 1066, it was observed throughout Europe. The English considered the comet a bad omen related to the death of King Harold II. However, the French saw it as a good omen after their victory at the battle of Hastings (as illustrated in Figure 6-1).

Figure 6-1 Halley Comet or "Travelling Star" in 1066 on the Bayeux Tapestry (Ray 2005)

More recently, in 1910, scientific predictions were made that the Earth would pass through the comet's tail, which resulted in the social expression of fears of poisoning by the tail's gasses. The comet's most recent passage in 1986 raised public interest as an unusual and aesthetic event.

While some historical representations now may seem opposed to modern science, some individuals, groups, and societies still refer to comets with dread. On March 26, 1997, in California, thirty-nine Heaven's Gate followers committed mass suicide. The followers believed they were catching a ride on comet Hale-Bopp's tail. The cult thought that the comet was hiding a spaceship that would bring them to a higher level of existence. To embark, they had to leave their physical containers (i.e. bodies) behind so that the spaceship could provide a new physical envelope. This illustrates the level of influence, albeit extreme, that celestial representations can have on our lives.

Current Perceptions of Near Earth Objects

The media's influence in shaping and transforming representations has grown enormously with the development of mass media broadcasts. The names, metaphors, or catch-phrases that the media uses in their descriptions produce a "common" understanding of disasters. Similarly, the representations of comets and asteroids in the public now carry not only giggles, but also visions of global destruction and technological means to avoid them.

The general public clearly understands the short-term and long-term outcomes of disasters caused by weather extremes and other natural disasters. They have either personally experienced such threats or have seen, heard, or read media reports. When compared with such catastrophes that are very real and easy to understand, the risks from NEOs do not seem as significant. Even though the damage caused by NEOs, especially ones with diameters larger than several tens of meters that may be more devastating than the 2004 Indonesia tsunami, public awareness of the hazard is low, and, in some places, nonexistent. The problem is compounded by the fact that, as already mentioned, even the astronomical community does not have a common opinion on the NEO threat. The probabilities given for impacts have shattered the image of one part of astronomy (i.e. the study of NEOs) to the point where some astronomers tend to stand away from it, judging it too far away from science. As Morton describes (Planetary Defence Conference), NEO astronomy has reconnected two independent approaches to astronomy: one which looks deep into space and one which looks at celestial influences on the Earth.

To illustrate this diversity of opinion and interest within the space-faring community, students and faculty from the ISU SSP05 were asked to rate the following questions based on a 1-10 scale (1=realistic; 10=unrealistic).

1. Will humans be able to launch a transponder onto a NEO?
2. Will humans be able to mine NEOs for Earth and/or Mars resources?
3. Will humans be able to board and fly a NEO for transportation to another solar system?

The results from the 67 answers are displayed in Figure 6-2.

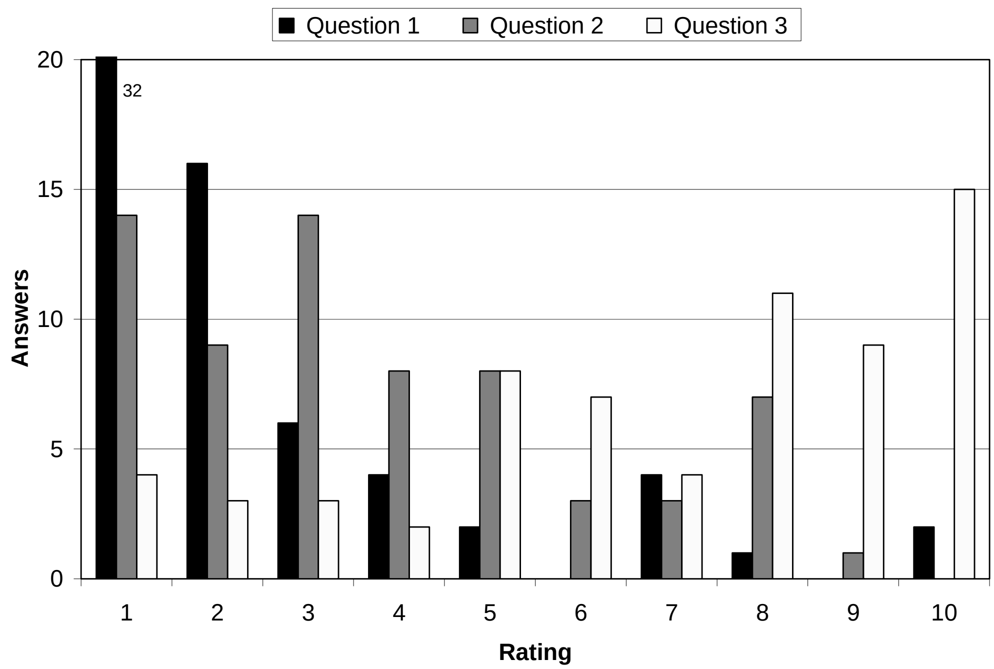

Figure 6-2 Survey of SSP05 Opinions on Potential NEO Uses

Although at first glance, the above questions may seem unrealistic, or perhaps impossible, it is important to note that several people in the space community still thought that these were viable options in the future. No timeline was given by design so as not to influence those polled. Another interesting point to notice is that the population polled have different backgrounds, nationalities, and ages; but all have an interest in space. The poll was designed to explore what the space community might think about NEOs through some of the mainstream ideas about opportunities to use comets for human advantage and positive outlooks about them.

For example, harvesting NEOs could interest the mining industry, while sending transponders could interest scientists. The result could be an increase in people's general knowledge and understanding about NEOs. But if these suggestions are regarded as ridiculous, there is a risk of backlash stimulating a giggle effect rather than scientific awareness.

Culture is a complex but important factor in explaining some meanings attached to NEOs. Various traditions regarding the role of mankind and nature provides understanding into how culture may influence one's representation of a cosmic threat. The tradition of Eastern philosophy of nature, for instance, envisions the fate of mankind as being part of the fate of the Universe. Oversimplifying even more, if mankind were not able to detect and/or mitigate a threat to the Earth, this might simply mean that it was not meant to be. This acceptance of a dreadful fate may seem contradictory to the Western tradition focused on mastering nature.

Recently publicized research on asteroids and comets (Deep Impact mission to comet Tempel 1), sensational disasters shown in blockbuster motion pictures (Meteor, Armageddon, and Deep Impact movies), and occasional news reports of predicted "near misses" have fueled public interest in the impact hazard of NEOs. However, as individuals are more aware of what they can experience by themselves, the lack of human experience of impacts has kept the public perception focused on the catastrophic consequences described by movies and popular science. Even scientific investigations, by concentrating on the study of very ancient and destructive events, have created "an unconscious bias within the scientific community that any future events will have similar consequences" (Weissmanin 1994). Despite growing awareness of the importance of historical traces (Peiser 1998), there are no remarkable examples of such a global scale catastrophe in recorded human history, be it eyewitness or historical reports.

Worst-case scenarios are more easily portrayed in the media, such as climate change, global scale ecological disasters, mass extinction of species, civilization collapse, or even the potential eradication of all humans. But, it is difficult for the public to accept or genuinely believe that this could be real. The lack of direct experience leads to a lack of acceptance or even of awareness that a celestial impact risk exists. Some of the public still may consider it as either fictional or as a low likelihood event that is not worth worrying about. There is an important gap between the intellectual acceptance of scientific possibility and the emotional acceptance that "it could happen here in one's lifetime."

6.1.2 Factors Influencing Public Awareness

NEO impacts, like other natural disasters, are characterized by complex relationships and interactions between physical hazards and society (Weichselgartner & Bertens 1998). Perceived risk does not necessarily follow the latest estimation of statistical risk, which itself is not a perfect reflection of true risk. In order to promote public awareness in the most efficient way, the scientific community must understand the interconnected factors which influence public awareness and opinion.

Social Representations of Scientific Knowledge

Commonly shared representations are processed by human societies to create a "common sense," or a framework of references, which are then individually used to give a sense of our own subjective reality. Some of our representations can easily change as a result of interactions with the environment, be it direct (people) or indirect (media). Moscovici (1984) showed how scientific knowledge is reduced in the general public to a limited set of social representations, which vary from group to group and which do not always obey rules of rationality.

Although contemporary societies offer more scientific explanations than myth-based civilizations, it is naïve to expect a universal understanding of "scientific facts," especially when such facts cannot be expressed without the use of probability and uncertainty. Modern science has become accustomed to assuming a predictive role in the media (e.g. weather forecasting), but only recently has it been asked to provide predictions on astronomic space and time scales.

Accuracy and Timescales

Predictions of NEO impacts often are modified through time as additional data becomes available and accuracy is improved (Chapman 2003). From the public's perspective, it may be difficult to believe that a real threat is expressed by a changing probability, which, in some cases can easily be interpreted as uncertainty. As a result, public awareness may be reduced and trust in the scientific community may be lost.

It is obvious that probability is not understood in the same way by mathematicians and the general population. For such low probability events as NEO impacts, the important issue to the layman is not the statistical frequency of impacts, but the determination of whether an asteroid or comet will collide with the Earth in the next few decades (Mardsen 2003). Unfortunately, NEO probabilities are based on heterogeneous data, which are not evenly distributed in time (Weissmanin 1994). Moreover, unlike weather warnings which are relatively short-term, NEO predictions can span months, decades, or centuries. The public may become quite confused with this unusually large time span, and may decide to lower its level of awareness and concern. There is little doubt that public perception eventually would change dramatically if there were a threatening encounter. High inclination objects would then be of particular significance.

Hazard, Probability, and Risk

The probability of a close approach is central to determining the threat of impacting asteroids and comets from outer space (Chapman 2003). The higher the probability, the more the general public is willing to accept that actual danger exists. However, when using probability, it is necessary to know the associated error. Uncertainty remains a fundamental attribute of forecasting sciences. It is very difficult for technical experts to communicate uncertainty to the general public in ways that will encourage people to follow suggested practical measures. Even experts can misinterpret a given risk. One can commonly experience the limits of scientific communication capabilities, such as when daily weather forecasts are rarely acknowledged when correct, yet always criticized when wrong. As expressed in the white paper of the Planetary Defence Conference (2004), probability might not be the best way to express risk in the case of NEOs, and might even confuse the public perception of this specific risk.

Some definitions might be useful to better distinguish between hazard and risk. A hazard is the result of a dangerous event (drowning or burning). This hazard can be compounded with a probability in order to express a risk. The resulting risk thus takes into account both the consequences and the probability associated with events of this nature. In such terms, NEO impacts at large represent a great hazard, but with a very low probability of happening and, thus, a low risk.

$$\text{Risk} = \text{Hazard}*\text{Probability}$$

Comets, especially long period ones, represent an even lower risk than asteroids (estimated by Stokes et al. 2003 at roughly 1% of the total threat). However, in terms of pure hazard, the size and high velocity of comets make them a greater hazard to mankind.

6.1.3 Shift in Perceptions

Since the threat of NEOs is defined in terms of probabilities and uncertainties; the public's perception is mixed with disbelief, fear, and denial. In order to change this cycle of uncertainty and increase awareness, vulnerability to the NEO threat needs to be accepted.

The Giggle Factor, Dread Factor, and Cassandra Complex

The "giggle factor" (Martin 2000) points to the fact that planetary defense often is laughed at (the SETI program, even now, is another target of this giggle factor). Planetary defense also can be connected to a "dread factor." According to Slovic (1987), individuals do not base their fears on statistics. Instead, each develops his own personal dread factor for various frightening scenarios based on personal experience and knowledge. Most people are far more worried by humans and technology than they are about natural disasters. Among natural disasters, celestial impacts are often awarded an even lower dread factor because of their infrequent appearance in recorded human history and everyday life.

The giggle and dread factors can be intimately connected. Things that make us laugh are sometimes those that we also fear. We laugh at and fear cosmic disasters because we are reluctant to conceive them as real threats, which can represent the end of mankind.

These two factors need to be associated with a third phenomenon, the Cassandra complex. A good definition of the Cassandra complex is given by Kahn (2001). "Intelligence faces two all-encompassing, never-ending problems…. The first problem is how to foretell what is going to happen.… Prediction may be getting better, but it can never be perfect. Even if it were, it would confront intelligence's other basic problem: how to get statesmen and generals to accept information that they do not like. This problem, which may be called the Cassandra complex, is as old as Mankind." At the heart of the Cassandra complex lies denial, which is a classical defensive process. Reality is denied in order to avoid its consequences. The Cassandra complex recently has been referred to in discussions of bioterrorism and US domestic security (2002).

Vulnerability

As a means to shift perceptions encompassed by the Cassandra complex, acceptance of our current vulnerability to the NEO threat is essential. Weichselgartner & Bertens (1998) define vulnerability in the context of natural disasters, as the "condition of a given area with respect to hazard, exposure, preparedness, prevention, and response characteristics to cope with specific natural hazards." This concept has the decisive advantage of encompassing both biophysical and social aspects of disasters.

Impacts at large could be considered a hazard to which the biosphere of the Earth (including mankind) is highly vulnerable, even though the risk itself remains low. Detection programs have been assigned the task to detect high hazard, or kilometer-sized, asteroids and comets. However, densely populated coastal areas represent a great exposure to any ocean impact. Preparedness for short- or no-warning impacts, typical of long-period comets, is, for now, non-existent (there are no "ready-to-go" mitigation missions). Even if a mitigation mission successfully reached its target in time, uncertainties regarding the composition of large objects might prevent proper mitigation, and even add to the initial impact hazard. Finally, our disaster response capabilities (rescue, relief, recovery, reconstruction) could easily be overwhelmed.

Just as it takes time to create social representations, it also takes time to change them. In the past, for example, it took generations to accept that the world is round, or that the Earth is not the center of the Universe. The acceptance of a steady cosmic threat is a new challenge to the human mind, as it implies the representation of our own death as a civilization or even as a species.

6.2 Public Response to Detection and Mitigation

In addition to general public awareness concerns about NEOs, public opinion plays a vital role in the development of specific mitigation and detection strategies. Without public support for the expenditure of funds and the development of national and international policies, it is unlikely that workable detection and mitigation efforts would result. Moreover, as more NEOs are discovered and publicized, public awareness of the threat escalates and, consequently, public opinion may become divergent.

6.2.1 Response to Developing Technologies

People's opinions about detection and mitigation strategies vary from positive support, passive acceptance, violent opposition, to total disregard. It is unlikely that consensus can be quickly realized. As an extreme illustration, after the July 2005 Deep Impact mission, a Russian astrologist decided to sue NASA for having deflected the Tempel 1 comet. She asked for US $300 million for moral damage, arguing that her grandparents' romance was linked to the comet, that the impact could lead the comet to hit the Earth, and that the change in the comet's path would alter her fate (Liss 2005).

Unless public benefits, both economic and otherwise, are clearly defined and well accepted by the general population, funding for proposed detection and mitigation strategies will remain problematic. Also, by addressing detection and mitigation strategies with the public, the population then will become aware of the potential spin-off benefits of technological advances made through these strategies which may benefit the world's economy and, thus, bring more support from the public for these proposed strategies. For developing detection and mitigation technologies, one possible cost-effective solution may be to develop NEO programs as inexpensive add-ons to space missions conducted for other purposes.

6.2.2 Response to Detection Strategies

Detection is a key component in any strategy that deals with a NEO threat. Some public interest groups may be concerned with the appropriate level of public attention given to the NEO threat. Issues that need to be discussed include whether more telescopes should be built, which funds should be shifted from their current efforts, and, with developing detection technologies, how much warning time likely would be available before impact with the tracked bodies. The public also may be concerned with the accuracy of the impact prediction (Chapman and Durda 2001).

6.2.3 Response to Mitigation Strategies

The public may debate whether we should adopt either a proactive method or a passive method for mitigation. For example, assume that we have tracked a NEO and have calculated that an impact would occur 100 years later; whatever the chosen method, the focus is when and where the mitigation procedure should start.

Response to Deflection

Deflection methods rely on changing a NEO's trajectory so that it crosses the Earth's orbit either in front of or behind the Earth. This kind of method may be favored by certain interest groups because there are limited environmental repercussions to the Earth. However, there may be public outcry from non space-faring nations concerned with the possibility that if there is only sufficient time to deflect the NEO to a remote region for impact in order to lessen loss of lives, then a low population region would be selected. Governments of low population states likely will need to develop preparation and evacuation strategies. Another concern is the risk of technology misuse, which could be greater than the risk of a NEO impact. Some public interest groups may believe that building deflection technologies in advance could be more dangerous than the threat they are designed to address (Chapman and Durda 2001; Harris 2002).

Response to Disruption

Because destruction of high inclination NEOs that are either relatively large, or are detected with minimal warning time, will require nuclear explosives, the public will be concerned with the issue of whether we have the capability to destroy the NEO. When the NEO is disrupted into multiple and possibly dangerous uncontrollable pieces, the public will want to know how we can deal with the radioactive debris. In a wide range of cases, disruption of the NEO poses the potential risk of greatly augmenting the danger. There is great concern for the practical problems of dealing with the numerous, randomly deployed fragments of a disrupted body. In the case of small-sized NEOs, however, considering disruption rather than deflection is appropriate (Chapman and Durda 2001). Members of the public also may be concerned that a series of additional consequences will be created, such as climate change and air pollution. Concerned interest groups may debate whether the cost will be more expensive than the impact, and whether such costs could be minimized.

Collateral damage is a real concern. Even if an incoming object were destroyed, it is feasible that radioactive debris or segments of the NEO still may impact the Earth. The public will be concerned about how to deal with radioactive fallout and the nuclear weapons themselves. It is possible that a failed launch may do more damage to the environment than that of the impact.

There also may be debate in the public forum over proliferation of nuclear technology for weapons development or as a contributing factor to a nuclear weapons race.

6.3 Media

The media has great influence over social representations, attitudes, and behaviors. Indeed, the first contact of the public with NEOs is usually through media coverage rather than educational programs or public outreach. Media reports could be unreliable because the media does not have the accuracy of science, nor the concern of educators, but offers itself as a powerful tool to convey the information that it perceives people need to know. To ensure that public awareness of NEOs and public response to detection and mitigation strategies are not distorted, it is necessary to understand how the media has responded to disasters in the past and how the media can best be used as a tool to responsibly inform the public.

6.3.1 Media Sensationalism

Mass media exerts a powerful force on today's society. Through the use of general communication tools such as television, radio, newspapers, and the internet, the media reaches a large number of people. Two important sociological characteristics of mass media are, that a very few people can communicate to millions, and, that the audience has no effective way of answering back. The media acts as a gatekeeper of information by deciding what information is released and what is not. This gives the media the ability not only to inform the public regarding impending disasters, but also to influence people's perceptions, attitudes, and behaviors towards these potential calamities.

Disasters that have earned the attention of international media include both slow-onset catastrophes, such as famine and droughts, and sudden disasters, such as earthquakes and hurricanes. While we can develop the technology to destroy or deflect some approaching objects, 100% accuracy is not possible. Not all objects have been found, and there is a 40% chance that a major comet or asteroid may arrive with very little advance warning (Chapman and Durda 2001). The mass media plays a crucial role in warning the public, and the manner in which the message is presented will be significant.

6.3.2 Mass Media Disaster Reporting: 100 Years of Influence

Although mass communication always has been an important social force, the development of new technologies over the last one hundred years has both expanded the media's influence and made its impact more immediate. It effectively has been used as a vehicle to mobilize people around an issue, be it the German media rallying Nazi sympathizers to the Third Reich or American newsreels rallying concerned citizens during the 2004 Tsunami relief drive. Historically, media hyperbole regarding high inclination NEOs has led to striking consequences.

Today, there is an opportunity to create a positive awareness concerning NEOs, raising interest in astronomy and giving explanations on comets in general. Several recent news reports have created an impression of "doom and gloom" for society, including recent reports regarding Asteroid 2002 NT7. The story of this asteroid illustrates both the craze and disinterest from media about NEOs. The asteroid was announced with a high probability of impact on February 1, 2019. It commanded sensational headlines for several days, although the case was quickly dismissed by further calculations. A news organization took information from NASA's site about the NEO and, out of context, sensationalized the story. Needless to say, afterwards there were no sensational headlines explaining that the comet would not hit the Earth. Risk perception experts acknowledge that such exaggerated reactions are not uncommon. They forecast that a predicted impact event is likely to elicit public responses that will be somewhat unpredictable, depending on how risks are perceived. The risk range categories have been classified as uncontrollable, involuntary, fatal, and catastrophic in the risk perception literature (Walker and Huebner 2004).

6.3.3 NEO Hype: "Crying Wolf"

Astronomers recently have developed effective search programs which have detected more asteroids passing very close to the Earth. These discoveries suggest that an impact in the foreseeable future cannot be excluded with total certainty. Such cases are being noticed by the media, and announcements of "impact predictions" are often made with a great deal of hyperbole and dire predictions. Recent headlines include: "Armageddon set for March 21, 2014," "Earth is Doomed," and "Asteroid Doomsday" (Britt 2005). When verification observations have removed the uncertainties, charges of "crying wolf" are laid -- "the scientists were wrong again." On August 24, 2003, astronomers in the LINEAR program initially calculated an asteroid trajectory that made the object appear to be hurtling 120,700 km per hour with the potential to strike the surface of the Earth on August 24, 2014, with a destructive power of 360,000 megatons TNT, which is 8 million times greater than the 1945 Hiroshima atomic bomb impact. This news was sent to the British press and within hours large portions of the population were jolted by the fear of this impending devastation. However, a revised version of the statement was later issued by LINEAR advising that the chances of impact were close to zero and that there was nothing to worry about from the celestial body in 2014.

Because the media determines what the public will see and hear, an uninformed and apprehensive public may be particularly vulnerable to influence. The business goals and/or political agendas of the information and entertainment media often run counter to the impartial purposes of informing and educating the public as a part of the public relations goals of the scientific community. There are many pressures in the media world to emphasize dramatic events in their coverage. "If it bleeds, it leads" is a common phrase in the television community used to explain how news stories are prioritized (Vergano 2003). A news program is primarily focused on the facts, but, in order to capture and sustain the audience, television and the print media tend to emphasize the dramatic, through generally violent, stories and images. The public is kept informed, but they are often unaware of any potential hidden agendas or distorted facts.

The media's influence through the news affects the public both consciously and subconsciously, and even, in some cases, sends us about our lives unnecessarily fearing remote dangers that were excessively and alarmingly portrayed in the news. Astronomer Duncan Steel suggested that asteroid stories have become so common that unless a reporter makes the news sensational, the story will not be carried (Morrison et al. 2004). Such melodramatic portrayals create a continuous notion of impending disaster that either diminish public confidence in the reliability of the information or create unnecessary fear.

6.4 Importance of Preparedness

Handling media issues is essential to maintaining credibility of the warnings or to limiting the "giggle factor" associated with very uncommon occurrences such as NEO impacts. If NEOs are regarded as a serious matter, it will ease the tasks ahead. Effectively dealing with media issues is a solid first step in preparing the public for NEO threats.

So far, historical experience tends to prove that governments are systematically surprised by unlikely disasters. Either the threat never occurred in the past, and thus is supposed to never happen in the future, or the knowledge of past disasters has been lost. What is of essence in the case of high inclination NEOs is that the forewarning can be very short. Unless actions are taken to detect high inclination NEOs and to prepare mitigation strategies for this specific threat long before the threat becomes a reality, there will not be sufficient time to prepare once a NEO is detected.

Government involvement also is a function of public perception of the problem. Depending on the public support, involvement, and emotion, governments can enforce some plans and ignore others. As an example of government involvement in public perception, on November 24, the Great Storm of 1703 hit southern England and the English Channel. This destructive storm was said to be an expression of God's anger. December 16 was declared a day of fasting by the government to acknowledge the "crying sins of this nation" and to "loudly call for the deepest and most solemn humiliation of our people" (Wikipedia 2005). The disaster management after the storm illustrates how the government used a cultural belief, in this case religion, to maintain awareness of a specific threat through time.

In some estimations, statistically speaking there is almost as much chance to die from a passenger aircraft accident as from a NEO impact (Table 6-1) (Chapman and Morrisson 1994). Still, the NEO threat is not addressed as flight safety is. The recurrent consequences of airplanes accidents such as casualties, emotional responses, and economic implications, are a constant reminder that there is a problem to solve. It is the opposite for NEOs for which there is hardly a chance for anyone to see one in his lifetime until a global disaster occurs.

Table 6-1 Chances of Dying from Selected Causes

Chances of Dying from Selected Causes in the United States	
Motor Vehicle Accident	1 in 100
Murder	1 in 300
Fire	1 in 800
Firearms Accident	1 in 2500
Electrocution	1 in 5000
Passenger Aircraft Accident	1 in 20000
Asteroid Impact	1 in 25000
Flood	1 in 30000
Tornado	1 in 60000
Venomous Bite or Sting	1 in 100000
Fireworks accidents	1 in 1 million
Food Poisoning	1 in 3 million
Drinking Water with EPA limit of TCE	1 in 10 million
Courtesy Dr. C. R. Chapman & Dr. D. C. Morrison	

6.4.1 Historical Scientific Responses to NEOs and Natural Disasters

The below examples illustrate how scientific communities and authorities in the past have reacted to comets and natural disasters. The examples show how, on one hand, authorities have taken advantage of events, and on the other hand, have not been able to process information to help prevent loss of life during a disaster.

Shoemaker-Levy

From July 16 through July 22, 1994, the comet Shoemaker-Levy impacted Jupiter after its fragmentation into several pieces, some of which were up to a few kilometers wide. "The disruption of a comet into multiple fragments is an unusual event, the capture of a comet into an orbit about Jupiter is even more unusual, and the collision of a large comet with a planet is an extraordinary, millennial event" (JPL 2000). This impact was a great learning opportunity for scientists and a great event for the entire amateur astronomers' community. The energy released by the impacts was greater than several of the world's biggest nuclear warheads, and the flashes could be observed as reflections on Jupiter's moons. The event, aside from putting scientists in high spirits, reminded us of the possibility of impact on our own planet, and renewed interest in inventorying NEOs, the frequency of impacts, and their consequences.

Tangshan Earthquake

On July 26, 1976, the industrial city of Tangshan, China, which had a population of one million inhabitants, was hit by an earthquake resulting in the death of 25% of the population. What is noticeable is that one county, Qinglong, suffered no casualties except for one resident who had a heart attack. This county was warned about earthquakes as a result of official training drills two years prior to the earthquake (UNO 1974).

Indonesia Tsunami

On http://en.wikipedia.org/wiki/December_26,http://en.wikipedia.org/wiki/2004, December 26, 2004, an Indian Ocean earthquake resulted in a deadly tsunami off the coast of Indonesia. Despite the fact that this catastrophe recently occurred, much has been learned from it. Concerning the warning, several hours separated the earthquake detection from the tsunami that, nevertheless, surprised the coastal population. The earthquake was evaluated by scientists as too weak to cause a tsunami. The forewarning signs of the incoming threat were not interpreted accurately because the memories of previous tsunamis were lost because of the uncommon nature of tsunamis in the region. Exceptions are found, such as on the Island of Simeulue, which experienced a tsunami in 1907. People knew that the ocean's backward water flow was a sign of an impending tsunami. Further, a British schoolgirl in Thailand who had lessons on tsunamis was able to warn people on the beach.

6.4.2 Plan of Action

The central impediment to creating a preparedness plan is that society does not have the same concern about NEOs as floods, fires, and earthquakes. The crucial point lies in the fact that events with low probability usually result in tremendous consequences that we cannot afford and the accidents of high probability usually lead to limited damage.

This chapter recommends the following steps to enhance public awareness of NEO threats. First, it recommends education of the public by scientific analyses and assessments. The key to promotion of scientific information lies in the increase of the amount and quality of information provided. It is necessary to make the public understand the consequences of NEO impacts by means of qualitative, descriptive, and quantitative comparisons with other natural disasters. However, in order to avoid unnecessary fear, and, to provide precise and accurate information, some light also should be shed on the positive outcomes of NEO detection and characterization such as scientific evidence of the Solar System composition and origin, and mining interests, as shown in Figure 6-2 above.

Second, governments have a responsibility to promote public awareness of NEO threats. International cooperation, especially the leading roles of space-faring nations, is crucial in building the overall framework of the risk management system for NEO threats. The framework should take advantage of experiences in the risk management for other natural disasters.

Considering NEO threats as a global concern, it is necessary to emphasize that all the plans of action should be executed in the framework of international cooperation. As proposed in

Chapter 5.3.2, in coordination with other international organizations (such as IAU), national governments, and scientific communities, INEOC is responsible for detection, assessment, mitigation, and communication with the public.

Impact Warning: To Warn or Not to Warn

Following the paths of past disasters, previous research has suggested that most people depend on television, internet, newspapers, and radio for information and guidance when disasters strike (Brasch and Ulloth 2001). Serious long-term effects occur because media, more frequently than not, fails to deal with critical factors that lead up to disasters and fail to determine the severity of disasters. As a result, the media too often may contribute to panic elements associated with disaster, while neglecting to take affirmative steps to help prevent disaster and alleviate its impact after it occurs. Thus, the public no longer responds to panic tactics, and the result is a decrease in public response to disasters.

Advance warning of a high inclination NEO would allow time for planners to generate alternatives, to consult with other governments and international organizations, and to evaluate new information for implementing plans for disaster relief. Ample warning increases the opportunity for special interest groups to form, generate dissent, and initiate political action. Advance warning is likely to be very expensive and may create an economic slow down or a lowered quality of life. On the other hand, warnings could be counterproductive if they were routinely proven to be false alarms, or if the public does not believe that there are ways to mitigate the threat. Governments may consider it beneficial to avoid publication of high inclination NEO warnings. This choice of providing little or no notice of an impending disaster raises prospects for high casualties and the catastrophic failure of rescue and recovery operations. Although governmental policy regarding the threat of high inclination NEOs can vary, it is evident that better information exchange and coordination among the scientific community and the public could serve to reduce official mistakes and miscommunications.

Future Considerations

The low probability, high consequences, and short warning time of a high inclination NEO threat make education of the public necessary prior to detection of a threat. One way to do this is by taking advantage of peaked public interest in NEOs because of such events as NASA's July 2005 Deep Impact's encounter with comet Tempel 1, or even Hollywood movies portraying asteroid or comet impacts on Earth in order to educate the public into the realities of an impact possibility (NASA 2005). Education prior to detection will help alleviate some of the fears of the unknown. For example, if a NEO with a size of 200 m were to impact the Earth in one of the oceans, then it is possible a tsunami would be generated comparable to the one that devastated Indonesia in 2004. Although this would be viewed as a great tragedy, this type of information would allow the public to better grapple with the reality of a threat and prepare accordingly, rather than simply imagining the end of the world and feeling hopeless.

Improvements in education can serve the long-term goal of minimizing irrational and exaggerated responses to the impact hazard. Early education in schools about asteroids and comets could prevent confusion later on, and public information sessions may also aid in clarifying uncertainty and misunderstanding. Educational resources relating to NEOs should be made available to the public, including books and reports, CD ROMs, and posters with information and images relating to NEOs. To avoid media misrepresentation, background issues should be communicated to the public in a factual, objective, and impartial manner using broadcast and print media.

Facilitating Communication between the Scientific Community and the Public

The most efficient way to facilitate communication with the public is to utilize the media. The media as a tool for communication has been successfully used for previous comet monitoring. For example, comet Shoemaker-Levy attracted worldwide attention (JPL 2005). In fact, a large portion of observations by the public was done via the internet from reliable NASA and JPL websites (JPL 2005).

In the event of a confirmed NEO threat, it is important for the source of the media's information to be the Threat Response Team of INEOC. Once the NEO threat is detected and initially evaluated, the Threat Response Team then should inform national governments. Then, local scientific communities can rely on the INEOC as a point of reference so that information for public consumption can be kept consistent, accurate, and reliable (SETI Institute 2005). If information is kept from the public after the initial INEOC report, leaks to the media most likely would occur and add confusion and misinformation about the threat. Therefore, it is vital for the scientific community to share their discovery with the public in layman's terms (Mardsen 2004). While astronomers are verifying and confirming their data, the local scientific communities should continuously update the public on the verification process and results. This model for communication often is used by local police authorities in the United States when a child is kidnapped. While searches are ongoing, a police spokesperson updates the public via news broadcasts and print reports on the status of the case. Sometimes, these kidnappings turn out to be hoaxes or misunderstandings. However, many times they are real crises. By informing the public of the situation and providing continuous updates, the public is able to help in local searches for the missing child. This model should be applied to NEO detection and monitoring. Local scientific communities should not be concerned with reporting sightings because the threat may or may not change. It would benefit the scientific community to have several continuous updates as information is analyzed and verified. The public will feel involved in the process and, thus, gain knowledge and better understanding of the realities of the NEO threat.

Once a NEO is detected, effective communication with the public must include information that is specific, relevant, and consistent, as emphasized above. Because the public consists of multiple audiences, it is important for the initial release of information to be communicated in multiple forms so that a maximum number of people can be reached (Planetary Defence Conference 2004). All verified and updated information should be made available to the public so that complete access to the latest data is possible. Finally, information should be stored so that it is easily accessible by the scientific community and public for further review and interpretation (especially amateur astronomers) (SETI Institute 2005).

Finally, local scientific communities should consider ways in which the public can communicate their questions and concerns back to the local astronomers. The internet is a good vehicle for this form of communication. However, it is important to find a balance between two-way and side-by-side communication with maintenance of consistent and reliable information, which is a challenge due to the open nature of the internet (Planetary Defence Conference 2004).

The Torino Scale

The Torino Scale, developed in 1999 by Rick Binzel of the Massachusetts Institute of Technology, is used to inform the public about potential impacts. It rates a NEO's threat on a scale of 0 to 10, based on its velocity, size, and probability of impact with the Earth (see Figure 6-3). The scale provides a color coded chart indicating the threat level of a detected NEO. Each number describes a local, regional, or global threat and provides the level of uncertainty of a direct impact.

THE TORINO SCALE

Assessing Asteroid/Comet Impact Predictions

No Hazard	0	The likelihood of collision is zero, or is so low as to be effectively zero. Also applies to small objects such as meteors and bolides that burn up in the atmosphere as well as infrequent meteorite falls that rarely cause damage.
Normal	1	A routine discovery in which a pass near the Earth is predicted that poses no unusual level of danger. Current calculations show the chance of collision is extremely unlikely with no cause for public attention or public concern. New telescopic observations very likely will lead to re-assignment to Level 0.
Meriting Attention by Astronomers	2	A discovery, which may become routine with expanded searches, of an object making a somewhat close but not highly unusual pass near the Earth. While meriting attention by astronomers, there is no cause for public attention or public concern as an actual collision is very unlikely. New telescopic observations very likely will lead to re-assignment to Level 0.
	3	A close encounter, meriting attention by astronomers. Current calculations give a 1% or greater chance of collision capable of localized destruction. Most likely, new telescopic observations will lead to re-assignment to Level 0. Attention by the public and by public officials is merited if the encounter is less than a decade away.
	4	A close encounter, meriting attention by astronomers. Current calculations give a 1% or greater chance of collision capable of regional devastation. Most likely, new telescopic observations will lead to re-assignment to Level 0. Attention by the public and by public officials is merited if the encounter is less than a decade away.
Threatening	5	A close encounter posing a serious, but still uncertain threat of regional devastation. Critical attention by astronomers is needed to determine conclusively whether or not a collision will occur. If the encounter is less than a decade away, governmental contingency planning may be warranted.
	6	A close encounter by a large object posing a serious, but still uncertain threat of a global catastrophe. Critical attention by astronomers is needed to determine conclusively whether or not a collision will occur. If the encounter is less than three decades away, governmental contingency planning may be warranted.
	7	A very close encounter by a large object, which if occurring this century, poses an unprecedented but still uncertain threat of a global catastrophe. For such a threat in this century, international contingency planning is warranted, especially to determine urgently and conclusively whether or not a collision will occur.
Certain Collisions	8	A collision is certain, capable of causing localized destruction for an impact over land or possibly a tsunami if close offshore. Such events occur on average between once per 50 years and once per several 1000 years.
	9	A collision is certain, capable of causing unprecedented regional devastation for a land impact or the threat of a major tsunami for an ocean impact. Such events occur on average between once per 10,000 years and once per 100,000 years.
	10	A collision is certain, capable of causing a global climatic catastrophe that may threaten the future of civilization as we know it, whether impacting land or ocean. Such events occur on average once per 100,000 years, or less often.

Figure 6-3 The Torino Scale (JPL 2005)

The Torino Scale is a good tool for making impact predictions understandable and measurable to the public, although some aspects need to be refined. First, once a NEO is detected and verified, the Torino Scale should be quickly used. This system allows for information to be passed to the public in a coherent and uniform manner, thus avoiding conflicting reports on the NEO. It also prevents leaks from trumping the scientific community. Second, once the Torino Scale value of a threatening comet is presented to the public, it should be used often to update the status of grading the NEO. This tactic by the local scientific communities to communicate efficiently and effectively with the public will prevent the media from sensationalizing a NEO sighting by trying to generate excitement in the public.

Third, the Torino Scale should be expanded to provide a timescale. While the scientific community understandably wants to avoid generating fear in the public, the public will insist on knowing a timeframe. If it is not provided by a reliable resource, then the public will search and find other sources for information, thus, possibly resulting in misinformation. The wording or color shading for the timescale can be manipulated to provide minimal anxiety. Because the impact probabilities continually change as new observations are obtained, by using a combination of colors, shading, and numbers, these changes may be better conveyed (Mardsen

2004). Finally, the scientific community should not underestimate the public's ability to process and understand information (Planetary Defence Conference 2004). Complementary information to the Torino Scale can be provided, such as explanations of outgassing being a major cause in perturbations, thus, requiring continuous verifications on the NEO's trajectory and as a possible natural change in the path which may divert it from a collision with the Earth.

By incorporating shading into the color system of the Torino Scale, the issue of time can be addressed. For example, a NEO threat rated as a 2, which is yellow, indicates an object has been observed and that it most likely will be downgraded to 0 after verification has taken place and perturbations in trajectory are analyzed. Taking this example, if the object is several years away, the yellow can be shaded very lightly. If the timeframe is quite short, then a deeper shape of yellow can be used (Mardsen 2004). Adoption and further refinement of this scale could help ensure that impact predictions are interpreted correctly by science journalists and the interested public within a familiar context.

Again, as continuous verifications are updated using the Torino Scale, this new information should be shared with the public until the threat passes (Britt 2005). For an illustration, 99942 Apophis, previously known as Asteroid 2004 MN4, is expected to come close to the Earth in 2029. Therefore, although the number indicating the proximity to Earth changed and may continue to change as perturbations are continuously observed, measured, and updated, the shading of the color should remain at a mid-level to indicate the time of passage within the 20 year range.

6.5 Conclusion

Overall, the media provides a reliable and familiar venue for the public in order to understand NEO threats as they arise. In addition, astrologists should engage the media in order to report accurate and continuous information to the public. It would be naïve to believe that the Earth will escape NEOs forever, and although accurate coverage of a NEO warning by the media may never be perfectly defined, these steps -- in light of current public awareness of NEOs and societal reactions to proposed detection and mitigation strategies -- will help facilitate communication between the scientific community and the public.

6.6 Scenario

Day 240: Detection
From the moment Cassandra is detected, there will be social consequences. After initial detection, the IAU takes time to confirm the computations. Despite efforts to control the information concerning the threat, within a couple of days, leaks to the media may well appear, leading to misinformation, speculation, and false alarms. After initial confirmations, the IAU contacts the local astronomical communities and space agencies to begin engaging the public with initial findings. Enhanced networking and redundancy now ensures that NEO websites do not break down because of overwhelming connections.

Day 270: Public Detection Announcement
Local scientific communities mobilize to work with the media to disseminate information to the general public. Following the announcement, there likely will be many different reactions in the public. Some people might disregard the information due to the previous "crying wolf" incidences. Others may take the matter very seriously and begin preparations for an impact. There also will be religious, cultural, and political reactions to the announcement. The scientific community, via print, broadcasts, and radio, explain in detail the Torino Scale and stress that the prediction is being continuously verified. As publicity for the impeding impact increases,

individuals likely may become apprehensive and frightened, and society will increasingly rely on information provided by the media. This information must be as accurate as possible, and all efforts should be made to avoid creating panic. Educating the public about impact preparation and the possible consequences of a NEO collision likely will be a priority. As more information on Cassandra's characteristics become available, the general public will become aware of the gravity of the situation and gradually accept the notion that serious preparations must be undertaken.

Some people may suspect that certain governments have not released all available information regarding Cassandra. Others may blame the international community for not adequately preparing mitigation measures to counteract this high inclination NEO threat. The media emphasizes the destructive effects of the impact.

Day 220: As concluded in the mitigation section, this scenario proves impossible to mitigate in the near future because of the incredible amount of energy required to reach this high eccentricity orbit using conventional rockets. Massive evacuations are organized throughout the remaining time prior to impact to limit casualties. Most of the world's population remains in disbelief or awe of the impending doom, and yet preparations are undertaken for worldwide disaster.

IMPORTANT ** Nevertheless, we still provide an overview of what could be done from 220 days if we could mitigate this threat.

Day 220: Mitigation Announcement
There are continuous updates regarding the path and characterization of Cassandra. Explanations regarding potential perturbations of the comet, such as outgassing, are provided to the public. There may be public outcry with the announcement of the chosen mitigation method. The use of nuclear devices is still, in 2014, a contentious issue, although, in this drastic situation, the majority of the population accepts the risks, rather than oppose their use. However, should the mitigation strategy succeed, some individuals may be concerned with the consequences of nuclear fragments. The public also may worry which country the comet would threaten. At this stage, the nuclear devices used to destroy the comet are described in detail, as well as the potential consequences of these devices. Fragments may still hit the Earth, and there are efforts to explain that the smaller pieces will be taken into account. Keeping the public informed at all times is crucial. Explaining what may be seen in the sky and how long the object will be seen also is important. The nuclear payload launch will probably raise safety concerns among environmental activists.

Day 190-170: Orbit Recalculation prior to Rockets Launch
The new orbit is estimated, and the plans for mitigation are relayed to the public through a public announcement. The launch of two rockets occurs without incident. The second rocket is being used to enhance the likelihood of a mission success. Large groups of protestors against the use of nuclear weapons are shown on the news. The media begins to cover fringe religious groups rallying to deal with the Armageddon. The scientific community responsible for public relations emphasizes to the media the importance of broadcasting reliable and accurate information.

Day 100-70: Mitigation Event
Public tensions rise again as the mitigation mission delivers its energy to Cassandra. Worldwide television coverage and astronomical observations are continuous as the world anticipates a successful disruption. Because the event cannot be seen with the naked eye, people around the world rely on their local scientific communities to relay the results of the event. In many cases,

the scientific communities also act as a calming force to the public by continuously providing updated information and by explaining plans to relieve the public of its fears. The disruption is a success using the first rocket. The second rocket is set to autodestruct, as it will not be required.

Day 60-30: Solar Occlusion
A solar occlusion occurs as the comet passes behind the Sun. The public holds its collective breath as they wait to see if radioactive fragments will still head on a collision course. The anti-nuclear weapons protestors, who had dispersed after the successful dispersion, have re-emerged to see if any radioactive fragments will hit the Earth. Much of the public now perceives the potential radioactive fragments as a lesser threat than Cassandra had posed. While the comet fragments are hidden on the backside of the Sun, local scientific communities take advantage of the time to further inform and educate the public about realistic possibilities such as the effects of the Sun on Cassandra's structure and orbit, results of the fragmentation, and outgassing.

Day 60-0: Orbit Recalculation
The new orbit estimates are recalculated as radioactive fragments appear from the shadow of the Sun. The outcome of the Solar graze is relayed to the public through the media.

Day 30-0: Threat Assessment
As the trajectories of radioactive fragments are analyzed as not threatening to Earth, the scientific communities relay via the media relief from the threat of Cassandra. The public now shares a sense of wonder at Cassandra, and a new worldwide interest in astronomical sciences emerges. People around the world actually enjoy watching the media display images of small pieces of Cassandra passing by the Earth.

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Chapter 7

Conclusions

The threat of a high inclination NEO is real. An impact leading to the end of humanity cannot be ruled out. Can we accept this destiny? No. We chose to acknowledge the threat and propose actions to be taken that could save humanity.

An impact could occur any day, so there is no better time to prepare than the present. Preparation begins by learning about the structure, composition, and behavior of potentially threatening NEOs so as to design the necessary systems to survey the skies for all objects that might eventually collide with Earth.

Currently, there is a need to improve the detection of faint objects over the whole sky. If this need is not met, most of these objects will not be detected unless they are very large or very close to the Earth. In both cases, mitigation strategies cannot be applied successfully. The mitigation technologies available today are not adequate to protect the planet from either a large NEO, or one so close by the time it is detected that there is insufficient response time.

The current situation leaves the use of a nuclear device as the most technically feasible option for high inclination NEOs. However, this is also the method with the most legal, social and political barriers to implementation. Launching states are liable for any collateral damages from launch or payload failure, so which governments will take the risk when trying to help humanity? How can the investment in and possible consequences of technical solutions be justified to the public? Such problems could become moot if an imminent fatal threat is announced. However, the report leaves no doubt that if there is a chance to avoid disaster it will be because the world has prepared by setting up the proper framework and systems for detection, characterization, and mitigation. To achieve this level of preparation, technical, legal, policy and social issues must be tackled methodically.

Even though the NEO threat is a global concern, the burden of developing and operating detection and mitigation strategies falls only on a few developed countries that are aware of the problem. Today, there is a lack of international organization and cooperation in a variety of areas: cost sharing, technical coordination, political and legal agreements, social considerations, and public outreach and education.

The Cassandra report has identified serious gaps in our preparations, proposed some practical solutions, and outlined the main difficulties to be faced in implementing the solutions. In order to be ready when a NEO threat is detected, the following recommendations are proposed:

Recommendation 1:
An International Near Earth Object Committee (INEOC) should be established to improve and enhance international cooperation with the following objectives:

- To create a command and control protocol that will be used once a future NEO impact is confirmed;
- To coordinate current and future efforts to assess, detect, characterize, and mitigate NEO threats, and manage data at an international level.

Recommendation 2:
Funding priority should be given to detection and monitoring of objects that pose a global threat, including those at high inclinations.

Recommendation 3:
There should be increased funding for the Minor Planet Center to improve and extend its competencies.

Recommendation 4:
Current investigations and modeling of the composition, structure and populations of comets and asteroids should be enhanced and expanded through rendezvous missions, especially in near Earth orbit.

Recommendation 5:
An effort should be made to coordinate and promote the detection and monitoring of NEOs by professional astronomers, amateur astronomers, and observatories.

Recommendation 6:
If possible, the periods of time when current and future spacecraft are not being used for their primary mission should be used to help in detecting, characterizing, and monitoring NEOs.

Recommendation 7:
A significant effort should be made to develop high magnitude detection systems and to increase the sky coverage, in order to extend the available response time.

Recommendation 8:
Alternative mitigation methods and launch vehicles should be researched, developed, and then tested through demonstration missions.

Recommendation 9:
A new version of the Torino Scale should be developed to incorporate the time to impact for better communication with the public.

Recommendation 10:
A strategy should be developed to promote public awareness of the threat posed by NEOs and its importance relative to common risks.

7.1 Cassandra Scenario

To recap the Cassandra scenario, it is assumed that the threat is first detected on November 10, 2014. Detection begins at 4 AU from the Earth, which is 240 days from a potential Earth impact. Initial observations determine that the object is approximately 600 meters in diameter, and orbits the Sun in a 135^{o} inclined orbit with a perihelion of 0.3 AU and a semi-major axis of 10,000 AU. The object is assumed to have an albedo of 10%.

The consequences of Cassandra's impact depend on its location on the Earth's surface. It is assumed the impact occurs in the middle of the North Atlantic, so the energy released at impact would be on the order of 3×10^{10} Mt. This would generate tsunamis that would impact the coasts of Europe and North America and cause widespread devastation to low lying areas.

By 2015, it is assumed that the INEOC framework will have been established and that a clear C&C structure will have been implemented. A sample process flow is shown in Figure 7-1. Through this framework, the objectives will be to inform the public, determine an adequate mitigation response, mobilize national governments to deal with the legal and policy issues, implement the accepted plan, and determine what, if any, further actions are required.

From the moment the Cassandra comet is detected, ongoing characterization and monitoring tasks would be undertaken to specify and enhance measurements of NEO class and identification, size and shape, albedo, spin rate, surface roughness, dust emission, etc. This would be performed using available techniques such as photometry and spectroscopy using radar, optical and infrared telescopes. Within three to seven days, the calculations would be done to confirm that the orbit of the comet presents a real threat to Earth. Continuous monitoring would be required as non-gravitational forces such as comet outgassing and comet break-up could alter the comet's trajectory.

Approximately 210 days before impact, a mitigation strategy would be decided upon and the necessary systems already in place would be activated. For the Cassandra scenario, the mitigation strategy would utilize a nuclear device attached to a spacecraft that would intercept and disrupt the comet. A launcher specifically designed to be capable of sending payloads at high heliocentric transfer velocities would launch this payload. This system would require significant development in propulsion technology.

To ensure the public is properly informed about the threat, a timeline of carefully coordinated actions would be implemented. The most accurate and up-to-date information would be provided and appropriate media protocols would be followed to avoid creating public panic.

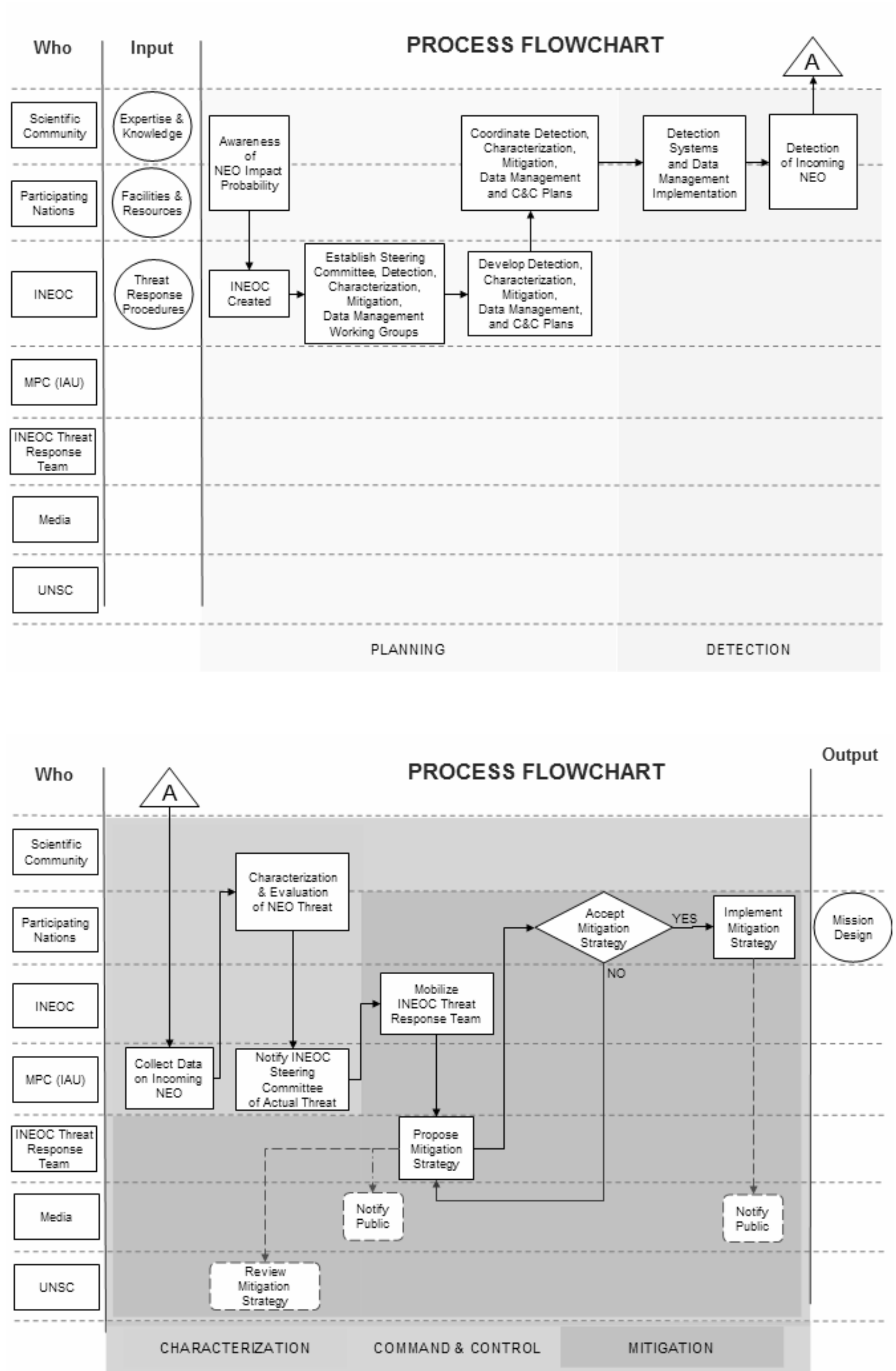

Figure 7-1 INEOC Process Flow

Appendix A

Existing and Planned Ground-based Detection

Lincoln Near-Earth Asteroid Research (Lincoln Laboratory, 2005)

The Lincoln Near Earth Asteroid Research (LINEAR) project started in 1998 as an MIT Lincoln Laboratory program funded by the United States Air Force and NASA. LINEAR uses a pair of Ground-based Electro-Optical Deep Space Surveillance (GEODSS) telescopes with a prime focus of 1 m and a f/2.2 focal ratio located at Lincoln Laboratory's Experimental Test Site (ETS) on the White Sands Missile Range in Socorro, New Mexico. The telescopes are equipped with large 1960 x 2560 pixels CCD detectors allowing a 1.2° x 1.2° Field Of View (FOV). With good atmospheric conditions, the two telescopes observe the sky with a limit of magnitude of approximately 20.5.

A third telescope of 0.5 m aperture is used to provide follow-up observations for the discoveries made by the two 1 m search telescopes. Observations are then sent to the main Lincoln Laboratory site on Hanscom, AFB in Lexington, Massachusetts, where they are linked with observations from previous nights, checked, and sent to the Minor Planet Center (MPC). Currently, the LINEAR program is responsible for the majority of NEO discoveries. As of July 15, 2005, it had discovered 1753 confirmed NEOs. (NASA, 2005a)

Lowell Observatory NEO Search (Lowell Observatory, 2003)

The Lowell Observatory Near-Earth-Object Search (LONEOS) started its observations in March 1998 in Flagstaff, Arizona and is funded by NASA. It uses a 0.6 m f/1.8 Schmidt telescope and is equipped with a 4096 x 4096 pixel CCD detector. With a FOV of 2.9° x 2.9°, the telescope is designed to make four scans per region each month over the entire visible sky down to a limiting magnitude of approximately 19.3. As of July 15, 2005, LONEOS was responsible for 237 confirmed NEOs. (NASA, 2005a)

Spacewatch (University of Arizona, 2005)

The Spacewatch Project, which started observations in 1989, is controlled by the University of Arizona's Lunar and Planetary Laboratory and is funded by NASA. Spacewatch uses a set of two telescopes based on the summit of Kitt Peak, Arizona.

- A 0.9 m f/5.34 telescope equipped with a mosaic of four 4608 x 2048 pixel CCD detectors, each of which allows a field of view of 2.9 deg^2 with a limit of magnitude 21.7.
- A 1.8 m f/2.7 telescope equipped with a 2048 x 2048 pixel CCD detector and a very narrow FOV of 0.54° x 0.54° with a limit of magnitude of approximately 23.3. A higher priority is placed on objects fainter than V=20.5 magnitude because they are less likely to be observed by other stations.

As of July 15, 2005, Spacewatch was responsible for 357 confirmed NEOs discoveries. (NASA, 2005a)

Near Earth Asteroid Tracking (JPL, 2004)

The Near Earth Asteroid Tracking Program (NEAT) is an autonomous celestial observatory developed by the Jet Propulsion Laboratory and funded by NASA and the United States Air Force. The NEAT system began observations in December 1995.

Currently, the program consists of two telescopes.

- A Schmidt 1.2 m f/2.5 telescope at Mount Palomar, California
- An Air Force Maui Observing Station (AMOS) 1.2 m f/1.9 telescope located on the Maui Space Surveillance Site (MSSS), Hawaii

Both are equipped with 4096 x 4096 pixel CCD detectors and with a FOV of 1.2° x 1.6°, allowing a limit of magnitude approximately 20.5. As of July 15, 2005, NEAT was responsible for the discovery of 392 confirmed NEOs. (NASA, 2005a)

Catalina Sky Survey (University of Arizona, 2004)

The Catalina Sky Survey (CSS) is led by the Lunar and Planetary Laboratory of the University of Arizona and is funded by NASA. It began operation in April 1998 and currently consists of a consortium of three cooperating surveys: the original Catalina Sky Survey (CSS), the Siding Springs Survey (SSS) and the Mt. Lemmon Survey (MLSS). The three telescopes all use identical thinned, multi-channel cryogenically cooled 4096 x 4096 pixel CCD detectors:

- The original Catalina Sky Survey (CSS) using a 0.7 m f/1.8 Schmidt telescope allowing a 2.9° x 2.9° FOV at the Steward Observatory Catalina Station (2510m elevation, 20 km northeast of Tucson, Arizona). Its limit of magnitude is approximately 20.0.
- The Siding Spring Survey (SSS) uses the Uppsala 0.5 m f/3.5 Schmidt telescope allowing a 2.0° x 2.0° FOV and is operated jointly with the Australian National University Research School for Astronomy and Astrophysics at Siding Spring Observatory, Australia (1150m elevation). Its limit of magnitude is approximately 20.0.
- The new Mt. Lemmon Survey (MLS,) uses a 1.5 m f/2.0 prime focus telescope allowing a 1.0° x 1.0° FOV at the Steward Observatory Mt. Lemmon station (2790-m elevation, 18 km north of Tucson). Its limit of magnitude is approximately 22.0.

As of July 15, 2005, the CSS was responsible for the discovery of 267 confirmed NEOs. (NASA, 2005a)

Panoramic Survey Telescope and Rapid Response System (Wynn-Williams, 2004)

The Panoramic Survey Telescope and Rapid Response System (PanSTARRS) proposal was submitted by the University of Hawaii's Institute for Astronomy in early 2002 in response to an Air Force Broad Area announcement inviting bids to develop observatory technology. It is designed to be the next level of advancement in NEO survey work and the first telescope, PS1, is scheduled to start its observations in January 2006.

Pan-STARRS will be composed of 4 individual 1.8 m f/4 telescopes observing the same region of sky simultaneously. Each telescope will be equipped with a 1 billion pixel CCD mosaic detector and will allow a total FOV of 7 deg^2. In survey mode, Pan-STARRS will cover $6{,}000°^2$ per night. The whole available sky as seen from Hawaii will be observed 3 times during the dark period of each lunation. With exposure times varying between 30 and 60 seconds, the expected limit of magnitude is 24.

This new system will have 3-16 times the collecting power of the current NEO survey telescopes and a massive array of state-of-the-art CCD detectors in the focal plane. This will enable the Pan-STARRS survey to examine objects approximately 5 magnitudes fainter than those currently observed by other NEO surveys.

Large Synoptic Survey Telescope (LSST Corporation, 2005)

The Large Synoptic Survey Telescope Project (LSST) is issued from the collaboration of a number of laboratories and organizations in the United States under a public-private partnership, called the LSST Corporation. The project is considered as one of the most important for the future of ground based telescopes and is led by the University of Arizona, which recently received US$ 2.3 million funding. Its first observation is expected in the year 2012.

The innovative 8.4 m f/1.25 LSST will be made of 3 mirrors, allowing a large FOV together with a fast focus. It will be equipped with a 3 billion pixel CCD camera with 3 refractive correcting elements. It would be the world's largest imager. The system will allow a field of view of 10 deg^2, a coverage of the entire sky within 3 nights, and the detection of objects with a limit of magnitude up to 24.

Three sites are in competition to host the telescope: Cerro Pachon (Chile), Las Campanas (Chile) and San Pedro Martir (Mexico). The final choice will be based on the results of complementary studies, including geotechnical and environmental investigations.

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Appendix B

Liquid Mirror Telescope Details

Formulas for assessing LMTs for High Inclination NEO detection

Step 1: Compute the integration time based on the location of the location of the LMT (Vangeyte et al. 2002)

Integration Time	$114.36 \frac{m}{4096} \frac{\arctan(\frac{pixel\_size}{focal\_length})}{0.3867} \frac{\cos(latitude)}{\cos(\delta_c)}$	Integration time is critical in the analysis of telescopes employing a CCD camera at the focal plane.
Variable	Units/Description	Study Parameters
M	Number of pixels in the readout path	2048 x 2048
δ_c	Declination of the center of CCD plane	~ Latitude of interest

Step 2: In a sky-limited observation of the point source this can be modeled as follows: (Stokes et al. 2003)

S/N Ratio	$\frac{S}{N} = \frac{(Ip)tA\Delta v}{\sqrt{Is(\Delta\theta)^2 tA\Delta v}} = \left(\frac{Ip}{\Delta\theta}\right)\sqrt{\frac{tA\Delta v}{Is}}$	
Variable	Units/Description	Study Parameters
Ip	(Photons/sec/m^2/Hz)	$3.4819x10^{-22}$
ʇ	Integration time (sec)	0 - 300 seconds
$A = 4\pi D^2$	Collecting area of telescope (meters)	1 - 4 meters
Δv	Filter bandwidth of telescope (meters)	10 Å [Keck Telescope BW]
Is	Sky brightness (Photons/sec/m^2/Hz/Sr)	Sky Noise [Earth] > 18 magnitude Sky Noise [Moon] < 18 magnitude

Step 3: Limiting Magnitude Calculation (Gehrels 1994)

Limiting Magnitude	$V\lim = 21.9 - 2.5\log(SNR(\frac{np}{At})^{1/2})$ A = 0.9*($\sqrt{\Pr imaryArea}$	
Variable	Units/Description	Study Parameters
A	Area	3-20 meters
ʇ	Integration time (sec)	0 - 300 seconds

Standard Equations: for computing LMT parameters:

(i) Pixel viewing Arcmin/pix $= \frac{206.265}{Focal\_Ratio * Diameter} * Pixel\_Size$

(ii) Field of View $= 3438 * \frac{CCD\_Dimensions * Pixel\_Size}{Diameter * Focal\_Ratio}$

(iii) Hourly Coverage $= Field\_of\_View * (\frac{3600}{Exposure\_Time})$

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Appendix C

Proposed Space-based Detection System

System Ground Elements

The ground segment of the proposed system processes data received from the space telescope and searches for objects that could be classified as NEO or high inclination comets. During long duration missions, a detailed catalogue of the sky would be created. Such a catalogue would help to identify unusual objects in the data received from the spacecraft by comparison of the new images with previously stored ones. The astrometric characteristics of the discovered objects would be compared with the existing catalogues and in case of a discovery, the formal notification would be sent to interested institutions.

Existing ground stations will be reused for communication with the LEO spacecraft to download huge amount of generated data. The Deep Space Network (DSN) antennas or similar antennas will be used to communicate with the telescope in a L5 orbit. The 1 AU distance between the Earth and the spacecraft will require high gain receiving antennas.

System Description

The key requirement for a detection system is its ability to detect very faint objects with a high magnitude and provide accurate astrometric measurements for the object's location and distance. Because of the possible requirements for a mitigation strategy, comets should ideally be discovered at a minimum distance of 5 AU from the Sun. At this distance, comets usually do not have a tail yet and their visible brightness is in the range of 24-26 magnitude depending on the comet's surface albedo (between 0.15-0.05) and its size. The proposed detection system would be able to detect objects of this magnitude.

The proposed mission will use a 1.5 m mirror telescope with a Ritchey-Chrétien design similar to used in Hubble Telescope. Such a design allows for a very short optical tube and a compact size, which are very important for spacecraft sizing. The mirror area of 7 m^2 and a FOV of around 3º is better than most of the ground-based systems. The telescope mirror and camera area will collect enough of the photons reflected by the comet's surface to allow the object's detection in a reasonable integration time of 30-40 seconds. Longer exposures would increase limiting magnitude, but introduce more noise into the images. Instead, images from two separate instruments taken at different times can be integrated to double the signal strength with limited increase in noise levels.

Effective detection systems require a wide FOV and good spatial resolution. This is reachable only with the use of a large CCD camera. The proposed spacecraft would use a 32k x 32k pixel CCD array similar to the designed for Pan-STARRS telescopes.

Every section of the sky has to be revisited to acquire images useful for the discovery of objects moving on the background of stable stars. Because the primary goal of the mission is to detect distant comets with a small velocity, the interval between observations of the same region of sky should be several days to observe the relative motion of the object. If two telescopes are operational at the same time, the whole available sky might be surveyed within a month. Both spacecraft can deliver four images of each sky section, assuming that integration and slew time will be around two minutes. Collected images will be used to search for suspected objects and calculate their trajectories.

Several problems need to be addressed in order to receive high quality images. The CCD cameras suffer from dark current, gamma rays and internal noise. On top of internal CCD noise sources, space observations have specific issues that generate noise in observations: galactic plane light, Zodiacal light, and star cluttering are a few of these sources. The countermeasures for those problems include integrating many frames for noise reduction, wavelets analysis and very specific software algorithms for image processing like SALTAD. (Hildebrand, 2005).

Key Technologies

The key technologies to be used in the proposed detection mission already exist. The spacecraft structure, propulsion, altitude control and thermal control systems can be based on currently available materials and technologies used in many existing missions.

The telescope mirror and structure can be constructed in reasonable time by any laboratory specializing in telescope development. A honey-comb-like lightweight structure would be used to limit the mass of the main mirror. An adaptive optic correction system would be used to mitigate the wobbling effect of spacecraft movements to increase image quality.

Large format CCD cameras have already been tested and are ready for mass production. The new technology of Orthogonal Transfer Array is proposed to extend camera lifetime and possibly isolate local defects without losing the part of the imaging device.

The proposed mission has very specific requirements for pointing accuracy and position control. The Minor Planet Center of the International Astronomical Union (Minor Planet Center, 2005) requires the precision of astrometric observations to be less than 1 arcsecond. This requirement could be satisfied by using a new fiber optic gyroscope and very precise momentum wheels for the spacecraft's orientation control. The fiber optic gyroscopes are based on ring laser gyroscopes and are commonly used in military and civil aviation and deliver better reliability and accuracy than any mechanical gyroscope.

The ongoing development of sophisticated image processing software will improve detection results. The SALTAD program algorithms, which were tested with Spacewatch images, showed 30% better results in asteroid detection than current software (Hildebrand, 2005). The implementation of the Moving Target Indicator and Matched Filter algorithms combined with other image processing techniques are cutting-edge image processing methods not yet used in NEO detection systems.

System Performance

The system performance can be estimated using simulation techniques based on existing ground based systems and NEO population characteristics. The Stokes et al. report (2003), gives the performance comparison for one and two meter systems in LEO orbit. This comparison was used to generate performance requirements for a 1.5 m telescope.

The proposed system will use a large format CCD camera, which gives better sensitivity and resolution than existing systems. The effects of spacecraft wobbling and jitter will impact the quality of observations by blurring the images. Because space systems offers continuous availability, its performance and coverage is significantly better than ground-based systems.

Proposed Mission Costs

The simple online Advanced Missions Cost Model (AMCM) (NASA, 2005b) was used to estimate spacecraft costs. The NASA/Air Force Cost Model (NAFCOM) cost estimation results published in (Stokes et al., 2003) were also used to verify the total cost of the proposed mission. As input values for cost models, the dry mass of LEO spacecraft was assumed to be around 700 kg. Two spacecraft were assumed to be built in parallel Calculations assume a small reusability of existing elements.

The total cost of the LEO mission with the 1.5 m telescopes, including a launch vehicle (Delta II US$ 56 million), to equal approximately $US 450 million. Taking into account the mission duration of 10 years, a similar amount will be spent during the initial spacecraft's mission life time to develop and launch its replacement. Using the Delta II rocket, both spacecraft might be placed in LEO orbit within a single mission.

The operation cost of the LEO telescopes was estimated using Mission Operation Cost Model (MOCD)and Spacecraft Operation Cost Model results from (NASA, 2005b) were used for verification. The total cost of 10 years of system operations will be around $US 60 million included already in mission cost.

The optional spacecraft for L5 orbit will have a weight around 300 kg larger than the LEO version because of higher requirements for power, communication, radiation protection, and propulsion systems. The cost of an upgraded version of the detection spacecraft will be around $US 360 million for the complete mission duration. The operations costs including usage of DSN for 10 years will be around $US 70 million. The cost was estimated using MOCD and verified with SOCM results in (NASA, 2005b).

Technology Readiness Level

Generally speaking, technologies to be used in the proposed system already exist and have been proved by several successful space missions. Around 80% of the proposed system elements will have to be designed from scratch but the experience collected during the Hubble and James Webb Space Telescope (JWST) (STSCI, 2005) design and development should speed-up initial phases of the project. The detailed design, development, and testing will require a 3-5 year period depending on funding availability.

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Appendix D
Orbital Mechanics Calculations

Detailed Explanation of Deflection ΔV Calculations

In this section a more detailed explanation of the deflection ΔV calculations discussed previously in Chapter 4 is provided.

As previously mentioned, the following assumptions are made for the deflection calculations:

- All orbits considered are elliptical
- Earth has a circular orbit around the Sun
- The centers of Cassandra and Earth are coincident on June 20, 2015
- The minimum miss distance as 14000 km (two Earth radii plus margin)

It is assumed that the Keplerian elements of the NEO are given or defined. In turn, the radius and velocity at each point in the orbit can be calculated from these elements.

Impact point of the NEO with the Earth can now easily be found by finding where in the NEO's orbit the radius is approximately 1 AU. Once again, it is assumed that the Earth and the NEO are in the same position at the same time when the NEO is at 1AU from the sun. This distance occurs at either the ascending or descending node of the NEO's orbit since at these points the NEO's orbit intersects the ecliptic plane.

Lambert's equation, which provides a relationship between two positions of a planet in an elliptical orbit and the time taken to traverse them, is then used to calculate the time from impact. Lambert's equation is defined as

$$\Delta t = \frac{E_2 - E_1 - e(\sin E_2 - \sin E_1)}{n} \tag{1}$$

where E_1 and E_2 are the eccentric anomaly values at two particular points in the NEO's orbit, and n is the mean motion, defined as $n = \sqrt{\mu / a^3}$. In this equation, E_2 is defined simply from the true anomaly at the point of impact with the Earth.

At this point, the components of the radius and velocity are defined by transforming the classical Keplerian elements to Cartesian elements, as detailed below, where [R] is the rotation matrix between the Keplerian and the Cartesian system.

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = [R] \begin{bmatrix} r\cos\theta \\ r\sin\theta \\ 0 \end{bmatrix} \quad (2)$$

where

$$[R] = \begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{bmatrix} \quad \text{and} \quad \begin{aligned} R_{11} &= \cos\Omega\cos\omega - \sin\Omega\sin\omega\cos i \\ R_{12} &= -\cos\Omega\sin\omega - \sin\Omega\cos\omega\cos i \\ R_{13} &= \sin\Omega\sin i \\ R_{21} &= \sin\Omega\cos\omega + \cos\Omega\sin\omega\cos i \\ R_{22} &= -\sin\Omega\sin\omega + \cos\Omega\cos\omega\cos i \\ R_{23} &= -\cos\Omega\sin i \\ R_{31} &= \sin\omega\sin i \\ R_{32} &= \cos\omega\sin i \\ R_{33} &= \cos i \end{aligned} \quad (3)$$

The velocity components can be calculated as followed

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = [R] \begin{bmatrix} -\sqrt{\frac{\mu}{p}}\sin\theta \\ \sqrt{\frac{\mu}{p}}(e+\cos\theta) \\ 0 \end{bmatrix} \quad (4)$$

where p is the semilatus rectum, defined as $p = a(1-e^2)$.

After the position and velocity of the NEO is known in Cartesian coordinates, the orbit perturbation analysis can now be performed. A delta V is assumed to be applied to the overall velocity vector, and the resulting velocity vector changes accordingly. The position vector remains unchanged at the point of the velocity perturbation; however, the overall parameters of the orbit change. The new Keplerian elements are calculated using a modified Laguerre classical elements transformation provided in (Chobotov, 2002). The interested reader can find the details of the procedure there.

With the new orbit parameters, the effective miss distance is then calculated. The Earth miss distance is calculated by taking the time of flight until impact at the point at which the velocity impulse is applied, and then finding the resulting radius elements for the new orbit after the time equal to the original time of flight to the impact has passed. This is done by using Lambert's equation again to find the resulting eccentric anomaly E, then finding the true anomaly from

$$\theta = 2a\tan\left(\left[\frac{1+e}{1-e}\right]^{1/2} \tan\frac{E}{2}\right) \quad (5)$$

After this true anomaly value has been found, the elements of the resulting radius vector can be found using the procedure for finding the Cartesian elements described previously. This resulting radius vector is then subtracted from the original radius vector to find the resulting Earth miss distance.