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Size-Dependent Earth Impactor Warning Times And Corresponding Campaign Mission Recommendations

Todd Alexander Borzych

SIZE-DEPENDENT EARTH IMPACTOR WARNING TIMES
AND CORRESPONDING CAMPAIGN MISSION RECOMMENDATIONS

by

Todd A. Borzych
Bachelor of Science, Massachusetts Institute of Technology, 1995

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This thesis, submitted by Todd A. Borzych in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

Dr. Ronald A. Fevig, Chairperson

Dr. James G. Casler

Dr. Michael G. Gaffey

This thesis is being submitted by the appointed advisory committee as having met all of the requirements of the Graduate School at the University of North Dakota and is hereby approved.

Dr. Wayne Swisher, Dean of the Graduate School

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Todd A. Borzych

April 11, 2012

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To Migle

ABSTRACT

NASA seeks to reliably detect potential Earth Impactors (EI) in time to defend the planet by deflecting them. Congress has given an unfunded mandate to NASA to lead Spaceguard, a coalition of worldwide observatories and scientists who find, track, and determine impact probabilities for potential EIs (Udall, 2007). This effort fits within the first stages of a typical military targeting cycle, which begins by detecting and characterizing targets. In the first half of this analysis, military targeting is applied to the EI challenge through the development of a methodology to characterize early warning times for different size objects. In the second half, recommendations for acting on different warning time scenarios are presented, to include augmentation of observation technology and use of a precursor transponder implantation mission.

An interdisciplinary approach is taken to measure the success of the Spaceguard efforts in increasing the warning times for approaches of variously sized bodies. A multi-step method is developed, beginning with determining past and present warning times for asteroids entering the 0.05 AU Astronomical Unit (AU) Minimum Orbit Intersection Distance (MOID) of Earth. Using source data from NASA's NEO Program database of close approaches, JPL's Small Body Database, and the IAU Minor Planet Center, the differences between the dates of first discovery of these Potentially Hazardous Asteroids (PHA) and the dates of 7300 penetrations of the MOID to graph warning times for known PHAs' penetration of the MOID were aggregated. The

method also includes the estimate of PHA discovery, rates of objects with high orbital uncertainties, and missed approach rates. A discussion of potential sources for error and directions to take for further development of the model is included. Finally, recommendations for campaigns against EIs are provided, given different warning time and size scenarios.

The most significant of the conclusions is that, given current technology, and given the limitations of the model used, the 100-300 m size range appears to contain the most likely EI Spaceguard will discover with enough warning time (over 30 years) to take some form of action. A counterintuitive additional conclusion is that this size range also may yield an object that will strike with no warning time. Another conclusion is that EIs smaller than 100 m will provide negligible warning time for centuries.

Targeting campaigns against the most-likely EI warning-time and size scenarios are discussed. These campaigns include first, additional observation technology; second, an inexpensive short-termed precursor transponder mission; third, a long-term observation mission; fourth, a suite of simultaneous observation and mitigation missions, and finally, evacuation and recovery operations. The overall conclusion is that additional resources should be allocated toward more robust survey technology, the first layer of defense, with continued development of precursor characterization-transponder mission technology, the second layer of defense.

CHAPTER I

INTRODUCTION

Prologue

A host of U.S. government organizations have been allocated billions of dollars to ensure that an adversarial nation or terrorist group never detonates a nuclear warhead on U.S. territory. This mission is vital and brings correspondingly vital amounts of funding. Yet funding allocations towards planetary defense against multi-megaton asteroid strikes have been relatively trivial, despite the fact that within the past thirty years the world has begun to awaken to the Near Earth Object (NEO) threat. We now understand that a countdown is taking place for an explosion larger than any nuclear device. We do not know how long the countdown will be or where the destruction will take place; we only know that a NEO will strike with a Tunguska or greater-size impact somewhere inside the next few centuries.

Several deadly NEOs are currently on this destructive path, their orbital parameters configured such that they will impact Earth with devastating results. Will we take the necessary steps to find these objects in time to defend ourselves against them? Will we augment Spaceguard's effort to find, and catalogue, track and maintain the orbits of the tens of thousands of Potentially Hazardous Asteroids (PHA)? Will we design campaigns of space missions to characterize, track, and later mitigate the incoming projectiles? Earth-Impactors (EI) are a natural hazard that humans may have the knowledge and ability to overcome, given sufficient budgetary resources. Political will and widespread understanding of the true nature of the threat is necessary to make this happen.

Overview

The development of a methodology for answering two questions is central to the first half of this thesis. The first question the methodology is developed to answer is: for space mission design planning purposes, what is the most likely size of the next impactor with enough warning time to take substantive action against it? Secondly, what will average warning times for penetration of the 0.05 AU MOID around the Earth be in the future? An approach to answering these questions is developed to better define the specific threat from NEOs. The approach is applied using inputs that are acknowledged to contain errors; however, as some inputs are refined by NASA and further research in the community, the method might eventually yield accurate and applicable results.

The second half of this thesis uses the results from an attempted application of the method to provide targeting campaign recommendations. This analysis is an interdisciplinary approach to the impactor problem set. The thesis contains discussion throughout about the success of NASA's NEO Program and Spaceguard and the revolution it has brought to providing advanced warning of an Earth Impactor. It also contains a projection of what future warning times will look like as NASA's efforts continue, if no new funding or technological innovations are added to the current regiment.

The primary method used for the first section was a compilation of early warnings for penetrations of the 0.05 Astronomical Unit (AU) Minimum Orbit Intersection Distance (MOID) as analogous to actual impact. Discovery dates for all known PHAs came from one NASA database, and all known close approaches from another. These were binned by size and time, and used to calculate the warning times for these close approaches. Estimates were then made for missed approaches, or approaches of objects that have not been discovered, and projected discovery rates of new bodies. Finally, estimates for the number of PHAs whose orbital uncertainty is too high to allow for long term projection were incorporated, counted them as "Level 2 PHAs" in the model, essentially considering them to be "lost in a sense."

The 0.05 AU distance from the Earth is used for warning time estimates throughout this paper. While there are differences between this and warning times for actual impact, it is used as a proxy for impacting warning times. The warning time for 0.05 AU penetration represents the time that will be available for initial decisions for action against each PHA close approach to the Earth. In a layered approach to planetary defense, every penetration of 0.05 AU from Earth should be considered a situation requiring a decision to be made. The decisions will involve one of the following mission campaigns, depending on the time left, the errors in the trajectory's ellipse, and resource allocation:

1. Ignore the penetrator for the time being. If there are already enough observations to demonstrate that the incoming body will not threaten the Earth, resources need not be focused towards this object for planetary defense purposes.

2. Focus additional ground based telescopes at the object. If the trajectory is only known well enough to project out a few decades or centuries, the object might merit further observation to ascertain future potential as an EI.

3. Focus RADAR assets on the object, if the error ellipse is large enough to have some probability of hitting Earth or entering a gravitational keyhole, or if the object is large enough to cause global catastrophic damage.

4. Launch a precursor characterization/transponder mission. If the uncertainty is low and the object has a reasonable chance of impacting, a transponder mission should be launched to refine the orbit of the object. This mission might simultaneously characterize the objects mass, density distribution, shape, and composition.

5. Launch near-simultaneous observation and mitigation missions. If the warning time is low and the object trajectory is uncertain enough that it has a reasonable possibility of impacting the Earth, it may necessitate the launch of a transponder-characterization-observation mission right before or at the same time as an attempted deflection mission. This observation mission would also carry out post-impact assessment of the object, analogous to USAF application of Battle Damage Assessment (BDA) to determine if a bombed target still remains a threat. Following this post-impact assessment, the object might require further deflection attempts.

6. Evacuation. If warning times are too low for deflection, ground and space-based assets should be rapidly focused towards refining the final approach of the object, in an effort to determine the most likely impact region for full scale evacuation.

7. Recovery operations. If warning time is zero and the object strikes, NASA and Spaceguard will be largely out of the picture, as FEMA and other organizations take over.

Earth Impact decisions involve weighing uncertainties and risks versus resource allocation. These decisions, if they begin at the outer layers of defense, can save time and resources later. Therefore, with every 0.05 AU approach, a decision, whether automated or human, must be made within the time between detection and approach. With every repeated entrance within 0.05 AU of the Earth's MOID, a decision to carry out one of the above steps should be taken.

The remainder of Chapter I describes the environment by defining key terms used throughout, discussing the relevance of warning times, introducing Spaceguard, describing the policy and funding environment for the program, and providing an overview of the current Potentially Hazardous Asteroid (PHA) population. Also provided are estimates of damage potential for different sizes of PHAs, given population density distributions on the Earth; this is important for understanding the relevance of different sizes of EIs.

Chapter II provides the methodology used for estimation of 0.05 AU approach warning times. This includes several data points required to build the model. Chapter III provides the results of the model in the form of graphs and charts of estimated future warning times for 0.05 AU penetrations. It also contains a discussion of sources of error for the model.

Chapter IV contains an application of the results of Chapter III. It specifically contains an analysis of how a transponder mission is an important key element of the layered defense approach to planetary defense, second only to ground and space-based observation. Once Spaceguard finds a threatening NEO, and all ground observation mechanisms are exhausted, a precursor transponder mission could be critical to determine if the NEO is indeed an impactor. A transponder mission, whether placed onto the NEO, in orbit around it, or trailing it, could provide enough orbital accuracy to make a final determination as to whether a potentially expensive deflection mission is necessary. Additionally, should an attempt at deflection take place, a transponder-observation mission would be vital to obtain post-deflection assessment to determine whether the object still threatens the Earth. For this reason, a substantial part of Chapter IV addresses the transponder mission concept, to include a discussion of the top three winners of the Planetary Society's Apophis Mission Design Competition for transponder missions.

Chapter IV also contains a discussion of the DoD targeting cycle and its application against NEOs, to include how a transponder mission would fit within the DoD targeting cycle. The author, who spent part of his military career involved in the targeting campaigns of Afghanistan and Iraq, sees similarities between the targeting processes used in the DoD with what must be used to face the next threatening EI. Chapter IV uses this concept and provides analysis and recommendations for targeting campaigns against EIs, given different warning times and sizes.

Chapter V contains an overall discussion of the findings and the campaigns. The current vulnerabilities associated with underfunding of Spaceguard are discussed, focusing primarily on the long-term lack of adequate warning times for bodies smaller than 300 m. It also contains an analysis of each size bin, and some final words on the need for better and more observation technology. Finally, it contains a discussion of future potential improvement on the methods used in this analysis.

Key Terminology

Most terminology used is standard within the NEO community; however, some new terms had to be introduced that are specific to this model. Key terms are as follows:

Near-Earth Object (NEO)- Asteroid or comet with perihelion distance less than 1.3 Astronomical Units (AU) (NASA NEO-P website, 2012)

Near-Earth Asteroid (NEA)- The asteroid subset of NEOs; this represents the vast majority of NEOs (NASA NEO-P website, 2012).

Potentially Hazardous Asteroid (PHA)- NEA whose Minimum Orbit Intersection Distance (MOID) with Earth is 0.05 AU (7.5 million km) or less and whose absolute magnitude is less than 22.0 ($H < 22.0$) (NASA NEO-P website, 2012). PHAs are the main focus of this study, although asteroids whose magnitudes are greater than 22.0 ($H > 22.0$) are also included.

Earth Impactor (EI)- Asteroid or comet that strikes the Earth (NASA NEO-P website, 2012). This study is confined to asteroids only, as they are both a more common danger to Earth and a more surmountable challenge. Comets, with their extremely high eccentricities, are much more difficult to predict and represent a threat that may require several centuries of technological growth to reliably mitigate.

Actionable EI- For the purposes of this paper, an actionable EI is one that is detected with enough time to potentially take additional ground observations, implement a precursor transponder mission, mitigate if necessary, and carry out a post-mitigation assessment mission.

Mitigation- an attempt to reduce the threat of a possible EI. In this paper, mitigation can include, and is often used interchangeably with, “deflection.”

Warning Time- For the purposes of this paper, Early Warning and Warning Time are the time between first detection and a close approach within the 0.05 AU MOID. As the Spaceguard effort grows, these warning times will grow significantly for objects over 300 m in diameter. Objects smaller than 300 m, as discussed in Chapter IV, will require improvement in observational technology to produce consistently long warning times.

Known object- For the purposes of this paper, a known object is a NEA that has been discovered and tracked.

Missed PHA- For the purposes of this paper, a missed PHA is a PHA that has passed within the 0.05 AU MOID but that has not been observed or discovered. Such objects can only be estimated.

Missed approaches- For the purposes of this paper, missed approaches are the estimated number of approaches within the 0.05 AU MOID from missed PHAs.

Spaceguard period- A 14 year period, for the purposes of this paper. Because our analysis began with a study of the success of the Spaceguard from its congressional mandate in 1998 to the end of 2011 (the date of download of all data), equal 14 year periods are used in the future projections of approach warning times.

Level 1 PHAs- For the purposes of this paper, Level 1 PHAs have low uncertainty trajectories; these are objects with enough observational arc or observation in enough oppositions that their orbital trajectories can be forward and back projected for the entire period of 1900-2200.

Level 2 PHAs- For the purposes of this paper, Level 2 PHAs are high uncertainty PHAs. These are objects with insufficient observations to project their orbits reliably more than one Spaceguard period forward or backward; in other words, objects whose orbits provide less than 14 years certainty in either time direction. These objects cannot be back- or forward- calculated with enough certainty to know whether or not they will enter the 0.05 AU MOID again or have entered it in the past. They are, in our model, considered “lost”. They result from insufficient observation, and occur mainly in objects of high H values. The term “Level 2” is used rather than “lost” however, because lost objects have other specific definitions in the NEO community. Timothy Spahr, head of the Minor Planet Center, explains that even though objects with high uncertainty are lost in the sense of not being able to point a small telescope at them, “they will be identified when they are accidentally re-found years later.” (T. Spahr, personal communication, Feb 2, 2012).

The Relevance of Warning Times

Warning times for earth-impacting bodies have historically been far less than zero. The vast majority of small body impactor evidence has been discovered well after impact. Examples of impacts that occurred without warning include the impact 50 thousand years ago that produced Arizona’s well-preserved Meteor Crater; the impact 65 million years ago that exterminated most dinosaur species on Earth, allowing mammals to rise; and the meteorite that struck the east coast of North America 35 million years ago, resulting in the Chesapeake Bay’s location and shape (Poag, 1999, p.

57). Unlike other major impacts, the recently discovered Chesapeake impact shows evidence of a mass extinction having occurred well after the impact; Poag conjectures that this counterintuitive result delayed mass extinction might have come from creating a “pulse of greenhouse warming in the midst of the long-term global cooling trend” (Poag, 1999, p. 102). Although the theory of delayed extinction merits investigation, the typical multi-kilometer Earth Impactor (EI) provides no such postponement to Armageddon. Each of the five largest impact-induced mass extinctions, occurring 438, 360, 245, 208, and 65 million years ago, “decimated 50-95 percent of the species living at those times” (Poag, 1999, p. 83).

However, as frightening as the stories of species-ending EIs may be, NASA announced at the end of 2011 that 93% of these large (> 1 km) NEOs have been found (Clavin & Brown, 2011) through the efforts of Spaceguard. To date, NASA has not found a projected collision within that set of NEOs for the next several centuries. This accomplishment, and the work of scientists worldwide in support of it, should be considered one of the more significant achievements of recent times. NASA could continue to refine its orbital prediction on these bodies out to several hundreds of millennia to determine if any very large body is destined to be an EI. If such an impactor were found, it would be an extraordinary gift to the planet if our species could find a way to prevent it from eventual impact.

At the other end of the spectrum, very small asteroids strike the Earth frequently. A recent event more understandable within the human concept of time is the 1908 Tunguska event, a multi-megaton size explosion which, without warning, leveled a swath of Siberian forest. A less threatening example was a smaller iron meteorite fall in the Sikhote-Alin region of Siberia in 1948 (Morrison, 2005, p. 93). Another occurred in 2009, when a very small asteroid (on the order of 10 m) penetrated the atmosphere, detonating over an island region of Indonesia in a daytime blast with the energy of about 50 kilotons, roughly three times the energy of the Hiroshima atomic explosion. The dust cloud remnants were easily visible from the ground and can be viewed on Youtube.com (Silber, 2009, p. 1). Fortunately, the object did not penetrate far enough to cause any destruction, although an object only two-three times as large, such as the Tunguska EI, could have had a more devastating local effect.

Warning times for approaches of asteroids that have missed the Earth have been, like warning times for impact, predominantly close to zero. Every few days small objects approach to within the 0.05 AU of the Earth. The growing body of observational evidence within the past few decades has taught us that our planet is swimming in an ocean of small bodies, whose impacts are shielded only by our relatively thin atmosphere and the vastness of space. Many such bodies pass by undetected, their fleeting close approaches occurring at high velocities relative to the Earth, fast enough to cause enormous damage if they strike the Earth. According to Daniels (2009), astronomers from the LINEAR program discovered a new 100 m diameter NEO on June 17, 2002 that had passed approximately 120,000 km from Earth, well inside the Moon's orbit. Daniels states, "Perhaps more alarming was the fact that the discovery took place three days *after* the asteroid flew by" (Daniels, 2009, p. 126).

A 2008 publicly released U.S. Air Force report described a more promising event; in July 2008, a binary NEO (2008 BT18) consisting of a 600 m NEO with a 200 m smaller object passed within 6 lunar distances of Earth. This set of NEOs, easily capable of large regional devastation, was discovered in January of 2008, six months prior to fly by (Air Force Future Concepts and Transformation Division (AF/A8XC), 2008, p. 9) This is promising in that the detection actually provided time for some form of action, even if only evacuation. It also raises attention to the question- what could be accomplished in such a short period of time? Movies such as Armageddon display astronauts deploying nuclear weapons on incoming EIs with only days to weeks of preparation, saving the world from certain destruction. These movies depict a situation in which the world knows of the EI in time for a crash mitigation program, and assumes that the government has such a crash mitigation program already in place.

However, a crash mitigation programs would likely take several years to decades to implement. Most of the core understanding of the required technology exists- launch vehicles, kinetic and nuclear impactors, precursor transponder missions- but assembly of such technologies in a crash effort would require time we might not have. Aside from technology, the relationship of the orbit of the EI with that of the Earth is also critical. As then NASA administrator Mike Griffin stated in his 2005 Testimony to Congress:

> It is estimated that a 30-year advance warning would be required to have a reasonable assurance of deflecting a NEO from a collision with Earth. Thus, if a future impactor were identified today, the time to explore the characteristics of the NEO, develop a deflection system, deliver it to the NEO, and apply the deflection early enough to prevent an impact, requires about a 3-decade lead time (as cited in AF/A8XC 2008, 13).

This estimate of 30 years, while somewhat arbitrary, is loosely based on the time to design and implement a crash deflection mission, the transit time, and the time required to change the course of the asteroid. In reality, a deflection mission could take less time with enough political will. However, because of trajectory uncertainties, political will may not have the force necessary to press for a deflection mission without at least 30 years of time. The reason behind this is that additional ground observations are required, followed by a precursor transponder mission to determine whether the object will indeed impact. Once the impact probability becomes high enough, political will can become strong enough to press for a crash deflection mission. However, the time necessary for the added ground observations and the precursor mission will take a significant part of the early warning time available up. A transponder mission alone might take seven years, not counting design and implementation as discussed in Chapter IV. This underscores the importance of better characterization of target warning times and sizes. Beyond the Hollywood and History channel portrayals, what is the true nature of the threat? How big will an impactor be, and how long will we have to react to it?

Preliminary Summary of Results

Figure 1 is example of one of the results of this work- a graph of projected 0.05 AU warning times for objects of approximately 500-1000 m diameters.

Charts for other size bins are found in Chapter III “Results”. The following is a brief overview of what they convey. For PHAa with diameters larger than 1000 m (as estimated from H values) not surprisingly, the Spaceguard effort has increased warning times for the majority of PHAs entering the 0.05 AU MOID to several decades, and even centuries. There is a negligible chance that the next near-term EI will come from this size-bin. However, due to the species threatening nature of this size bin, efforts should continue to ensure that all objects in this population are eventually accounted for, with orbits defined well enough to project out tens of thousands of years. It is still a little early in the process to declare absolute victory.

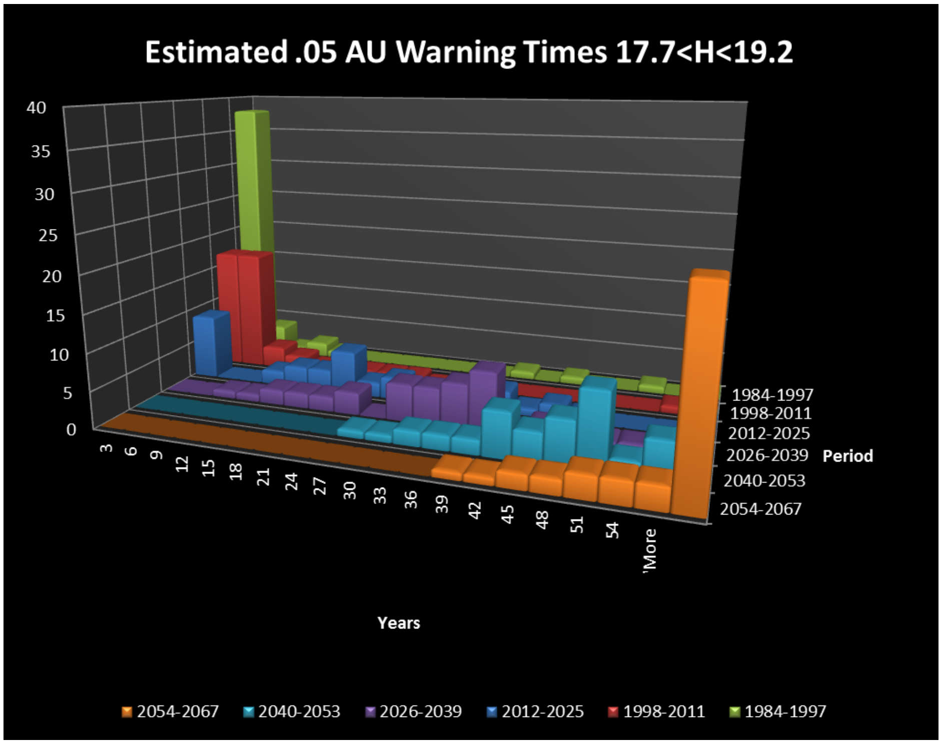

Figure 1. Histogram for 500-1000 m 0.05 AU Warning Times.

This plot indicates that warning times prior to entry within 0.05 AU of the Earth may be on average greater than 30 years in the 2012-2025 Spaceguard period (purple). After 2054, all 500-1000 m objects are likely to provide well over 60 years warning time. Prediction accuracy is limited by the inputs to the methodology.

For PHAs in size bin 500-1000 m (by H Value) should become actionable, meaning that a precursor transponder mission and/or deflection mission would be possible, by 2026 at current rates.. If an EI is discovered within the next 14 years, there is only a small chance that it will be from this part of the population, because so few are left in this population relative to smaller sizes. Most PHAs in the 300- 500 m size bin (as estimated from H values) will be discovered and will have well defined orbits at current rates by around 2040.

PHAs by H value that are roughly100- 300m in diameter provide a more complex scenario. Even with currently high discovery rates in this size bin, the majority of these bodies still pass by unseen, providing virtually no warning time for many decades to come at current rates. Moreover, many of these are not observed long enough to bring uncertainty levels down to allow for accurate future orbital predictions. The weaker orbital elements established therefore “only allow prediction intervals of a few decades or less” (S. Chesley, personal communication, January 29, 2012). However, there are many objects in this size bin, so there is a reasonable chance that the next actionable EI will be discovered in this part of the population. So many are discovered that the low percentage with well-established trajectories outnumber high certainty discoveries in all other size bins. Therefore, this size bin holds a reasonable chance of providing an EI that will have over 30 years of warning time.

Objects smaller than 100 m have on average less than zero warning times for 0.05 AU MOID penetrations, meaning that they are often discovered days or months after their close approaches. With no technological improvements, this will continue for centuries due to two factors. First, this size bin has by far the highest population of objects, more than all the other size bins combined. It will therefore take a very long time for completion of the population, even if every discovered object had high orbital certainties. Second, very few of the objects have high trajectory certainties. While a high number of objects in this bin are discovered every year, only around 5% (as derived later) have adequate certainty in their orbits to forward project more than a couple of decades, with current technology. This bin represents by far the most likely from which the next surprise EI will be drawn. But there is also a reasonable chance that if an actionable EI (over 30 years warning time) is discovered, it will come from this size bin.

Knowing this, we can focus our action on the most likely situations in the next few decades, which include discovering an actionable EI within the 100-300 m size bin, followed by the 300-500 m and 25-100 m size bins.

These rates are for the next *actionable* EI, providing potentially enough time to react and launch a precursor or mitigation mission. The most likely next impactor in absolute terms is still not actionable, and is to be found within the smallest size bin (25-100 m). Without significant technological advancement, these Tunguska-type events will provide no warning times for several centuries.

Campaigns can be designed for each of these eventualities, and these are the subject of Chapter IV. The methodology presented here does contain sources of error, principally in the estimates for the total number of PHAs; the results will doubtless therefore have some error associated with them. It is even possible that this error could be magnified in some cases (as discussed in Chapter IV). If the error turns out to be relatively manageable, the results could indicate that NASA should design long-term campaigns for objects in the 100-300 m, 300-500 m, and 25-100 m size range, in that order of precedence for now. This order will change within the next 2-3 decades, as the 300-500 m objects are discovered, eliminating them from the pool of potential EIs.

Long warning time targeting campaigns should first seek to increase knowledge of the orbital probabilities through ground observations, followed by a relatively low-budget precursor transponder mission and, if necessary, followed by an additional more expensive suite of long-term (multi-year) observation missions, which would provide pre-and post-mitigation assessment.

Spaceguard and the Near Earth Object Program

Only in recent years has human technological understanding advanced to the point at which substantive warning of impact events has moved from the realm of science fiction to the truly plausible. Such warning times have become significant for objects over 1000 m in diameter only during the last 14 years, since the 1998 NASA adoption of the Spaceguard Survey concept. Chapman and Morrison proposed such a survey in 1992 in a congressionally requested NASA study (Morrison, 2005, pp. 87-88). This study, advocating the search for asteroids larger than 1-2 km in diameter, was further supported by a 1995 NASA study chaired by Gene Shoemaker, who "described a practical way to carry out such a Spaceguard Survey using modest-sized ground-based telescopes equipped with modern electronic detectors and computer systems" (Morrison, 2005, p. 88). NASA proceeded to establish its Near Earth Object Program (NEO-P) in 1998 with the congressionally mandated goal of finding 90% of NEOs over 1000 m in diameter.

In 2003, NASA carried out a "Study to Determine the Feasibility of Extending the Search for Near-Earth Objects to Smaller Limiting Diameters." A cross-section of the NEO community conducted the study, which advocated the allocation of additional resources to find, track, and forward project the orbits of over 90% of NEOs larger than

140 meters within no more than 20 years, at costs ranging between $236 million and $397 million. The study emphasized that “NEO search performance is generally not driven by technology but rather resources.” (NASA: Near Earth Object Science Definition Team, 2003, p. iv)

Following this, Congress directed NASA, without providing additional funds, to implement a NEO survey program, “for objects as small as 140 meters in size in the NASA Authorization Act of 2005.” (Udall, 2007, p. 2007) According to Lindley Johnson, Program Executive for the Planetary Science Division, which oversees NEO-P, congress allocated NASA an additional $2M in 1998 to start the program. In all other years up to and including 2009, NASA took the funding for NEO-P, amounting to an average of $4M per year in real year dollars, out of its Planetary Science research and analysis budget. In 2010, congress appropriated an additional $2M above NASA’s requested budget as an earmark to fund the radar operations at Arecibo (L. Johnson, personal communication, Feb 12, 2012), the National Science Foundation’s (NSF) high-powered radar in Puerto Rico. NASA is, in effect, leading the worldwide planetary defense effort from its science budget.

In FY11 NASA sought to establish a separate funding line amounting to a 400% increase to $20.4M for NEO-P in its budget request, although that budget was never acted on by congress. At the behest of the Obama administration, NASA again put a separate funding line for $20.4M towards NEO-P in its FY2012 budget request to congress. This support likely came because of a National Research Council (NRC) report published in January of 2010 that “finally convinced most everyone that more effort should be spent in this area” (L. Johnson, personal communication, Feb 12, 2012). Perhaps in a few hundred years, the relatively minor amounts of US Government funds allocated to Spaceguard will be viewed as the most cost-effective dollars spent on government programs in the 21st century. However, should a damaging strike occur, the view would likely be that the congress and administrations were at fault for providing comparatively very little funding towards a significant mission. Only $4 million per year (and more recently $20.4 million/yr) has been allocated towards discovery, tracking, modeling, and software development for the NEO Program. While this sum may prevent unpredicted impacts from the large objects, it may not suffice to provide adequate warning for objects below 300 m in diameter in the near future. The number of objects below 300 m is higher than all the size ranges above 300 m combined, and objects in this range can still cause local or regional catastrophic damage. Furthermore, without an eventual space-based infrastructure, the relatively low percentage threat from comets will always be present.

Given the minor budget allocated to Spaceguard, the results have nevertheless been excellent and have provided confidence that it may eventually be possible to predict most EIs down to 140 m with enough warning time to take action. On Oct 6, 2008, some immediate proof for a success of the effort came when part of the Spaceguard infrastructure detected 2008 TC3 19 hours before it exploded 37 km over the Sudan. The automated Catalina Sky Survey telescope at Mount Lemmon, Arizona, discovered the object, which had a magnitude H=30.9+/- 0.1, something virtually impossible to do 20 years prior. Incredibly, orbital solutions from ground observations were able to accurately predict the location of impact in the Nubian Desert, and the above ground explosion was visible to eyewitnesses on the ground and US government satellites (Jenniskens, 2009, p. 485). Estimates of the size of 2008 TC3 indicate it was only a few meters in diameter. It was not massive enough to strike the ground with substantive remaining kinetic energy, although a total of 3.95 kg of its post-explosion mass made it to the ground unexpectedly. 2008 TC3 is very relevant to the topic of warning times for one significant reason: although no current technology could have mitigated this EI in the time available, the very fact that Spaceguard's Catalina Sky Survey discovered 2008 TC3 prior to impact at all is inaugural. Until then, no EI had ever been detected several hours prior to reaching the ground. This detection was a direct result of Spaceguard's growing capabilities, both technologically and organizationally.

Detecting small bodies hours prior to impact could be vital for evacuation of a target area and shows immediate promise for the future. And the Spaceguard effort is working to detect potential EI events years, decades, and even centuries prior to impact, in time to send a deflection mission, or even a precursor characterization/ observation mission prior to a deflection mission.

The Relevance of Size

The size of a threatening EI is intertwined with its warning times. Size also matters for campaign plans, damage predictions for impact, evacuation plans, post impact recovery plans, and deflection methodology. The population count for NEAs and PHAs may be inversely correlated to the diameter, with the vast majority of objects measuring under 100 m in diameter, and only around a thousand greater than 1 km. Small PHAs, while more common than large ones, are also more difficult to detect and track. Small PHAs often have orbital uncertainties so high that predictions out a decade or two are difficult or impossible. In our model, these bodies with high orbital uncertainties are referred to as “Level 2 PHAs”; these PHAs are counted as essentially lost, because no adequate warning time will come with such high uncertainties.

The Current Population

The method and results in Chapters II and III required the use of population data throughout the analysis. Much of this population data came from NEOWISE. NEOWISE is the asteroid detection add-on to the Wide-field Infrared Survey Explorer (WISE) mission, which surveyed the entire celestial sky while orbiting in Low-Earth Orbit over the course of 12 months (NASA Press Conference, 2011). WISE was designed to look for stars and galaxies, but a side benefit of its scans was a large amount of data collection on NEOs. WISE scanned in the infrared (IR) part of the spectrum. NEOWISE data shows an estimated 19,500 mid-sized (100-1000 meter) NEOs, potentially threatening our planet with local or regional devastation, down from 35,000 previously estimated (NASA Press Conference, 2011). PHAs are a subset of these NEOs, discussed later. Asteroids, due to their varying albedos, can appear smaller to optical telescopes than they really are, and the IR scans of WISE alleviated this problem. The NEOWISE estimates did not apply to NEOs smaller than 100 m in diameter, which from previous studies are thought to number close to 1 million (NASA Press Conference, 2011). Other analysis of the NEOWISE data showed that 93% of the larger than 1 km NEOs have been discovered. Significantly, none of these appears to threaten the Earth for the foreseeable future (NASA Press Conference, 2011). Figure 2 represents the NEOWISE count.

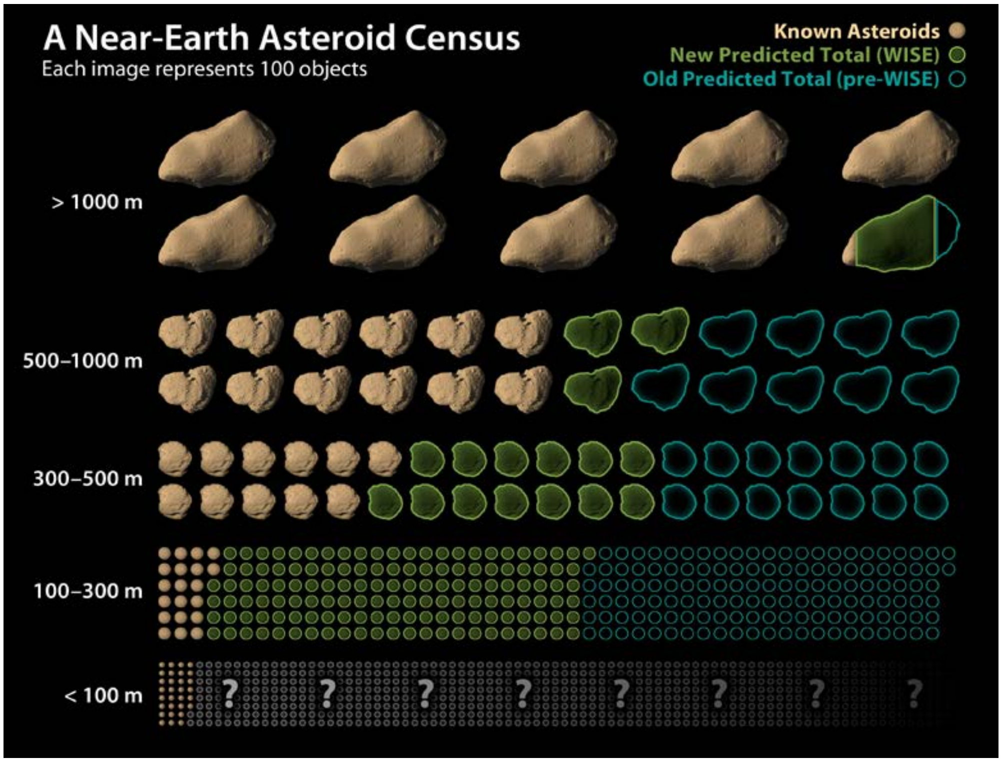

Figure 2. NEO Population.

This figure shows the total discovered objects in brown, and the total predicted objects in green. Each image represents 100 objects. Previous estimates are in blue. The brown and green estimates are used in this analysis. For objects under 100 m, NEOWISE was not used for estimates. Image credit (NASA/JPL-Caltech, 2011).

Size bins in this study are the same sizes used in the NEOWISE program, for consistency. These bins range from the largest PHAs (> 1 km) down to a minimum of 25 m, below which most objects will burn up prior to impact. Time bins are based on the period beginning with the congressionally mandated effort to find objects over 1000 m and ending after the NEOWISE study was completed, by the end of 2011. This 14 year period is called, for the purposes of this paper, a Spaceguard period.

Another useful source of data for the NEO/PHA populations was the NEA Size-Frequency Distribution chart (L. Johnson, personal communication, January 5, 2012) found in NASA's 2003 NEO Science Definition Team report, as updated by Mainzer et al. with the NEOWISE data in 2011. The updated diagram, included below, gives several approximations of the number of objects for various sizes as well as their destructive energy levels and approximate impact intervals. Different investigators carried out these approximations with very different methods to include the use of lunar cratering records, bias correction of controlled surveys, ratios of re-detections versus new discoveries, relative bias estimates, infrasound, and orbiting infrared sensors detecting bolide impacts on the upper atmosphere (NASA: Near Earth Object Science Definition Team, 2003, p. 17). Results from NEOWISE indicate that the "cumulative size distribution is best represented by a broken power law with a slope of 1.32+/- below 1.5 km" (Mainzer, et al., 2011, p. 3). This was used as the lower bound for the number of PHAs less than 100 m.

Using data from the NEOWISE count in Figure 2 and the NEA Frequency count in Figure 3, specifically using the 1.32 power law as the lower bound and the constant power law as the upper for under 100 m, the following Table was produced. This table contains the total number of estimated NEAs and the total number of detected NEAs as of the end of 2011. The third row is a simple percentage of the total number that has been discovered.

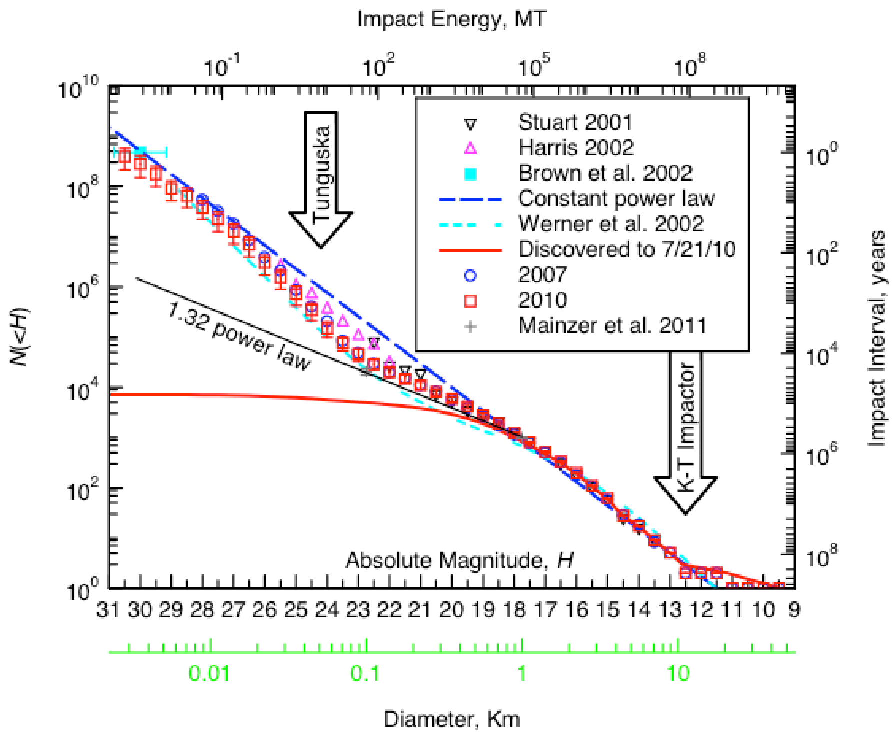

Figure 3. NEA Frequency, Absolute Magnitude, Size, Impact Interval and Energy Plot.

This plot shows, on the left side, the estimated number of NEAs larger than a given size. Also indicated are the impact intervals and impact energies for given size ranges. H to size conversion at the bottom uses an albedo estimate of 0.14. Image credit (NASA NEO Science Definition Team as updated by Mainzer et al., 2011)

Table 1. Population Overview, December 31 2011.

	>1km	500m-1km	301m-500m	100m-300m	25m-100m
Estimated Total NEAs	981*	1500*	2400*	15,700*	50,000-1M**
NEAs Detected to date	912	1200	1100	2000	3000
% NEAs detected as of Dec 2011	93%	80%	46%	13%	.6%
* from NEOWISE graphic ** from NASA NEO Science Definition Team graphic- high uncertainties in this size range					

Note: The above table provides estimates of the total NEAs in the given size ranges as well as the NEAs detected in those size-ranges as of the end of 2011. The third row displays the percent completeness of the population.

Damage Potential for Various Sizes of EIs

Another critical element of any thorough NEA targeting study is damage potential. Understanding damage potential helps us to understand better what courses of action should be taken given different warning time scenarios.

Impacts by NEAs larger than 1 km are both extremely devastating and extremely rare. Most of these objects have been found, and none of those found are on path to strike our planet for at least several centuries. If such an object did strike, the impact would be the "destruction of a region or ocean rim; potential worldwide climate shock, approaching global civilization destruction level" (Chapman, 2003, p. 3). The object that killed off the dinosaurs after their very long reign was potentially 6 km in diameter, although its size varies by study. NEAs in the 500-1000 m range would also be devastating on both land and water at the regional if not global scale, depending upon which end of that size bin an EI comes from.

NEAs in the 300-500 m range can create a large, deep crater on land and devastation for a small nation (Chapman, 2003, p. 3). They could cause considerable damage to a large nation, depending on the size, density, composition, entry angle, and velocity. The effects also depend greatly on whether the impact takes place in a populated area or rural area. A water strike from a NEO in this range anywhere in the Atlantic could "devastate the coasts on both sides of the ocean by a tsunami over 100 meters high" (Hills, 1997, p. 1)

NEAs between 100 and 300 m in size have the capacity to create a devastating air burst or a strike on the ground or ocean. A 200 m object contains the energy of 600 MT of TNT, the size of several of the largest nuclear weapons ever tested. On land, this would create “an enormous crater, 3 to 4 km across and deeper than the Grand Canyon” (Chapman, 2003, p. 10). The death toll could range from the thousands to millions. Ocean strikes are more likely because oceans cover 71 percent of the Earth’s surface. A 200 m object striking the ocean could generate a tsunami in the 10 m range, “comparable to the biggest ocean-wide tsunami recorded during recent centuries,” (Chapman, 2003, p. 10), although Ward and Asphaug’s model shows that waves may reach even as high as several hundred meters (Ward, 2000, p. 21). Because a large percentage of the world’s populations live in coastal areas, an ocean strike could cause significant casualties.

NEAs in the 25- 100 m range can cause Tunguska size devastation. The damage will vary greatly, as does the strike frequency; a 30 m stony meteorite will not bring near the devastation of a 30 m iron meteorite, which are significantly rarer, on the order of 6% of falls (Emiliani, 1992, p. 152) Objects in this range, which constitute the most frequent EIs, might damage or destroy on the order of 2,000 square km, as was the case with Tunguska (Chapman, 2003, p. 12). These strikes happen frequently, once every few centuries, but without an order of magnitude leap in technology, they are likely to occur without warning. A saving grace is that water impacts, at least at the lower end of this range, likely do negligible damage. (Chapman, 2003, p. 12) Also, because the radius of damage is lower for smaller impactors, there is a reasonable chance that an airburst over land would happen in a relatively unpopulated area. This happened with Tunguska, but since 1908, human population has increased in many rural and urban areas. Current populations have increased in non-arable land areas, so comprehensive modeling is required to give an accurate answer as to the danger of a smaller strike.

Accurate damage/death estimates could come from models used by the US Government (e.g. the Defense Threat Reduction Agency or the Department of Energy) for modeling nuclear air-blast fatalities. Such models generally use population layers and are more reliable than simple estimates of either inhabitable or arable land. Without such a model, simple estimates are possible by using available population predictions for urban and rural areas, but the error is much greater.

The use of estimates of “arable” land is tempting; however, such estimates would likely contain a great deal of error, because today’s population extends to a substantial portion of non-arable land. The United Nations projects that by 2030 some 1.1% of total land area, or a little over 1 million square kilometers, will contain 5 billion people (as cited in Angel 2005, p. 1). Assuming that NEAs have essentially the same chance of striking anywhere on the Earth, this represents a .3% chance that an air burst will happen over an area with average population density from 3-8,000 people per square km. A very low probability percentage strike above a city, therefore, could cause casualties on the order of 6-16 million people. The remaining land area will contain the other approximately 3 billion people, with very low density distributions from 0-1000+ people per km square.

Large swathes of land in Canada, Russia, and Australia are primarily uninhabited. These areas take up some 34.5 million km^2 of the available land mass. Antarctica makes up another 14 million km^2, and with a few much smaller countries added in, the total land area with 0-10 population density/ km^2 people amounts to roughly 60 million km^2, or 41% of available land. There is a 12% chance of a strike in these areas. The other 59% of land (17% of surface area) has a large range of population densities. The following chart is a compilation of these data for a 25-100 m strike, with current population estimates (2011-2012). It should be noted that with rapidly rising populations, both the population density and areas with higher population densities will likely increase.

Table 2. Casualty/Damage Potential 25-100 m (2011).

Area	Chance of Strike	Potential Casualties/Damage
Water	70.9%	Little or no death/damage
Sparsely populated land (0-50/ km^2)	12.1%	0- 100,000 deaths/ little to no damage
Lightly to Moderately populated	16.7%	0-200,000 deaths/ little to moderate damage
Heavily populated (3,000-8,000/km^2)	0.3%	6-16 million deaths, billions of $$ in infrastructure damage

Note: The above chart displays the current chance for strikes over water, sparsely populated land, lightly to moderately populated land, and heavily populated land. The third column displays the casualty and damage potential. A more robust model could be generated using DoD or DoE models containing population and weather layers. With the current population explosion, these numbers will increase.

As seen from the above table, although the chances are highest for an undetected 25-100 m strike within the next few centuries, the chance for the “perfect storm”, or a strike on a highly populated area, is less than 1%. However, with growing population, the 29% chance of a strike in a rural area can no longer be arbitrarily discounted.

CHAPTER II

METHODOLOGY

Steps to the Method

The following describes the method used to determine the most likely size range containing the next EI with enough warning time to be actionable. It is also the method by which warning times for penetration of the 0.05 AU MOID around the Earth are developed in this model. In the process, the success of Spaceguard over the past 14 years is characterized, and the outcome of the next similar size periods is projected. This database analysis was carried out and then used the conclusions to formulate basic mission campaigns for the most likely scenarios.

First, the planetary defense problem set was related to layered defense strategies used in the US military. Discovery and tracking and predictive analysis are the most crucial and first of the layers in planetary defense, followed by the use of in situ transponder missions to characterize the PHA and provide refined orbital parameters. Secondly, the situation of a PHA only detected on its last orbit prior to strike is examined. Then warning times for entry into the 0.05 AU MOID as a corollary to actual EI warning times are examined.

The 0.05 AU MOID warning times were derived by compiling all of the times between first detection and each approach within the 0.05 AU MOID for “known” objects. These known objects have been detected already and have orbits which have been forward and backward projected between 1900-2200, depending upon the uncertainties in the orbits. Past and recent rates for detection of new objects were analyzed and forward projected over several decades. Next, an analysis of the typical percentage of objects that have high uncertainty was accomplished. In this model, they are considered lost because their future penetrations of 0.05 AU cannot be reliably predicted past a few years. Following this, estimates for how many approaches within the MOID are entirely missed in an average 14 year Spaceguard period are made. These are called "missed approaches." Many very small objects come fairly close to the Earth without our knowing it. The number of missed approaches will decrease as more NEAs are discovered. Finally, all of the above data is compiled into histograms of 0.05 AU warning times for each size bin.

Layered Planetary Defense

Rather than relying purely on technical means to detect a NEA on its last approach prior to impact, the "layered" approach to planetary defense provides a more robust result. This approach to planetary defense falls in line with defense mechanisms for any physical security found in the military. For example, airbase security might be divided into layers, with the outer layer stopping the majority of significant attacks, through information collected on potential threats. If information fails to alert security forces far enough in advance, the base perimeter might be construed as the next layer of defense. Following this, an individual building's security mechanisms, followed by, for example, security on individual computers or for individual rooms. The most valuable of the layers is generally the informational layer.

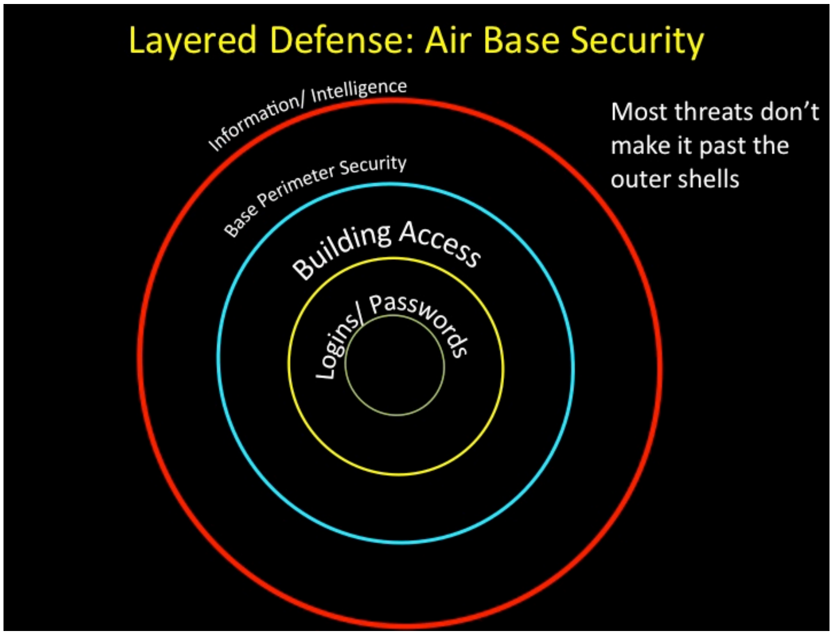

Figure 4. Example of Layered Defense for Airbase Security.

This analogue is used to design a similar approach to Planetary Defense. Here, the outer layers encompass information gathering against NEOs, to determine the general population of objects whose q values are less than 1.3 AU. Next is another informational layer, the subgroup of NEAs which come within 0.05 AU of the Earth called PHAs. A third informational layer is radar imaging for refinement of orbits, when possible. When an object provides a reasonable probability of being an EI, RADAR imaging is a logical tool for refining the probabilities of impact. One of the probabilities required is for the likelihood that an object will enter a gravitational keyhole with Earth, whereby the Earth's gravity interacts with the PHA such that it has a significant increase in the likelihood of impact on subsequent approaches. Each object has its own "personal" keyhole, whose calculations help determine the ultimate chance of impact (Garretson, personal communication,, December 1, 2011).

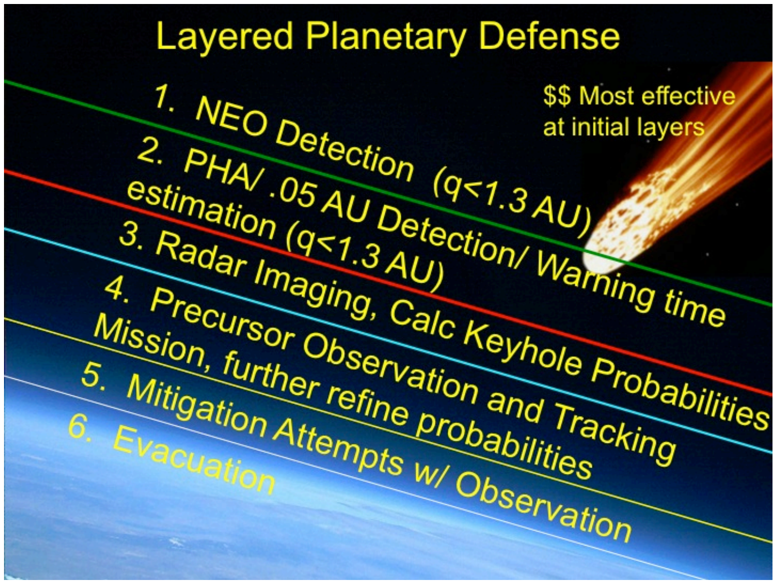

Figure 5. Layered Defense Applied to Planetary Defense.

If, through the first three “informational” layers, an object is determined to have a reasonable likelihood of striking the Earth, the next layer of defense comes into play- that of finding a very precise orbit and characterization data through a precursor characterization/transponder mission. This mission, costing less than $300 M, could save billions of dollars by demonstrating conclusively that a large-scale mitigation mission is unnecessary. Moreover, if a precursor mission determines that the likelihood of impact is even higher than originally estimated through ground observation, deflection attempts are the next layer of defense. A host of deflection mechanisms have been theorized, to include nuclear, kinetic, and slower mechanisms such as gravity tractors and propulsion systems. Should deflection attempts prove unsuccessful, the next layer of defense is evacuation of areas most likely to receive the unwelcome impactor. If an object is detected a few days or weeks prior to impact, it may be possible to calculate the likely location of impact to at least attempt evacuation.

Planetary Defense Only Using Last Approach

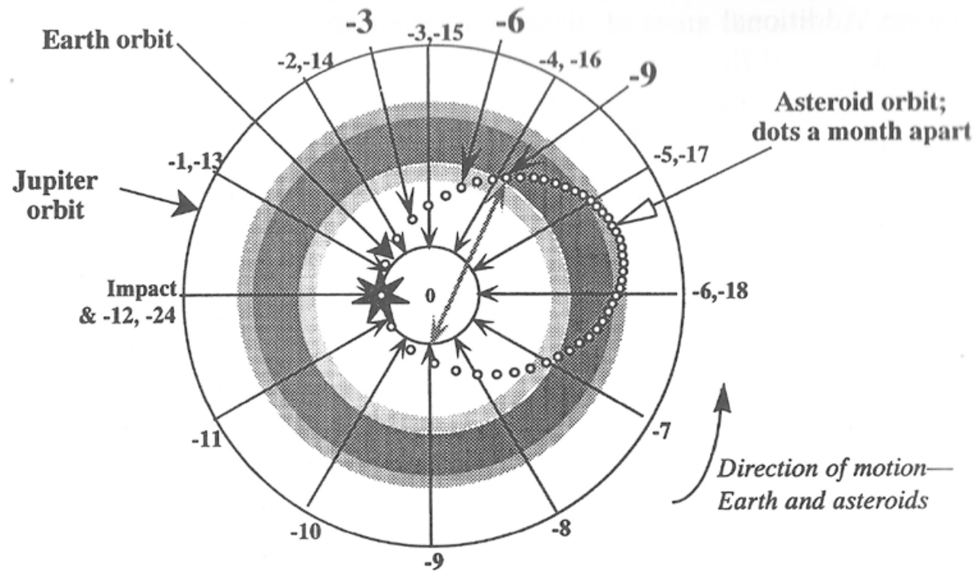

Figure 6.1: Four-Year Apollo Asteroid Collision Orbit

Figure 6. Planetary Defense Only Using Last Approach.

This chart from Doomsday Asteroid (1996) shows how typical observations can yield poor results if warning time is only a function of detection technology on the last pass. The asteroid is the dotted loop; each dot corresponds to one month of its orbit, so the dots cover are close together at aphelion, corresponding to higher velocities. (Cox & Chestek, 1996)

As Cox and Chestek (1996) explain, if we trace back from the impact, we will see that by only observing during opposition, observation of the EI is only possible around one, two, or three months before impact, using the midnight direction. “However, the gray, two-headed arrow shows the direction in which we should have been looking nine months before impact to see the asteroid” (Cox & Chestek, 1996, p. 98). But this would require a space-based telescope. The double-sided arrow in Figure 6 corresponds to where the Earth and asteroid are at nine months prior to impact. “Note that an Earth-based telescope would be in daylight, facing the sun (the “O” in the diagram), and therefore would be blinded by it." (Cox & Chestek, 1996, p. 99) If a spacecraft was positioned several months ahead of the Earth's orbit, for example, at the T-4 arrow (corresponding to four months prior to impact) on the chart, it could increase the warning time for the last pass prior to impact substantially.

This diagram shows how even now, ground-based observations will at best yield a few months warning time if the EI strikes on the first observed pass. Fortunately, this is an unlikely phenomenon for large objects, which have mostly been detected and pose no immediate hazard. However, it is a possible outcome for objects smaller than 300 m.

Space-based mechanisms could increase the final approach warning times for EIs by several months. As Cox and Chestek point out, an early warning telescope, positioned three months ahead of the Earth, could provide six months of warning for a PHA that would normally provide only two months of warning (Cox & Chestek, 1996, p. 110). Lindley Johnson, Director of NASA's Discovery Program Office and NEO Program, cited the possibility of placing a space-based asset in a Venus orbit looking out to increase NEO detection success (L. Johnson, personal communication, January 5, 2012). Even a few months more warning time would at the very least allow for greater trajectory resolution, impact location predictions, and planned evacuations. Moreover, with the right planning, it might even allow for a crash program for interception.

Layered Defense: Using the 0.05 AU MOID

After examining the "detection on last approach" warning time scenario, we next examined the more manageable (but still difficult) process Spaceguard has undertaken of finding as many objects as possible, in the hopes of detecting an EI well before its last approach. This section contains the next step- producing graphical representations of past and present warning times for asteroids entering the 0.05 Astronomical Unit (AU) Minimum Orbit Intersection Distance (MOID) of Earth. This MOID is a spherical region, similar to that of the Earth's surface. (Note: It may be possible to obtain more precise estimates by using a portion of the MOID, close to the ecliptic, due to the fact that objects with higher inclination may be less apt to strike the Earth (M. Gaffey, personal communication, 20 Apr 2012).

Penetration of this spherical MOID around the Earth should be viewed as a critical event. Warning time to this critical event is in some ways analogous to warning times for impact with the Earth. However, because the body does not actually strike the Earth, this warning time should be considered the amount of time available for a decision to be made- whether to focus more observational assets on the body, send a precursor to it, or other orbital refinement techniques.

For this part of the analysis, data for 7,300 predicted and past close approaches within the 0.05 AU MOID were combined with the dates of first discovery of these asteroids. The source data came from NASA's NEO Program database of close approaches (NASA NEO- Program, 2011), JPL's Small Body Database (NASA JPL, 2011), and the International Astronomical Union Minor Planet Center (IAU MPC, 2011). The dates of discovery were then subtracted from the dates of close approach for each penetration of the MOID. The main spreadsheet was then divided into separate bins by size, and the results graphed. Figure 7 illustrates the concept:

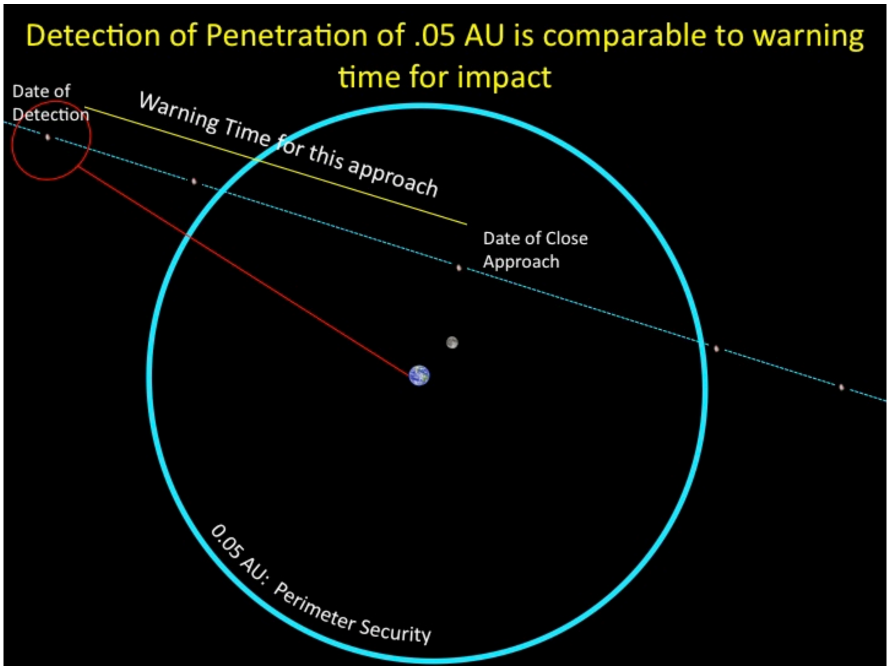

Figure 7. Visualization of 0.05 AU Approach Warning Time.

The offending NEA is in the upper left-hand corner. Subtracting the date of discovery from the date of close approach provides the warning time for this approach. While not an exact analogue to EI warning time, it gives us a defined period of time for decided action or inaction.

Data Sources for NEA Warning Time Analysis

Downloaded data included all approaches for NEAs projected to fly within 0.05 AUs of Earth between 1900 and 2200. The initial data came from NASA's NEO-P website, which gives options for downloading NEA data for different H magnitudes, distances from Earth, and timeframes. NEOs that enter within 0.05 AU were chosen because of the standard international definition of PHAs. Also, the size of the database for 0.05 AU penetrations, while large, is possible to work with using Microsoft Excel.

Although objects smaller than 150 m are not defined as PHAs, data were utilized for all sizes of NEAs, to include those below 150 m.

Size-Albedo-Absolute Magnitude Relationship

After bringing data for all PHAs into our Microsoft Excel database (to include those objects smaller than 150 m), conversion of the absolute magnitude to an estimated diameter for the objects was carried out. Absolute magnitude is defined as the “visual magnitude an observer would record if the asteroid were placed one AU away, and one AU from the Sun and at a zero phase angle (NEO-P, 2012) The standard conversion formula was used, relating absolute magnitude (H), albedo (p), and the diameter of an assumed homogeneous spherical object, as used by NASA JPL (Chesley S. C., 2002, p. 425):

Equation 1

Relationship of albedo, absolute magnitude, and diameter

$$D = \frac{1329}{\sqrt{p}} 10^{-0.2H}$$

The relationship between the diameter and magnitude are an approximation. Bowell et al. explains, “the principal source of error in the size of the object generally arises from the albedo uncertainty. However, the computed value of H can easily be wrong by a half magnitude or more since several simplifying assumptions are made about the object’s phase relation” (as cited in Chesley, 2002, p. 3). NEOWISE has demonstrated that in the infrared part of the spectrum, NEOs which appear very small visually may actually be very large objects with low reflectivity (albedo). Objects with very high reflectivity may, in contrast, be estimated as larger than they actually are.

We may see, with visual observation, only the tip of the ice berg. Figure 8 from NEOWISE illustrates the difference between visible light and infrared light emitted by a set of NEOs.

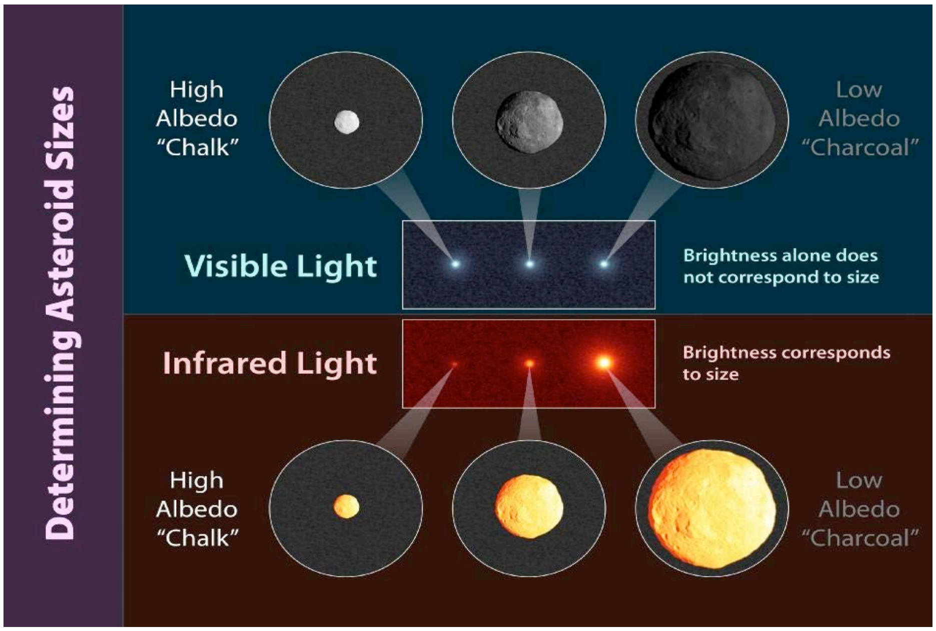

Figure 8. Visible versus IR Asteroid Size.

Here we see that a dark object such as charcoal would, in visible light, look the same size as a much smaller chalk object. However, in the IR, charcoal radiates much more heat, giving it a signature comparable to its size. (NASA/JPL-Caltech, 2011)

H value is inversely related to size, all other things being constant (equal albedos). For objects of equal albedo, high H values correspond to small objects, and low H Values correspond to larger objects. The issue is that albedos for NEAs are far from equal and are estimated to cluster around 0.05 and 0.25 (NASA NEO-P website, 2012). Average albedos used on NASA's NEO-P website previously assumed a mean albedo for NEAs of 0.11, which meant that a corresponding H value for a one km NEA was H= 18.0. According to NASA's Planetary Science Division Program Executive, the database was changed in recent years to reflect an updated estimate for average albedo to .14 for NEAs, carried out by J.S. Stuart in 2003 (L. Johnson, personal communication, January 5, 2012). Using equation 1, this establishes an absolute magnitude of 17.75 +/-.1 for diameters of 1 km, vice the previously used H = 18.0. This means, essentially, that NEOs may be slightly smaller on average than previously understood. However, the type of asteroid is important when looking at albedos. A more comprehensive method for accomplishing warning time estimates might look at the population of types of asteroids, using average albedos for each type, rather than for the entire population.

With the average albedo of 0.14 and H values from the NEO-P database, equation 1 was used to populate the spreadsheet with estimated sizes of our objects (NEO-P, 2012). Objects were then separated out into the size bins of >1 km, 500- 1000 m, 300-500 m, 100-300 m, 25-100 m, and <25 m.

Inserting Dates of First Observation

Next, data with the following parameters were downloaded from the JPL Small Body Database Engine into a separate workbook: full name, primary designation, first observation date, last observation date, magnitude (H), and MOID (AU) (NASA JPL, 2011). The full name and primary designation were both included to make sure the two databases matched accurately. First observation date is the date when the PHA is first discovered. Last observation date was not used for this analysis; however, it was downloaded along with several related data elements for potential future work on the relationship between observation arc length and uncertainties. The MOID data was the distance from a MOID around the Earth; all objects whose MOID was less than 0.05

AU were downloaded. Manually combining the Small Body Database data with the NEO-P data to produce a single database took several weeks due to the differences in the way the data is arranged. The resulting single database contained the name of the object, its primary designation, its magnitude, the date of first observation for each object and the date for each approach within 0.05 AU.

Detection-to-Approach Times for Known Objects

Using the combined database, the dates of first known observation and closest known approach dates were converted to a format suitable in Excel for subtraction. The next step was the subtraction of dates of first observation from the approach dates, and conversion of this to a time value. This difference, whether negative or positive, represents the warning time for each close approach. These objects are called known objects, and their corresponding approaches are called known approaches, because they have been discovered.

Table 3. Subset of the 7,300 Close Approaches with Warning Times.

Name	Discovery	Close Approaches	Warning Time (yrs)	Magnitude (H)	Diameter Estimate, albedo .14 (km)
2003 RB	02/13/2002	08/25/2070	68.58	17.9	.93
2002 CU11	02/07/2002	08/30/1925	-76.49	18	.89
2002 CU11	02/07/2002	08/30/1983	-18.45	18	.89
2002 CU11	02/07/2002	08/30/2014	12.57	18	.89

Note: Table 3 portrays four approach events, but only two NEAs. NEA 2003 RB was discovered in February of 2002 and has a calculated close approach 68.58 years later in 2070. NEA 2002 CU11 has three close approaches shown in the table. The event in 1983 had a negative warning time, meaning the object was only observed 18.45 years after that close approach event. In 2014, however, 2002 CU11 has a close approach event with 12.57 years of warning time, within which a decision for further observation or greater action could be made.

Subtraction of the dates of discovery for the 7300 close approaches from their dates for close approach within the .05 AU MOID was then accomplished. The following is an example of four approach events from that combined spreadsheet of 7,300 events; the electronic version of the full spreadsheet is available on request:

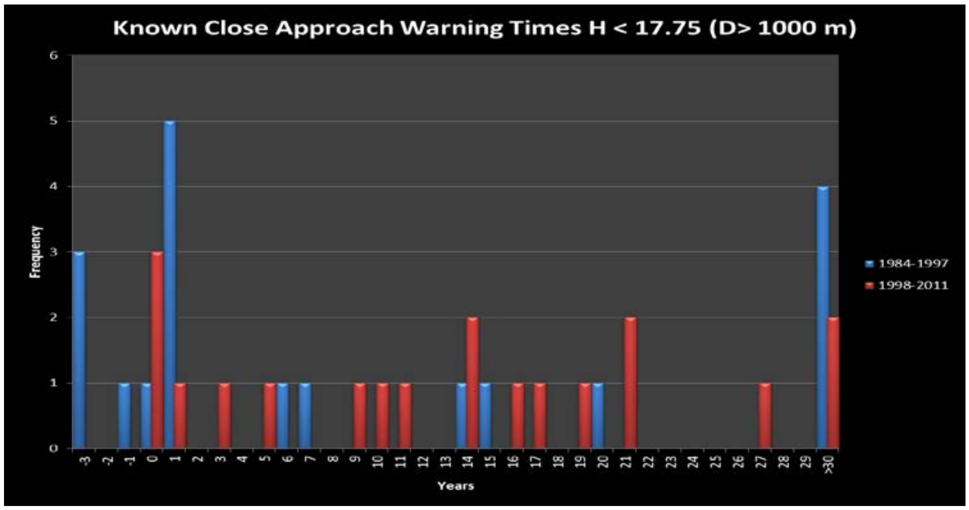

Figure 9. Known Object 0.05 AU Warning Times (D>1000m).

We can see from this figure that for objects with H values less than 17.75, corresponding roughly to diameters greater than 1 km, the warning times for known approaches between 1984-1997 were most often less than 1 year, with several objects detected only years after they passed by. In the second period, all approaches were known about prior to penetration in this size range.

There is a slight shift to the right in these warning times, which is to be expected due to better technology. NEA detection is not static; the technology has increased dramatically, and the focus on the problem set has as well. Because technology has increased and resources have been allocated towards the NEO problem set, the warning times appear to have increased between the two periods. In effect, the above graph measures some of the effect of improved technology on warning times. However, this chart (and the next three), do not contain estimates for missed approaches or high uncertainty trajectory objects. That will follow in Chapter III, Results, which compiles the above data with missed approaches, trajectory uncertainties, and the projection of future discovery rates.

Objects in the other size ranges all show the same trend towards greater warning time, due to the increased efforts and technology of Spaceguard. The following figure displays the change in 0.05 AU warning times for the diameter range 500-1000 m:

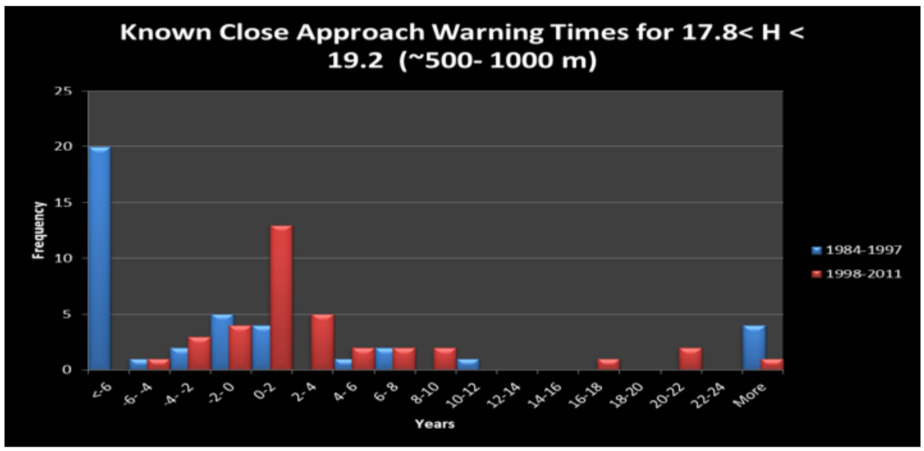

Figure 10. Known Object 0.05 AU Warning Times (500 < D< 1000m).

As expected, warning times for known objects in this size range increased from one period to the next. The bulk of the objects in the first period (1984-1997, in blue) had negative warning times, prior to the congressional mandate. Average warning times for these mid-sized objects increased in the next period, in blue, with 13 objects approaching within the 0.05 AU MOID between 0 and 2 years after initial detection.

While the graph below gives the appearance of dramatic improvement, without incorporating missed approaches and uncertainties, it is just a building block.

The size bin between 100 and 300 m has a more apparent increase in both number of objects discovered and in warning times for these objects. Prior to the Spaceguard period, objects in this size range were not often detected. From 1998-2011, detection rates in this size bin increased dramatically. Warning times shifted to the right, but still measured only in days. In other words, most of these objects were discovered either a few days before or after their close approach since 1998. This shows the effect that Spaceguard had.

The chart for ~300-500 m objects follows. Again, there is the expected increase in warning times for known objects.

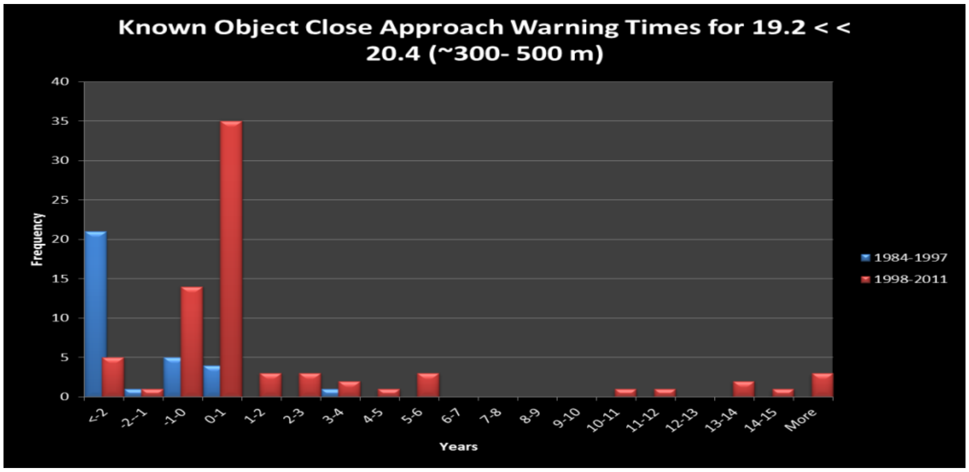

Figure 11. Known Object 0.05 AU Warning Times (~300 < D< 500m).

This figure shows that from 1984-1997, over 20 approaches had negative warning times. In other words, the objects were detected over two years after their approaches. In 1998-2011, however, with increased technology, there dramatic improvement; most known approaches happened between 0 and 1 year after object discovery. Also visible is a dramatic increase in discovery rates.

Here is the histogram for 100-300 m close approaches:

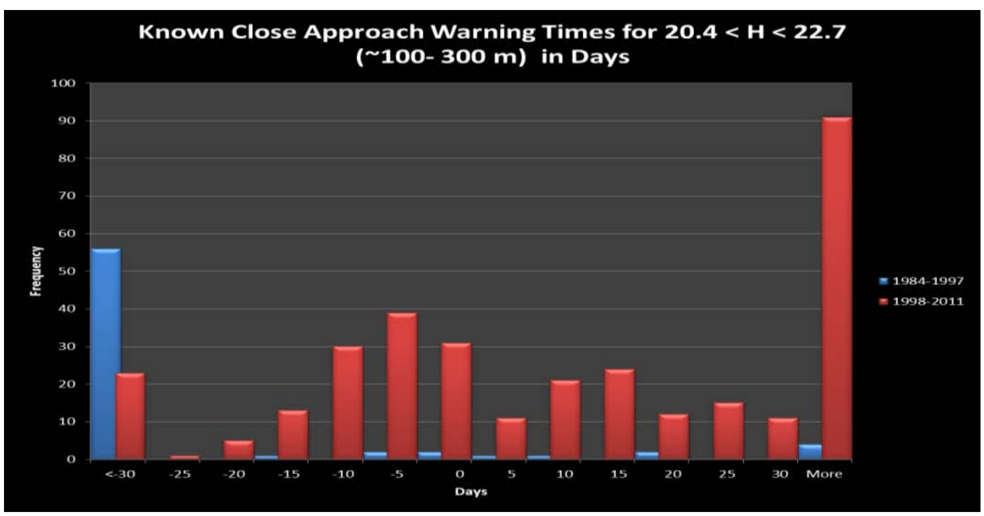

Figure 12. Known Object 0.05 AU Warning Times (~100 < D< 300 m).

Most observed objects in this size range were discovered either a few days before or *after their 0.05 AU penetration. Later we will see that many objects in this size range are also missed completely.*

Finally, here is the chart for objects from 25-100 m in diameter:

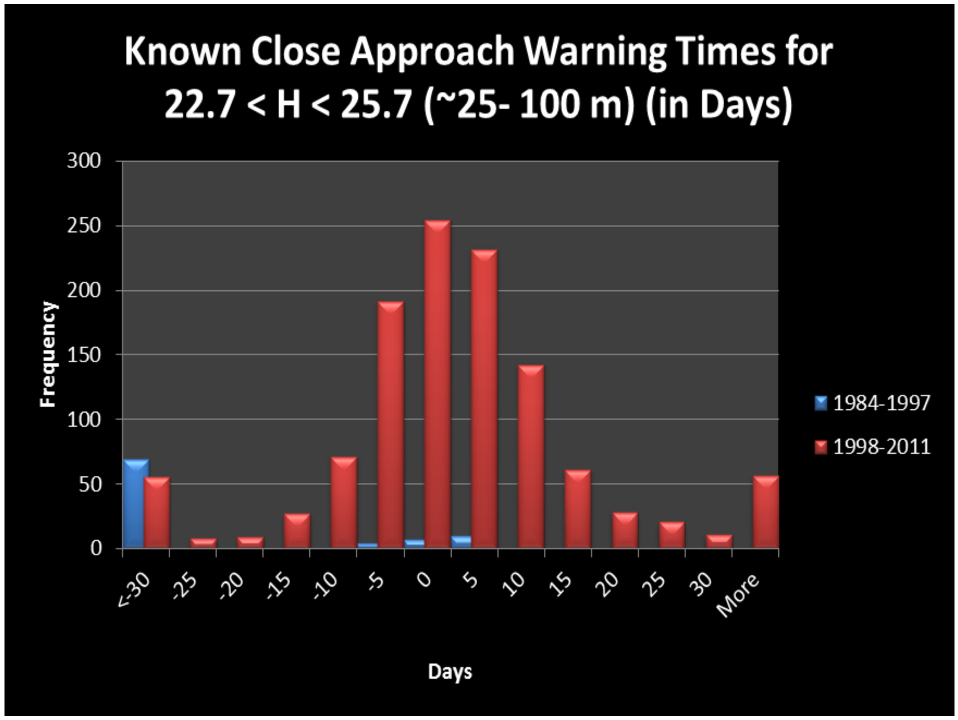

Figure 13. Known Object 0.05 AU Warning Times (~25 < D< 100 m).

Object discoveries and approach warning times increased dramatically for very small objects. From 1997-2011 (red), most approaches happened between 5 days before and 10 days after discover. Missed approaches, graphed later, will significantly change the distribution of warning times shown above.

The above charts who how far in advance NASA was able to predict close approaches for discovered objects in the 14 years after 1998 as compared to the 14 years prior to 1998. However, these graphs do not account for the PHAs that passed within 0.05 AU without being detected; these objects are referred to as "Missed objects" in this paper. Nor do these graphs account for objects whose orbital uncertainties are very high. In later sections, this is attempted. First, detection rates, the next step for making projections of future warning times for 0.05 AU penetrations, are examined.

Detection Rates for New Objects

Counting detection rates over the last Spaceguard period and extrapolating these out over several more such periods will give us an estimate for future discoveries, based on current technology. Because there are upper limits to the number of objects in each size range, it is possible to estimate when most of the objects will be detected. As more objects are detected, the likelihood of finding an undetected object goes down. Since the majority of large objects have been found, detection rates have declined. Detection rates for very small objects, however, have experienced marked increases, because the number of these objects is so vast that it will be decades to centuries before they are all detected.

The following is a spreadsheet showing the detection rates counted from the same NEO-P dataset downloaded at the end of 2011 (NASA NEO- Program, 2011). Size bins again match those used by NEOWISE for consistency. An important distinction here is that this table displays detection rates for PHAs, as opposed to close approaches. One PHA can have several close approaches over the period 1900-2200.

Table 4. Number of PHAs Detected from 1998-2011 by Year.

	>1km	500m-1km	301m-500m	100m-300m	25m-100m	<25m	<100m
1998	4	13	9	21	8	4	12
1999	4	5	9	14	14	2	16
2000	7	15	16	28	27	2	29
2001	3	20	16	30	41	7	48
2002	9	24	22	39	51	12	63
2003	2	11	16	30	48	22	70
2004	5	14	12	40	99	33	132
2005	6	11	19	43	100	51	151

2006	0	7	15	23	101	60	161
2007	1	8	15	37	119	61	180
Table 4. Cont.							
	>1km	500m-1km	301m-500m	100m-300m	25m-100m	<25m	<100m
2008	2	6	18	46	138	84	222
2009	0	5	9	44	140	117	257
2010	1	3	11	39	135	140	275
2011	0	5	11	36	117	116	233
Total	44	147	198	470	1138	711	1849

Note: This table shows the number of PHAs detected each year for the combined Spaceguard effort from 1998-2011. An upward trend for discovery of very small objects is visible. This is likely due to technology increases. Also visible is a downward trend for large object discovery, as the population nears completion. Source data from NASAs Close Approach database. (NASA NEO-Program, 2011)

Table 5. Estimated PHAs Still Undetected.

Determining # PHAs left to detect:	>1km	500m-1km	301m-500m	100m-300m	25m-100m
1. Estimated Total NEAs	981*	1500*	2400*	15,700 *	50,000- 1 M**
2. NEAs Detected to date	912*	1200*	1100*	2000*	3000*
3. % NEAs detected as of Dec 2011	93%	80%	46%	13%	.3%- 6%
4. PHAs counted in database***	116	204	219	485	1166
5. Total PHAs expected	125	255	478	3,807	19,433-389,000
6. PHAs left to detect++	9	51	259	3,322	18,267-387,800

* from NEOWISE graphic
** from NASA NEO Science Definition Team graphic; significant uncertainty in this size range
*** From the NEO-P dataset downloaded at the end of 2011.
\+ Divide row 4 by row 3.
++ For completion (subtract row 4 from row 5)

Note: This table lists the estimated total NEAs from the NEOWISE graphic and from the NASA NEO Science Definition Team graphic. Below this, it lists the number of NEOs detected so far, and the percent completion of the population. Following this is the number of PHAs counted in the database downloaded at the end of 2011. These numbers change as more NEOs and PHAs are discovered, so a cut-off point for the study was the end of 2011. Based on the total NEOs and percentage of NEOs discovered, we estimate the number of PHAs that will be in the database when it eventually reaches completion, for each size bin. The final row is an estimate for the number of PHAs left to detect for each size bin. The largest uncertainties will be found in the very small PHAs.

For the large bodies (over 500 m), detection of the last objects appears to have leveled out.

Discovery of objects over 1000 m is declining steadily as the population of objects left undiscovered decreases. Any number of projections could be used to estimate how many future discoveries may take place. A best fit curve yielded 1.88 discoveries per year for objects over 1000 m and 3.66 per year for objects between 500 and 1000 m, but almost any curve could be chosen. A range between 0 and 3 discoveries per year for objects over 1000 m, and for objects from 500-1000 m, between 2 and 5 objects per year, appears to be fairly normal in recent years.

Very small bodies (< 100m) are much more difficult to find and track. They also have much larger populations and increasing detection rates. For these bodies, we used a simple average of the detection rates from 2004, one of the early years of the Catalina Sky Survey, to 2011. According to Dr. Timothy Spahr, head of the Minor Planet Center, detection of smaller objects has increased dramatically due to the Catalina Sky Survey (T. Spahr, personal communication, Feb 2, 2012). Without reliable statistics on newer technologies, we use Catalina Sky Survey detection rates as our base. When better technologies come on line, this study could be updated to reflect faster detection rates. For PHAs 100-500m, we also used a simple average for the 2004-2011 period. Our resulting projected detection totals are shown in table 6.

Table 6 does not take into account the high uncertainty in the orbits of small object, which are a complicating factor and are addressed in the next section. It appears that within two more 14-year periods, all objects greater than 300 m will have been discovered and tracked; moreover, it appears that objects in the 100-300 m range might all be detected sometime in the 22nd century. However, it may take longer than this because of the high uncertainty in many of the trajectories for objects under 300 m. For objects under 100 m, even without including trajectory uncertainties, it will be 164 years before a full catalog is possible, unless significant technological improvements take place. And once trajectory uncertainties are incorporated, the time it takes for completion will grow considerably for smaller objects.

Table 6. Estimated Objects Detected by the End of Future Period, Excluding Loss Rates.

	>1km	500m-1km	301-500m	100-300m	25-100m
PHAs left to detect	9	51	258.8	3322.2	19,433-389,000
Average new objects per year (2004-2011)	~1-3	~2-5	~14	~39	~120
Yrs from now until all objects detected *with 0 loss rates**	3-9 yrs	10-26 yrs	~19 yrs.	~86 yrs*	~164-over 3,000*
Detected 2012- 2025	9**	47**	192.5	539	1661
* Higher uncertainty rates for the small bodies would cause many of the very small bodies to be lost, increasing the time for completion. ** Calculated using best fit curve; all others are calculated using averages					

Note: The first row of this table (from the preceding table), and is an estimate of the number of PHAs left to detect in each size range. The second row is an estimate for the average number of detections per year into the future, given no significant technological changes. The third row estimates how many years it will take for completion, excluding loss rates. The fourth row contains the estimated number of objects detected in the next Spaceguard period.

Level 2 PHAs: High Orbital Uncertainties

We next estimated the number of Level 2 PHAs in our database- those PHAs whose orbital trajectories have such high uncertainties that they cannot be reliably projected far enough into the future to provide substantive warning times. The more Level 2 PHAs there are, the longer it will take for completion of the population.

Dr. Amy Mainzer, who runs NASA's NEOWISE program at JPL, pointed out that although many NEAs are "discovered", the astrometric uncertainties are often so large that an astronomer might have difficulty finding the object. (A. Mainzer, personal communication, October 6, 2011). For small objects, there are several barriers that prevent high certainty trajectory predictions. One of these is the great difficulty finding and observing for extended arc lengths over more than one opposition, bodies that are faint. Small objects, "typically have much weaker orbits that only allow prediction intervals of a few decades or less" (S. Chesley, personal communication, January 29, 2012).

Moreover, according to Dr. Paul Chodas, the source of these uncertainties is in the radial distance of the object from the Earth for NEAs with short observations arcs (only observed for a short period of time). A radial distance of a few thousand km will "map into an uncertainty in the heliocentric semi-major axis, which over time maps into a large uncertainty along the orbit path of the object. When this uncertainty becomes too large, we can't be certain that a predicted close approach will occur at all, since the object could be anywhere within a large region" (P. Chodas, personal communication, January 30, 2012). As an example of such uncertainty, McMillan notes that " PHA 2003 BK47 was discovered by Spacewatch at V = 21.8 and pounded (sic) with 50 observations spanning more than a month, yet the uncertainty of its ephemeris at its next favorable apparition in 2011 will be 2-3 degrees" (McMillan, 2009, p. p. 3). If the uncertainty is too high, over time, the object can be effectively lost.

Additionally, non-gravitational forces affect small bodies over centuries in ways which are not all very well modeled. According to Lindley Johnson and the NASA JPL website, JPL considers the eight major planets, Earth and Moon separately, Ceres, Vesta, and Pallas when calculating orbits of NEAs, just as the Minor Planet Center website does (NASA JPL, 2011). All major gravitational perturbations, therefore, are accounted for, and except for very small objects, the orbits of PHAs are predictable if enough observations are made.

For very small objects, however, could non-gravitational forces have enough effect on PHAs to require their re-detection years later? Could such non-gravitational forces delay completion of the population by modifying the orbits of small objects such that they are eventually lost? According to Dr. Steven Chesley, NASA JPL, the Yarkovsky affect increases as the inverse of the asteroid diameter and causes orbital trajectory deviations on the order of 10-20 km in 500m objects over the course of a decade. (S. Chesley, personal communication, Nov 14, 2011). Allouis et al. (2007) state that, “The Yarkowski (sic) Effect alone can shift the position of Apophis by over 100 km between 2017 and 2029, which means it cannot be ignored in the orbit propagation models (EADS Astrium, 2007, p. iv). Apophis has a diameter of approximately 270 m. Over the course of 5,000 years, an object in the Apophis size range could, therefore, have its trajectory modified by over 50,000 km, or four Earth diameters. For objects under 100 m range, such 50,000 km orbital deviations could take place in a few hundred years, prior to completion of the survey of these very small objects.

Over the course of the time it would take to discover all objects under 100 m in diameter, therefore, non-gravitational effects might necessitate their rediscovery, if the Spaceguard program does not have consistent funding and continued application over the course of several decades to centuries.

To approximate the percentage of high uncertainty objects (Level 2 PHAs), a compilation of the number of close approaches in each Spaceguard period over the course of 300 years (from 1900-2200) was completed.

Table 7. 0.05 AU Approaches Detected and Back-/Forward- Calculated, 1900-2200.

	>1km	500m-1km	301m-500m	100m-300m	25m-100m	<25m
1914- 1927	17	35	34	59	57	21
1928- 1941	12	40	39	77	68	30
1942- 1955	17	35	46	72	92	45
1956- 1969	22	29	39	66	87	57
1970- 1983	10	34	32	76	71	64
1984- 1997	19	41	33	69	92	60
1998- 2011	19	37	75	328	1166	804
2012- 2025	15	32	49	96	68	48
2026- 2039	9	37	42	68	90	46
2040- 2053	12	41	41	79	90	70
2054- 2067	17	33	36	78	90	59
2068- 2081	21	36	36	78	79	38
2082- 2095	18	27	43	58	77	29
2096- 2109	14	42	44	81	53	20
2110- 2123	19	29	35	63	42	17
2124- 2137	19	40	39	62	39	19
2138- 2151	12	32	40	59	39	13
2152- 2165	6	34	38	53	34	7
2166- 2179	11	36	43	43	33	7
2180- 2193	14	23	28	42	23	6
2194- 2200 (only 6 yrs.)	12	17	18	18	18	4
Total (20.428spacegaurd periods)	315	710	830	1625	2408	1464
Average per period	15.42	34.76	40.63	79.55	117.88	71.67
Standard Deviation	4.33	5.04	9.54	59.75	247	173

Note: Note that for bodies larger than 500 m, the approaches in all periods are close to the mean.

However, for bodies smaller than 500 m, there are a significantly greater number of approaches in the 1998-2011 period than in the periods after and before it. This means that many of the small objects discovered between 1998 and 2011 had uncertainties too high to forward and backward project their close approaches for more than a few years. If the uncertainties were lower, one would see a fairly constant rate of close approaches, as is the case for the larger bodies.

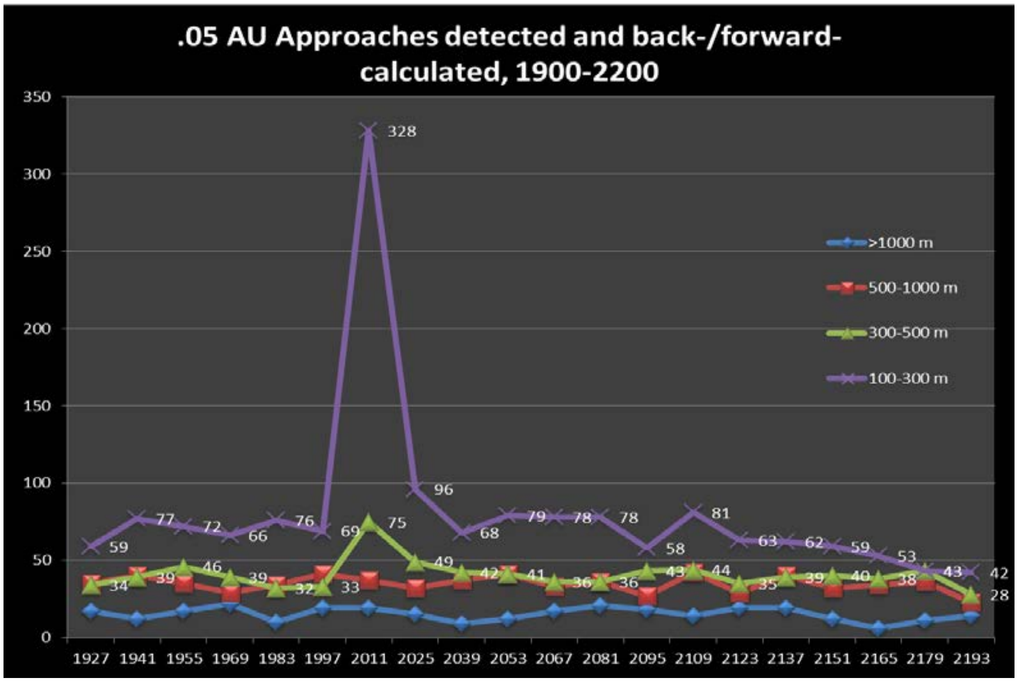

Figure 14. 00.05 AU Close Approach Trends 1900-2200.

Note that for large bodies (blue), the number of approaches is fairly. Bodies under 500 m, seemingly have a higher number of close approaches in the 1998-2011 period. This peak gives us an estimate for the percent of approaching bodies with high trajectory uncertainty. If all objects were detected had well-known orbits, the peaks would be the norm.

Level 1 PHAs discovered from 1998-2011 should have highly refined orbital trajectories, which have been projected forward to 2200 and back to 1900. If all PHAs have Level 1 trajectories (high certainty), the number of approaches should be consistent throughout 1900-2200. This is the case for large bodies, which have high trajectory certainties, because JPL can project all approaches back to 1900 and forward to 2200. However, small bodies, with high uncertainties, show a significant increase in close approaches between 1998-2012, with a sharp decline in the following periods.

This is because, due to uncertainty, the approaches for these small objects could only be projected a few years out. By measuring the percentage decline from the peak, we can get an idea for the percentage of objects with trajectory uncertainties too high to map out to future periods. This provides us the percent of Level 2 PHAs in the observed population.

Approaches in the >1000 m bin and 500-1000 m bin have no significant peak. All values for those size bins are within 2.1 standard deviations from the mean. However the peaks for the 300-500 m and 100-300 m bins are larger than three standard deviations from the mean. The peak for the 25-100 m size bin, not depicted above, is 1166, similarly over 3 standard deviations from the mean.

The next table displays the method used for and results of calculating the percent of objects with Level 2 trajectories- that is, trajectories which cannot be projected out more than another Spaceguard period, or 14 years. Level 1 trajectories can are well defined between 1900-2200 and beyond. The first rows of table 8 originate from the preceding table (as displayed in figure 17):

Table 8. Estimated Percentage of Level 2 PHAs (high uncertainty) for 0.05 AU Penetrations.

Estimated Diameter Range	301- 500m	100- 300m	25- 100m	<25m
H Value	20.3-19.3	22.7-20.4	25.7-22.8	>25.7
1. Average approaches per 14 yr period	40.6	79.5	117.9	71.7
2. Average w/o peak	38.9	66.8	63.9	34.0
3. Peak	75	328	1166	804
4. Level 2 PHAs in Spaceguard period.	36.1	261.2	1102	770
5. Estimated Percent Level 2 PHAs in period	48.2%	79.7%	94.5%	95.8%

Note: This table estimates the number of PHAs in a period that are not observed long enough to have Level 1 (highly certain) trajectories. The first row gives the estimated H value for that size range. Item “1”, is the average of all of the approaches in the preceding table. “2” is the average when the peak from the 1998-2011 time period is deleted. Item 3 is the peak value.

Item 4 subtracts the average “2” from the peak value “3”. Item 5 comes from dividing item 4 from item 3; this is the percent PHAs with high uncertainties. In our model, these are essentially “lost” for warning time purposes because they do not have reliable orbital projections.

Another method by which average uncertainty rates could be calculated might be to perform a count within the Minor Planet Center or JPL Small Body Database Browser of how many objects in various size bins have been observed at more than 1 opposition or for some minimum arc length for high certainty. Using another method might provide another means to calculate the loss rates for veracity. In any case, the rates in the last row for Level 2 PHAs will be incorporated into our model later on, after another part that cannot be left out is addressed- missed approaches.

Estimating Missed Approaches

Our next step was to model a simple estimate of missed approaches to add to our overall model. Missed objects, and their corresponding missed approaches, are important because they are objects that have flown into and out of the 0.05 AU MOID without detection. The objects might have been simply missed due to lack of coverage or technology to see all very small objects, or they might be undetectable because the objects might, for example, “spend all their time interior to the Earth’s orbit and are therefore detectable only at solar elongations of less than 90°” (Grav, 2011, p. 425). In our model, missed approaches are added in, with warning times of 0.

An iterative process captured in the next 5 tables and described below was used to calculate the number of missed approaches out to the Spaceguard period ending in 2067. The number of known approaches was subtracted from the total estimated approaches over the 300 year period (1900-2200) for each size bin and then dividing this by the number of periods to determine the average # of missed approaches per period. This simplistic approach may provide some estimates. Monte Carlo Simulation could be used for an in depth project to estimate missed approaches.

Equation 2

$$A_m = A_T - A_K$$

Where A_m is the estimated number of missed approaches from 1900-2200, A_T is the estimated total number of approaches from 1900-2200, and A_K is the number of known approaches from 1900-2200. Known approaches do not constitute all approaches. Objects which have not yet been detected may penetrate the .05 AU MOID. These "missed approaches" are the total approaches minus the known approaches. The error in this estimate will be comparable to the error in the total estimated approaches.

Next this is divided by the number of 14 year periods within our data period of 1900-2200, which is 20.4, to determine the average # of missed approaches per period.

Equation 3

$$\overline{\mathrm{A_m}}_{SG} = \frac{\mathrm{A_m}}{20.43}$$

Where $\overline{\mathrm{A_m}}_{SG}$ is the average number of missed approaches per Spaceguard period and 20.43 is the number of Spaceguard periods within the 1900-2200 time period.

In order to find this, A_T must first be estimated. A_K, the number of known approaches from 1900-2200, comes from our database pull from the NEO-P website (NASA NEO-Program, 2011). To calculate A_T (the total estimated approaches), the number of known approaches was divided by the percentage objects that have been detected to date. The assumption is that the total number of approaches is proportional to the total objects:

Equation 4

$$A_T = \frac{A_K}{P_d}$$

Where P_d is the percentage of objects detected. Equation 4 is based on the following logic: If we know the percentage of 500-1000 m diameter objects that have been discovered (P_d =80%), and the number of approaches corresponding to these known objects ($A_K = 710$), the remaining 20% of undiscovered objects add a proportional number of approaches. Therefore by dividing the known approaches by the percent of objects discovered, an estimate for the total approaches is made at $A_T = 710/.8= 888$ approaches. The missed approaches A_m are then the total (888) minus the known (710), or 178 missed penetrations of the MOID. This method has error proportional to the error in the percentage of undiscovered objects. More confidence in the results could come if some form of Monte Carlo simulations could yield better estimates for the total numbers of PHA approaches.

Compiling the Data

These simple equations and additional ones discussed after the next table, which contains an iterative process beginning with the compilation from the previous population tables for the following spreadsheet. The goal of this process is to project future detection rates, missed approaches, and level 2 PHAs (high uncertainty). Table 10 contains the initial steps of this process.

Using equation 2, the number of missed approaches is the total number of approaches minus the number of known approaches, or 710 for 500-1000 m PHAs. This gives us the missed approaches for 1900-2200, or 178. These are divided by 20.4, the number of Spaceguard periods in 300 years, to get an expected number of missed approaches of 8.69 per period. So in each 14 year period a 500-1000 m object may penetrate the 0.05 AU MOID 9 times without our knowing about it. These missed penetrations, receive a warning time value of less than or equal to 0.

Table 9. Estimated Missed 0.05 AU MOID Approaches 1998-2011.

1998-2011	>1km	500m-1km	301-500m	100-300m	25-100m
Given					
a. Total estimated PHAs	125	255	478	3807	19,433-389,000
b. Total PHAs by 2011 (table 5)	116	204	219	485	1,166
c. PHA detections (table 4)	44	147	198	470	1138
d. % objects detected by 2011 (table 5)	93%	80%	46%	13%	.3%- 6%
e. Known Approaches 1900-2200 (table 7)	315	710	830	1625	2,408
f. % Level 2 PHAs- highly uncertain trajectories (table 8)	0	0	48.2%	79.7%	94.5%
Calculate:					
1. Total approaches 1900-2200 (equation 5)	339	888	1,811	12,756	~40,000->750,000
2. Missed approaches 1900-2200 (equation 2)	~24	~178	~981	~11,131	~38,000->748,000
3. Missed approaches per period (equation 3)	~1	~9	~48	~545	~2,000-37,000
4. Expected # Level 2 PHAs this period (= row c* row f)	0	0	~95	~374	~1,076

Note: This table contains 5 rows of data from previous parts of our discussion. These data are first used to calculate the total estimated approaches by dividing the known approaches (e) by the % of objects detected (c). Missed approaches are derived by subtracting the known approaches (e) from the total (1). The expected missed approaches per period is equal to the total missed approaches (1900-2200) divided the # of Spaceguard periods, or 20.4. Finally, the expected number of PHAs with high uncertainty (Level 2), is calculated by multiplying the percent of level 2 PHAs by the discovered PHAs in the period.

The next table reflects the first to attempt to project the number of PHA detections, approaches, missed approaches, level 1 PHAs (high certainty trajectories), level 2 PHAs (highly uncertain trajectories) into the next Spaceguard period, which ends in 2025. Coincidentally, this is also the year that President Obama has declared as the year by which we should send a human to an asteroid.

Tables 10 through 13 result in several values that are used in the graphs in the following section. This includes the missed approaches, new known approaches, and level 2 PHAs. The following is a breakdown of how each of these elements was calculated.

Table 10. Projected Missed Approaches, New Approaches, and Level 2 PHAs 2012-2025.

2012-2025 Projection	>1km	500m-1km	301-500m	100-300m	25-100m
Given:					
a. Total estimated PHAs (table 5)	125	255	478	3807	19,433-389,000
b. Total estimated Approaches 1900-2200 (table 9 #1)	339	888	1,811	12,756	~40,000->750,000
c. Projected PHA detections 2012-2025 (table 6)	8	47	193	539	1,661
d. Expected # Level 2 PHAs, previous period (table 9)	0	0	95.41	374.34	1075.61
e. % Level 2 PHAs (table 8)	0	0	48.2%	79.7%	94.5%
f. PHAs detected by 2011 (table 9)	116	204	219	485	1,166
Calculate:					
1. Level 1 PHAs by 2025 = row f –row d + row c	124	251	316	650	1,751
1b. Approaches to Object ratio = row b / row a	2.72	3.48	3.79	3.35	2.07
1c. Approaches per period for new PHA detections = row c * row 1b /20.4	1	8	36	89	168
2. % PHAs detected to Level 1 by 2025 = row1 / row a	99.4%	98%	66%	17%	9%
3. Missed approaches 1900-2200 =(100%- row 2)* row b	2	14	613	10,580	36,000-748,000
4. Missed approaches this period = row3/20.4	.1	.68	30	518	1,788
5. Level 2 PHAs this period* = row c * row e	0	0	95.41	374.34	1,075.61
* For example, for 301-500 m bin, of 193 projected detections, 48% have highly uncertain trajectories = 95.41 lost objects for that period. See section referencing loss rates for an explanation of that rate.					

Note: By 2025, almost all PHAs over 500 m will be found. 66% of PHAs over 300 m will be found, but for smaller objects, from 100-300 m and 25-100 m, only a small percentage will have been found. The discussion following describes each calculation in the table.

1. Total Level 1 PHAs by 2025. This is the total number of PHAs with high certainties to their trajectories that we expect will be discovered by 2025. This is equal to the PHAs detected by the end of the previous period (2011) plus the new PHAs detected in the current period (2012-2025) minus the level 2 PHAs from the previous period (whose orbital uncertainty only allows up to 1 period of projection forward) or:

Equation 5

$$PHA_{L1f} = PHA_{L1i} + PHA_d - PHA_{L2f}$$

Where PHA_{L1f} is the number of level 1 PHAs known by the end of the period, PHA_{L1i} is the number of level 1 PHAs known at the beginning of the period, PHA_d is the number of PHAs detected in the period, and PHA_{L2f} is the number of level 2 PHAs known by the beginning of the period.

1b. Approaches to Object Ratio. Every object penetrates the .05 AU MOID several times over the course of 300 years. The ratio of the number of penetrations to the number of objects from 1900-2200 is our approach to object ratio:

Equation 6

$$R_{A/_{PHA}} = \frac{A_T}{PHA_T}$$

Where $R_{A/_{PHA}}$ is the ratio of approaches to PHAs, and PHA_T is the total estimated number of known PHAs.

1c. Approaches per period for newly discovered PHAs. For each new object discovered, there are several new known .05 AU penetrations spread out over 1900-2200. Averaging this out to find the number of newly added approaches to the model follows:

Equation 7

$$A_{SGn} = PHA_d \times R_{A/_{PHA}} \div 20.43$$

Where A_{SGn} is the number of approaches per Spaceguard period for newly detected PHAs.

2. Percentage Level 1 PHAs detected by period end. This is the percentage of PHAs detected by the end of the period with enough orbital certainty to project their trajectories for the whole period 1900-2200. It is given by dividing the total level 1 PHAs known by the end of the period by the estimated total number of PHAs:

Equation 8

$$\%PHA_{L1f} = \frac{PHA_{L1f}}{PHA_T}$$

3. Missed approaches 1900-2200. As previously mentioned, the number of missed approaches changes with each new period; every time a new PHA is discovered and its orbit projected, its approaches become known. Approaches missed from the database are determined by multiplying the percentage undetected PHAs by the total estimated approaches calculated in equation 5. So the number of missed approaches in each new period will change as more objects are discovered.

Equation 9

$$A_{m,f} = \left(1 - \%PHA_{L1f}\right) \times A_T$$

4. Missed approaches this period. This approximately equals the updated total missed approaches divided by the number of 14 year periods and is represented by the variable $\overline{\mathrm{A_m}}_{SG,f}$. The number of missed approaches in a particular period is unknown; only the average across all periods can be used.

Equation 10

$$\overline{\mathrm{A_m}}_{SG,f} = \frac{\mathrm{A_m}}{20.43}$$

5. Level 2 PHAs this period. This is the number of PHAs discovered whose orbital trajectories cannot be predicted out past 14 years. This is calculated by multiplying the projected PHA detections in this period by the estimated percentage of level 2 PHAs calculated earlier (in table 8). The percentage of level 2 (high uncertainty) PHAs should remain fairly constant until new observing technology and/or improved observing methods are introduced. Projections in this paper are based only on current observing technology and techniques. The equation for Level 2 PHAs is:

Equation 11

$$PHA_{L2f} = PHA_d \times \%PHA_{L2f}$$

Where $\mathrm{PHA_{L2f}}$ is the number of number of level 2 PHAs known by the end of the period, $\mathrm{PHA_d}$ is the number of PHAs detected in the period, and $\%\mathrm{PHA_{L2f}}$ is the estimated percentage of PHAs detected in the period with low certainty orbits.

The following three tables show the results of iterating these equations over the next three Spaceguard periods..

Table 11. Projected Missed Approaches, New Approaches, and Level 2 PHAs 2026-2039.

2026-2039 Projection	>1km	500m-1km	301-500m	100-300m	25-100m
Given:					
a. Total estimated PHAs	125	255	478	3807	19,433-389,000
b. Total estimated Approaches 1900-2200 (table 9 #1)	339	888	1,811	12,756	40,000-750,000
c. Projected PHA detections this period (table 5)	0	4	193	539	1,661
d. Expected # Level 2 PHAs, previous period (table 10)	0	0	95.41	374.34	1,075.61
e. % Level 2 PHAs (table 8)	0	0	48.2%	79.7%	94.5%
f. PHAs detected by 2025 (table 10)	116	204	219	485	1,166
Calculate:					
1. Level 1 PHAs by 2039 = row f – row d + row c	124	255	416	759	1842
1b. Approaches to Object ratio	2.72	3.48	3.79	3.35	2.07
1c. Approaches per period for new PHA detections = row c * row1b/20.4	0	1	36	89	168
2. % PHAs detected to Level 1 by 2039 = row 1 /row a	99.4%	99%	87%	20%	9%
3. Missed approaches 1900-2200 = (100%- row 2) * row b	2	9	235	10,212	36,000-750000
4. Missed approaches this period (=row 3/20.4)	.1	.43	12	500	1,779
5. Level 2 PHAs this Period = row c * row e	0	0	93	429	1,570

Note: As seen from comparing item 1 to item a, by 2039, virtually all objects over 500 m have been found and objects from 300-500 m are nearing completion. But objects from 100- 300 m still have decades before completion. With this level of completion, large objects will still have on average two undetected penetrations of the MOID (item 3) in the three hundred year period, with approximately .1 missed approaches (item 4) in the period. Small objects will be missed frequently, with 500 missed penetrations (item 4) of 100-300 m objects through the MOID in the period. Within the same size range, about 429 PHAs (item 5) will have very high uncertainties to their trajectories, so they will not provide reliable orbital projections.

Table 12. Projected Missed Approaches, New Approaches, and Level 2 PHAs 2040-2053

2040-2053 Projection	>1km	500m-1km	301-500m	100-300m	25-100m
Given:					
a. Total estimated PHAs	125	255	478	3807	19,433-389,000
b. Total estimated Approaches 1900-2200 (table 9 #1)	339	888	1,811	12,756	40,000-750,000
c. Projected PHA detections this period (table 5)	0	0	62	539	1,661
d. Expected # Level 2 PHAs, previous period (table 10)	0	0	93	429	1,570
e. % Level 2 PHAs (table 8)	0	0	48.2%	79.7%	94.5%
f. PHAs detected by 2039 (table 11)	124	255	416	759	1842
Calculate:					
1. Level 1 PHAs by 2053 = row f – row d +row c	124	255	478	869	1933
1b. Approaches to Object ratio	2.72	3.48	3.79	3.35	2.07
1c. Approaches per period for new PHA detections = row c * row 1b/20.4	0	0	12	89	168
2. % PHAs detected to Level 1 by 2053 = row 1 / row a	99.4%	99%	99%	23%	10%
3. Missed approaches 1900-2200 = (100%- row 2)* row b	2	9	18	9,844	36,000-750,000
4. Missed approaches this period (= row 3/20.4)	.1	.43	.89	482	1,769
5. Level 2 PHAs this period = row c *row e	0	0	30	429	1,570

Note: Table 12 shows that by 2053, virtually all of the objects over 300 m have been found (item 2), but objects from 100- 300 m still have decades before completion. Objects 25- 100 m may have several hundred years until completion, because even after 55 year, only 10 % will be detected to level 1, with 1,769 approaches passing by undetected every 14 years.

Table 13. Projected Missed Approaches, New Approaches, and Level 2 PHAs 2054-2067.

2054-2067 Projection	>1km	500m-1km	301-500m	100-300m	25-100m
Given:					
a. Total estimated PHAs	125	255	478	3807	19,433-389,000
b. Total estimated Approaches 1900-2200 (table 9 #1)	339	888	1,811	12,756	40,000-750,000
c. Projected PHA detections this period (table 5)	0	0	30	539	1,661
d. Expected # Level 2 PHAs, previous period (table 12)	0	0	30	429	1,570
e. % Level 2 PHAs (table 8)	Unkn.	Unkn.	48.2%	79.7%	94.5%
f. PHAs detected by 2053 (table 12)	124	255	478	869	1933
Calculate:					
1. Level 1 PHAs by 2067 = row f – row d + row c	124	255	478	979	2024
1b. Approaches to Object ratio	2.72	3.48	3.79	3.35	2.07
1c. Approaches per period for new PHA detections = row c * row 1b/20.4	0	0	0	89	168
2. % PHAs detected to Level 1 by 2067 = row 1 / row a	99.4%	99%	99%	26%	10%
3. Missed approaches 1900-2200 = (100%- row2)* row b	2	9	18	9,477	35,900-749,000
4. Missed approaches this period (= row 3/20.4)	.1	.43	.89	463	1,760
5. Level 2 PHAs this period = row c * row e	0	0	14	429	1,570

Note: This table shows the final period projected. By 2067, virtually all of the objects over 300 m have been found by the end of this time period, but objects from 100- 300 m still have decades before completion. Objects 25- 100 m, because of uncertainty levels, have advanced less than 1% in completion, with 1,760 approaches passing by undetected every 14 years.

Future Close Approach Warning Times

The next step was to combine the data from the preceding table with the graphs in the section "detection-to-approach times for known objects" to develop a picture of when warning times into the 0.05 AU MOID will be long enough on average to provide time for a pre-cursor transponder mission if necessary. The amount of time needed to act on an object is debatable, but for the purposes of this study 25-60 years was used, falling loosely in line with previously cited NASA Administrator Mike Griffin's testimony. As with the known object close approaches the next part of the process begins again at the >1000 m size bin, this time adding in estimates for missed detections and lost objects as calculated in the last tables. In the histograms that follow, all values from the previous histograms showing known object warning times are present, except that all negative warning times are grouped as "≤0". Negative warning times (and 0 warning times) for a 0.05 MOID penetration represent a failure of our detection systems, no matter how small or large the negative value is. Missed approach warning times, in these graphs, are also grouped in the ≤0 bin, because if an object penetrates the 0.05 AU MOID without any detection, our detection systems have failed to provide warning. Projected detections are added in as a uniform distribution over the 14 year period of detection. Other possibilities would include using a normal distribution, or a random distribution. Evidence of the 7300 events shows a fairly uniform distribution of approaches, as previously shown in figure 17, when observational bias due to small object uncertainties is removed. Chapter III, Results, contains the charts that attempts to combine all of this information.

Potential Improvements to the Method

The methodology developed here is not meant to be a definitive answer with no error associated to it. Rather, the method is something that over time could be developed into a mechanism by which more accurate warning times could be derived. A few additions and improvements to the method would be desirable, either as a post graduate project, or as a development within the NEO community. The following paragraphs discuss such possible improvements.

Better refinement of the estimates of total PHAs would greatly improve the model. In this study, PHAs came from estimates for total NEAs and the percentage of NEAs so far discovered.

A more refined technique for estimating the total number of missed PHAs and missed approaches is another possible improvement. This could involve Monte Carlo simulations using a synthetic NEA population. Another method might compare past technology non-detections to current technology detections.

Another improvement would be improved statistical research on the distribution of warning times for future discoveries. Are warning times distributed over a uniform, normal, or Poisson distribution?

Improved methods for determine the percentage of objects that are lost or that have high uncertainty trajectory rates could improve the model. This could involve using the JPL database to determine the number of objects that have been viewed on more than one opposition.

A thorough study of the distribution of PHA and NEA orbits as related to discovery rates would be an improvement. Are current observation techniques missed a particular subset of NEAs, such as those with high inclinations, or those which have periods that might keep them hidden by the sun?

Another consideration is the usage of a disk rather than a MOID. NEAs with high inclinations may potentially have less chance of striking the Earth than those whose orbits are close to the ecliptic (M. Gaffey, personal communication, 18 April 2012).

Smaller size bins could be examined. It is becoming apparent that the next actionable EI will be in the less than 500 m size range, and most likely under 300 m. However, a refined study could potentially estimate this on a continuous graph rather than by large size bins. Is the most likely size 100 or 200 m?

Sensitivity checks could be carried out to see what the answer is should variations in the inputs be within some range. For example, the average albedo of PHAs used in this model is .14 based on the most current estimates. A sensitivity check could be carried out to determine the effects on the results if this average albedo were changed by one or two standard deviations in either direction.

The above suggestions could potentially make the method and model more robust.

CHAPTER III

RESULTS

General Description

Beginning with the largest size objects, the following histograms represent the predictions for future warning times for approaches within 0.05 AU of the earth that this nascent model provides. The data displayed is divided into three categories. One color depicts close approach warning times of known objects from the NEO-P database, as previously displayed in the warning charts earlier in this thesis. Another color depicts the estimated missed approaches previously discussed. Again, missed approaches are given a warning time value of 0. Another color depicts estimated close approaches of newly discovered objects.

PHAs > 1000 m

The following three histograms display warning times for penetrations of the 0.05 AU MOID counts for PHAs greater than 1000 m or $H<17.75$, during the years 1998-2011 and two subsequent periods. These graphs contain a fairly obvious set of conclusions, namely that Spaceguard has been a success for this size range. During the first period, most PHAs in this size range passed through the MOID with less than 21 years of warning, although a few approaches were anticipated by over 60 years. One approach, in red, is the estimated number of missed approaches during that time period. In other words, there was likely one undiscovered PHA over 1000 m that passed within the 0.05 AU MOID during that time period, as shown in table 10. In the later period, most penetrations of the MOID happen with between 6 and 48 years of warning, with a very small chance of a single missed approach. Between 2026 and 2039, all penetrations within the MOID will have been anticipated by over 24 years, with no missed approaches.

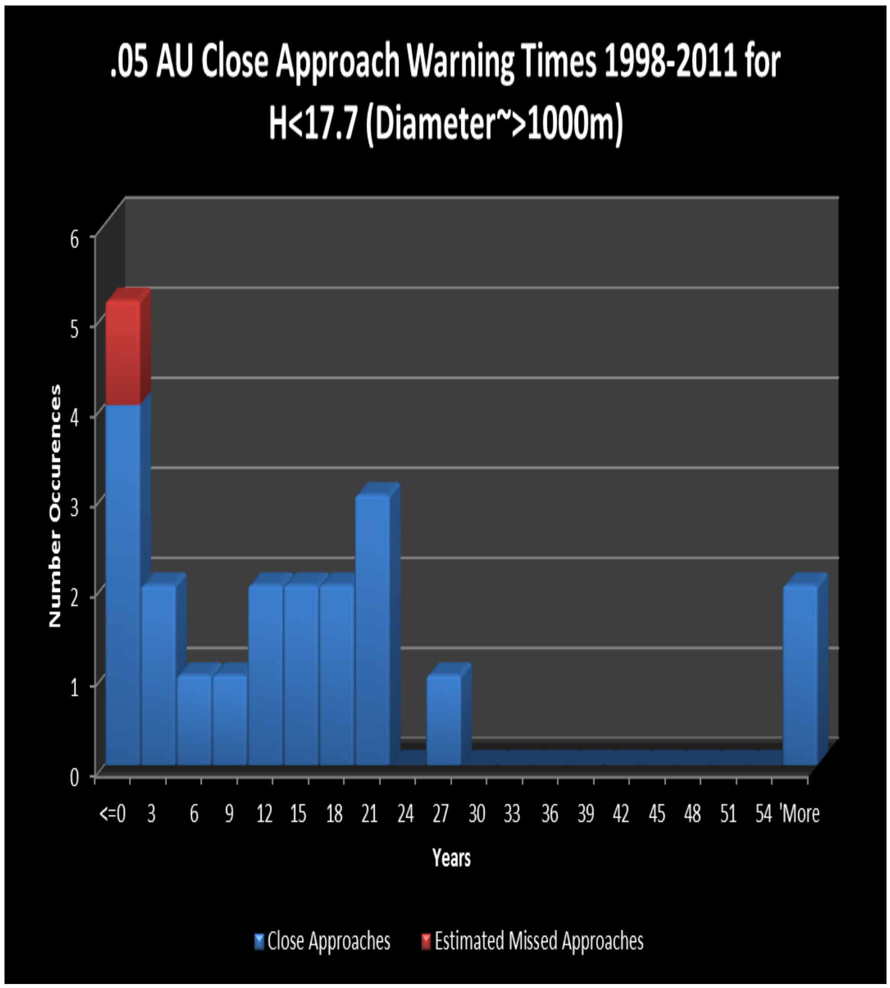

Figure 15. Close Approach Warning Times 1997-2011, D> 1 km.

This figure shows that for most penetrations of the 0.05 AU MOID, there between 0 and 21 years warning time. For example, 2 PHAs were detected 12 years before their close approaches. As estimated in table 10, there is 1 approach (shown in red) by an undetected large object within the 0.05 AU MOID during this time period.

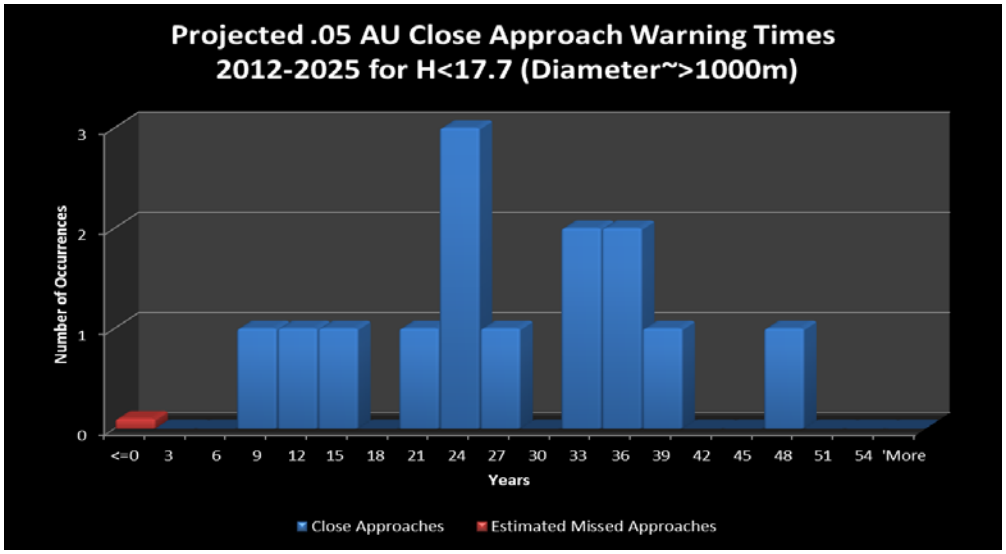

Figure 16. Close Approach Warning Times 2012-2025, D> 1 km.

In the next 14 years, every penetration of the MOID will have been anticipated by over 6 years, with 43% of approaches known for over 30 years. There is still a slight chance of a missed approach (0 warning time) in this time period.

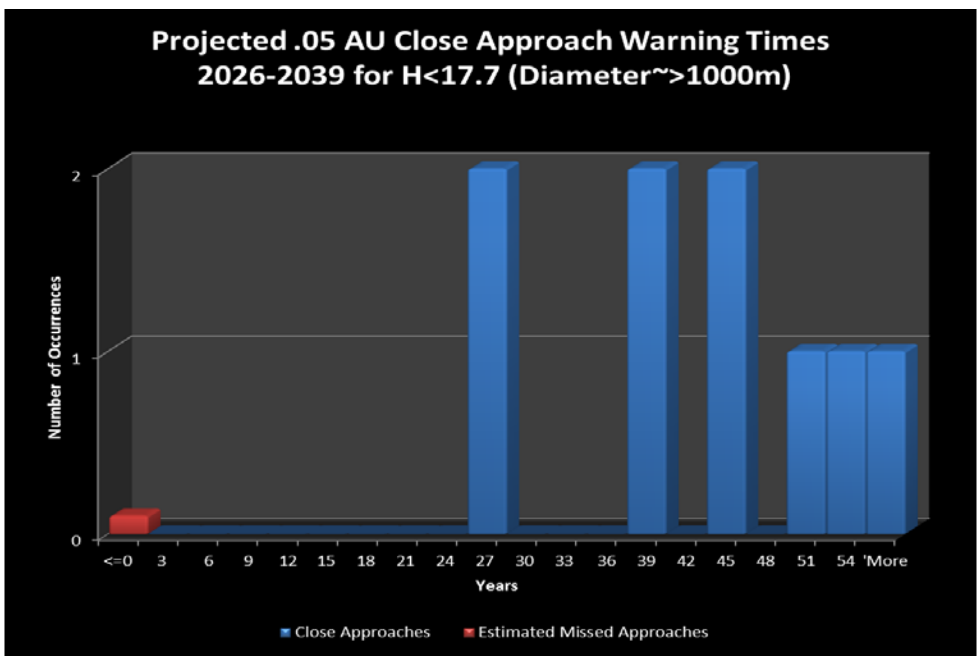

Figure 17. Close Approach Warning Times 2026-2039, D> 1 km.

In the period from 2026-2039, 78% of approaches by large objects will have over 30 years warning time, and 99% will have over 24 years. There is still a very slight chance of a missed approach as shown in table 12. These results were fairly obvious given the known success of Spaceguard with this size range.

The following graph sums up the anticipated progression of early warning for large object penetrations of the 0.05 AU MOID from 1984 through 2039. From the end of the Spaceguard's first 14 years, up through the present, these 0.05 penetration warning times move up significantly. The mean is 27.4 years for projected 2012-2025 approaches, incorporating the single missed approach. This climbs to a mean of 38.07 for 2026-2039 approaches, well beyond the previously mentioned 30 years in Mike Griffin's testimony, which, though somewhat arbitrary, is a reasonable estimate for carrying out the full target-cycle, which will include first additional ground observations, then a precursor mission to determine the necessity of the deflection mission, and then the deflection mission.

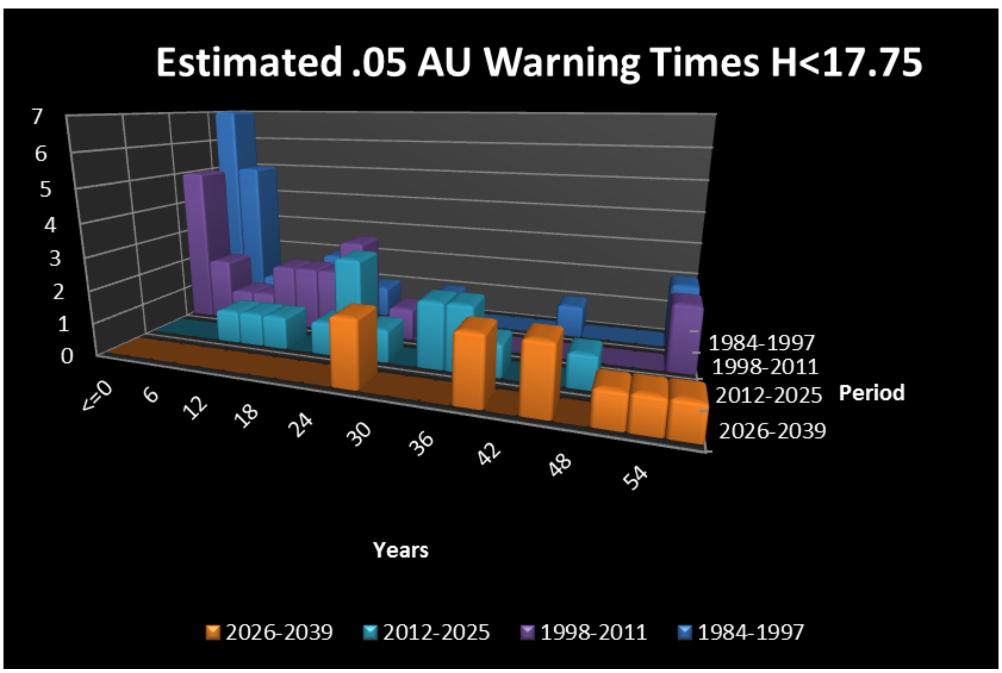

Figure 18. 3-D 0.05 AU Approach Warning Times 1984-2039, D> 1 km.

This graph displays a fairly obvious high success rate for Spaceguard with large objects. The right side of this chart shows the periods studied, beginning at the back with the earliest and moving forward to the projected periods.

Figure 18 displays an obvious result for large objects, Spaceguard has been a success. All PHAs in this size range will be discovered and tracked with enough certainty to provide an average of 27 years notice of their next penetrations into the MOID within the 2012-2025 period. Following this period, warning times for penetrations will continue to increase.

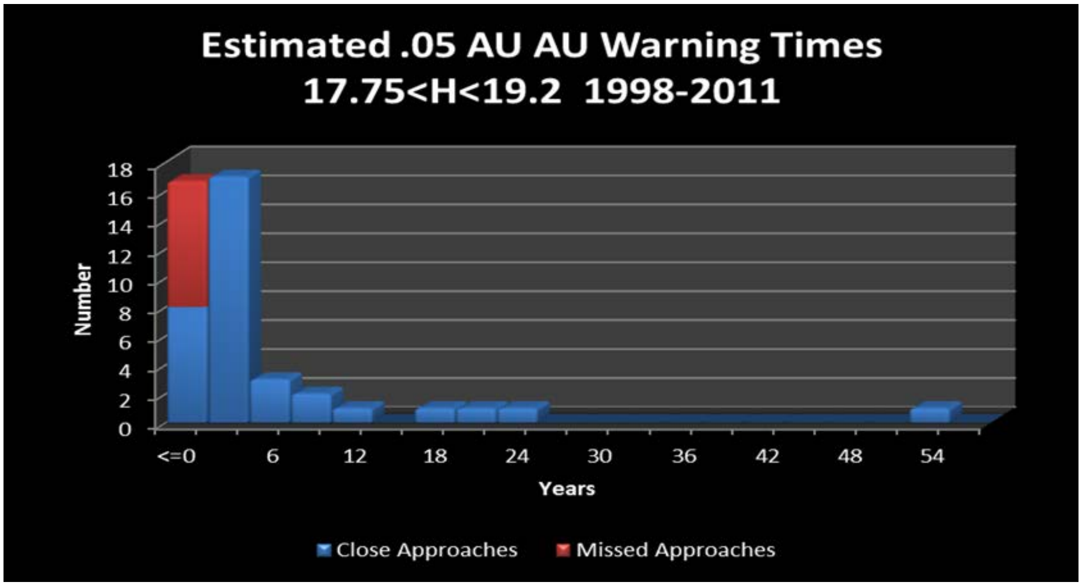

Figure 19. Close Approach Warning Times 1998-2011 D= 500-1000m.

Depicted are the 8.69 missed approaches (in red), along with the majority of known approaches with under 3 years warning time.

PHAs ~500- 1000 m

Spaceguard has had and will have almost as good success for PHAs in the 500-1000 m size range. The following graphs show that during the first period, most PHAs in this size range passed through the MOID with less than 6 years of warning. There were approximately 9 missed approaches (in red) of undiscovered PHA in this size range, as shown in table 9. In the following period, most penetrations of the MOID happen with between 6 and 42 years warning. However, as table 10 shows, there are projected to be eight approaches by newly discovered PHAs in this size range within the next 14 years, as well as 0.68 missed approaches by PHAs not yet discovered. Also, most warning times for MOID penetration will be above 21 years. PHAs discovered during the 2012-2025 time period will have some corresponding approaches in the 2025-2039 period. These estimated approaches of newly discovered objects are in green. Between 2026 and 2039, 89% of penetrations of the 0.05 AU MOID will have early warning of over 15 years, with no missed approaches. In the following period, 92% of penetrations will have over 30 years warning time.

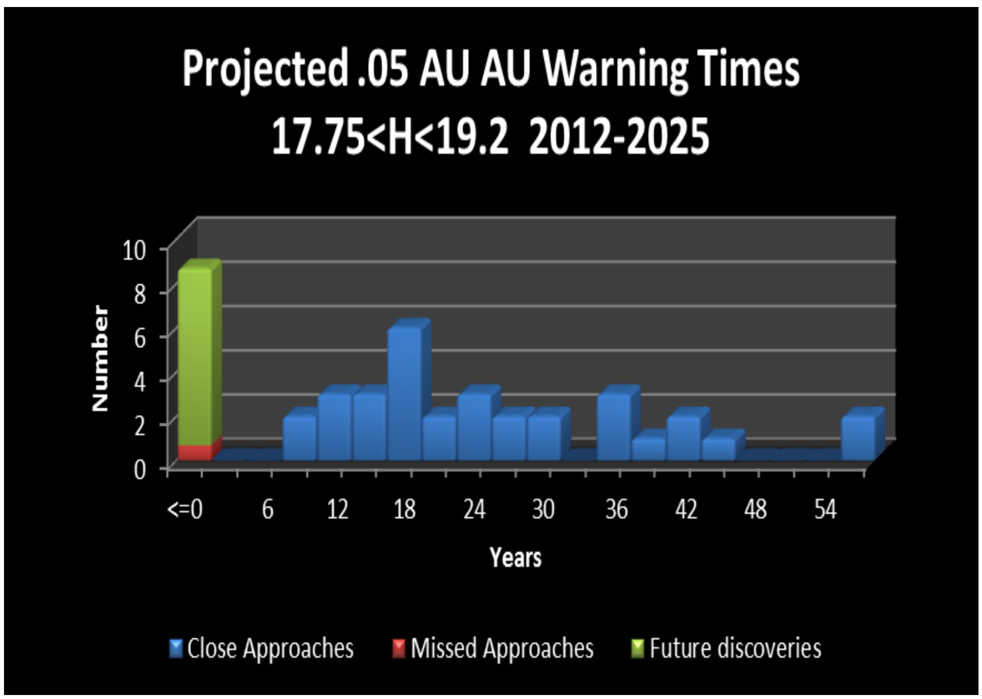

Figure 20. Close Approach Warning Times 2012-2025 D= 500-1000m.

Here we see a small chance of having a missed approach (in red). Additionally, an estimated 8 penetrations will occur during this time period of PHAs discovered after 2011 (see table 11, row 1c.). These are given warning times of less than or equal to zero due to lack of information, although it is more likely that some spread around zero would be the case. The rest of the penetrations have over 6 years warning time.

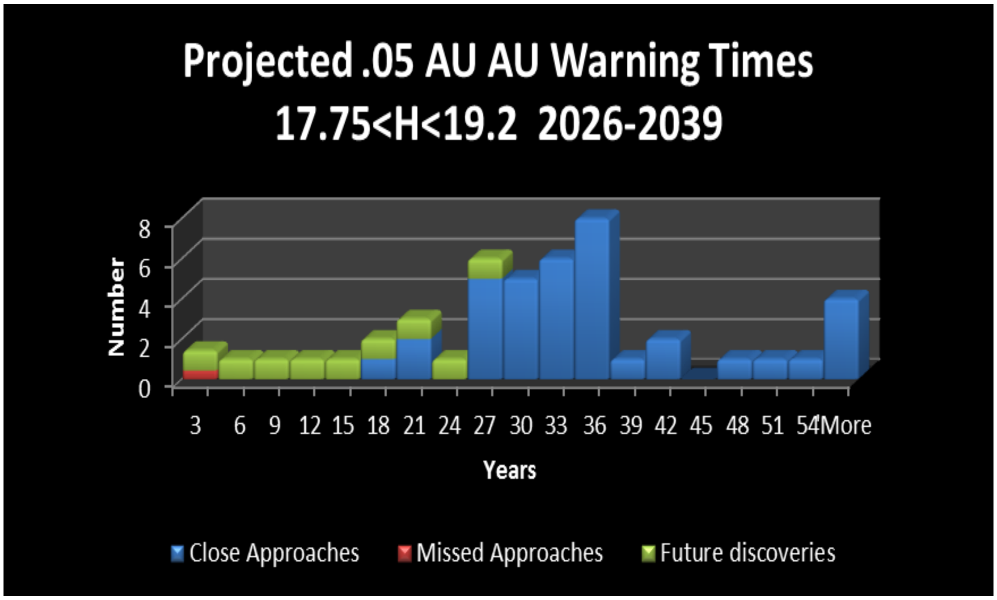

Figure 21. Close Approach Warning Times 2026-2039 D= 500-1000m.

About 52% of 0.05 AU penetrations after 2026 will have over 30 years warning time, when accounting for missed approaches and approaches of objects discovered after 2011. Projected discoveries after 2012 are given a uniform distribution (in green).

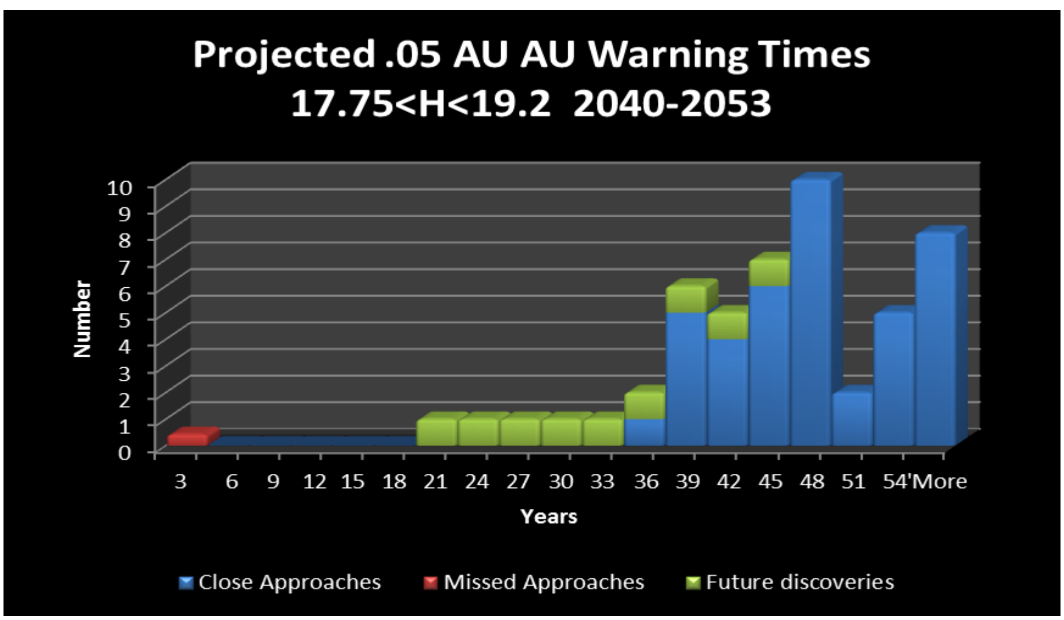

Figure 22. Close Approach Warning Times 2040-2053 D= 500-1000m.

Including all missed approaches, approaches of objects discovered after 2011, and approaches of all currently known (prior to 2011) objects, 92% will provide over 30 years warning time for penetration of the 0.05 AU MOID.

By 2011 80% of 500-1000 m objects have been detected. Warning times for penetration of the 0.05 AU MOID are projected to move up to a mean of 20.9 in the next 14 years. Mean penetration warning time grows to 33.5 years for 2026-2039 approaches, because by this time, most objects will have been discovered, with only a slight chance of a missed approach. By the period 2054-2067, all approaches will be anticipated by over 30 years, and 61% of approaches will have over 60 years of warning time. This gives enough time to go through all necessary decision points in a layered planetary defense.

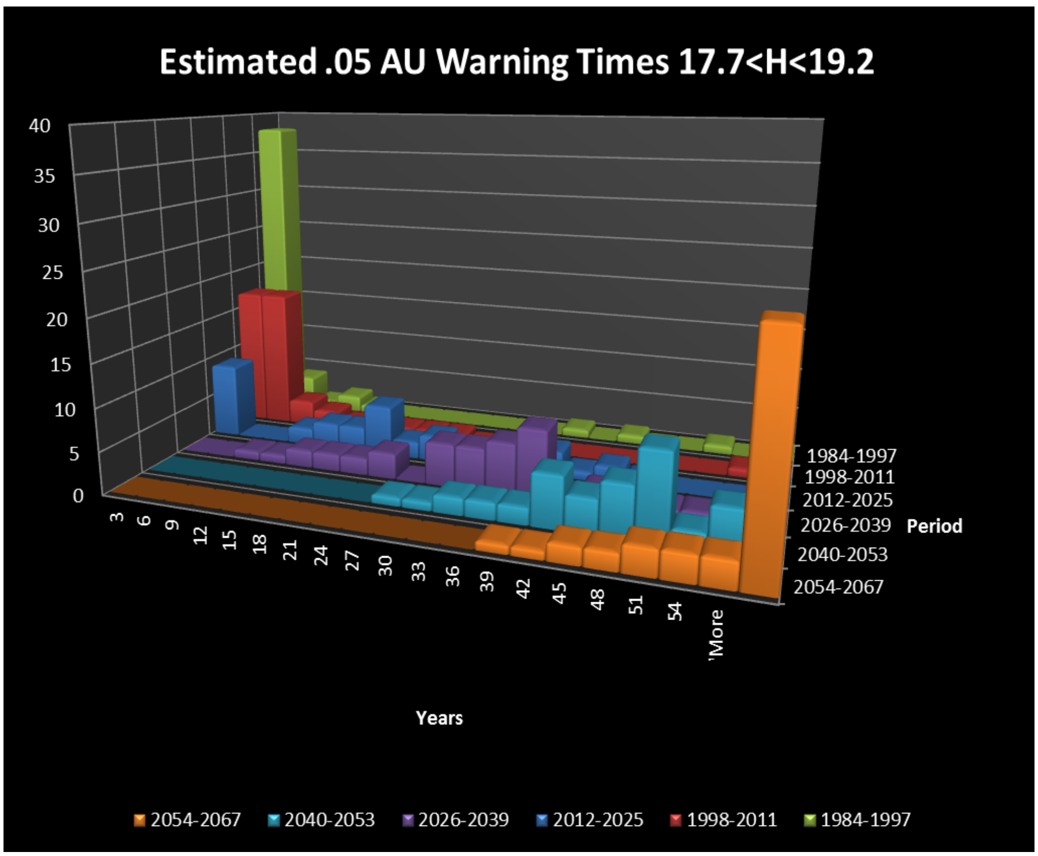

Figure 23. 3-D 0.05 AU Approach Warning Times 1984-2039, D= 500-1000.

Warning times for penetration are already moving up quickly for this size bin. By 2026, 30 years warning time for penetration of the MOID will be common.

PHAs ~300- 500 m

Spaceguard has some success for PHAs in the 300-500 m size range, but progress in the next two periods will be critical in establishing completeness within this size range. The following graphs show that during the first period, most PHAs in this size range passed through the MOID with less than 1 year of warning. Table 9 displays 48 missed approaches (in red) of undiscovered PHA in this size range**.** The following period shows little progress, because of an anticipated 30 missed approaches and 36 approaches of newly detected objects. Between 2026 and 2039, only 29% of penetrations within the MOID will likely have early warning of over 24 years, due to the anticipated number of missed approaches and new discoveries still occuring in that period. A factor that causes a delay of completion in this size group is the higher uncertainties in the trajectories. In the following period, 33% of penetrations will have over 24 years warning time, and 63% will have over 10 years warning time.

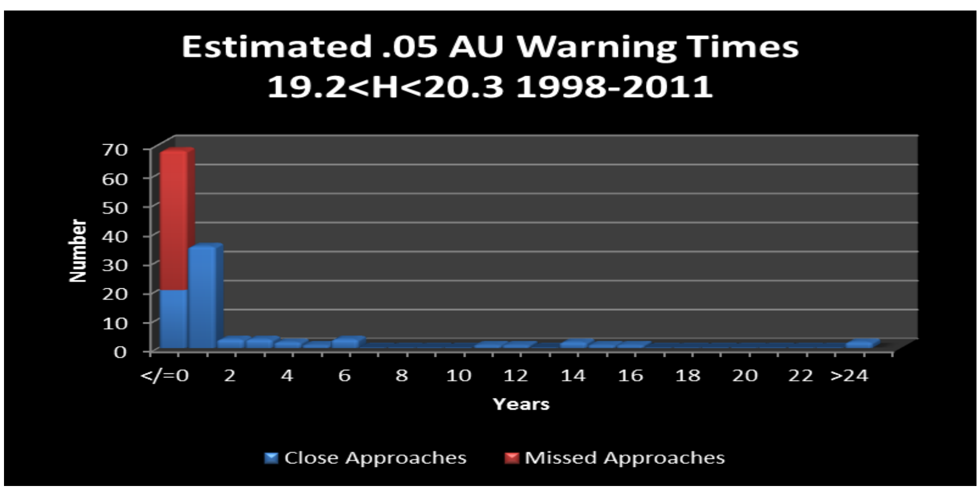

Figure 24. Close Approach Warning Times 1998-2011, D= 300-500 m.

A high number of approaches in this size bin, estimated at 48, have been missed since the 1998 congressional mandate, which applied only to larger objects. 84% of penetrations had warning times less than 1 year, (the first two columns).

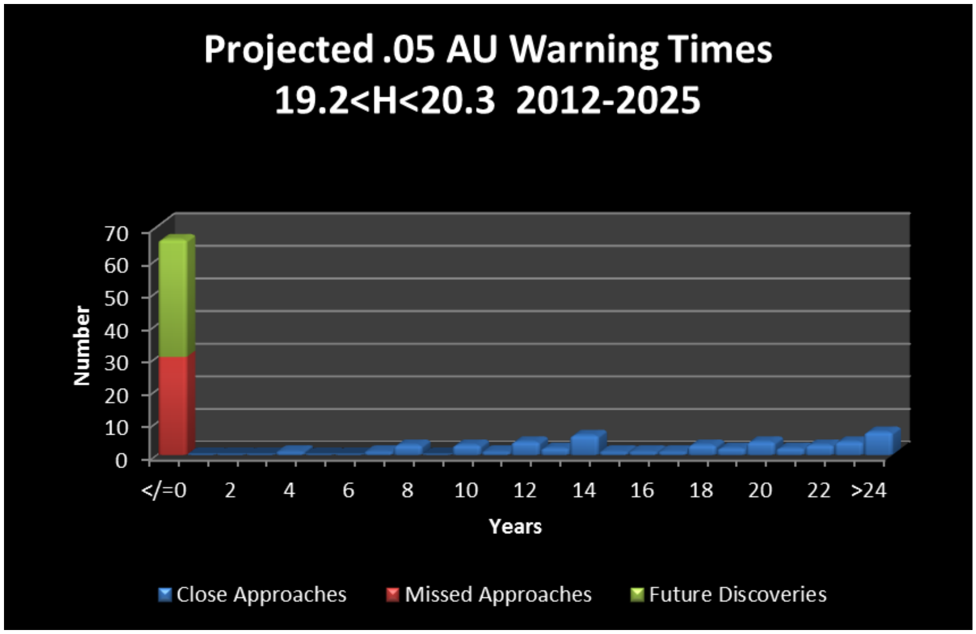

Figure 25. Close Approach Warning Times 2012-2025 D= 300-500 m.

Approaches of newly discovered PHAs and missed approaches will bring the average penetration warning times down close to 0 in this period.

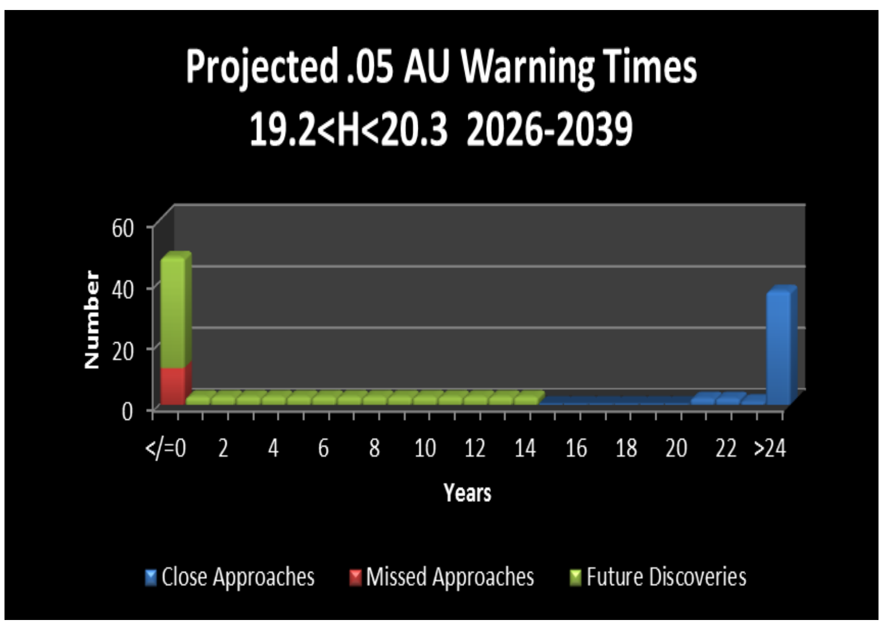

Figure 26. Close Approach Warning Times 2026-2039 D= 300-500 m.

As newly objects projected for discovery after 2012 provide longer warning times in this period, the picture improves a little. About 30% of penetrations should have warning times over 24 years in this time period.

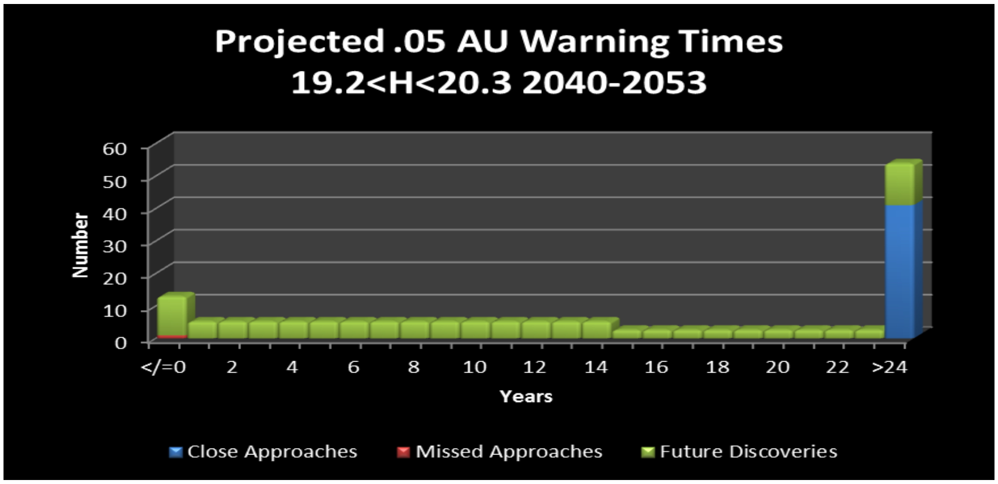

Figure 27. Close Approach Warning Times 2040-2053 D= 300-500 m.

Here, the missed approach rate declines, as the population of 300-500 m objects reaches completion. Newly discovered objects also decline as the population reaches completion. By the next period there will be virtually no missed approaches or newly discovered objects.

The following summary chart shows that early warning times for penetration will go from near 0 to over 24 years for 33% of PHAs in this size range by the end of 2053. By 2067, after completion, warning times will reach the required 30 years for most objects.

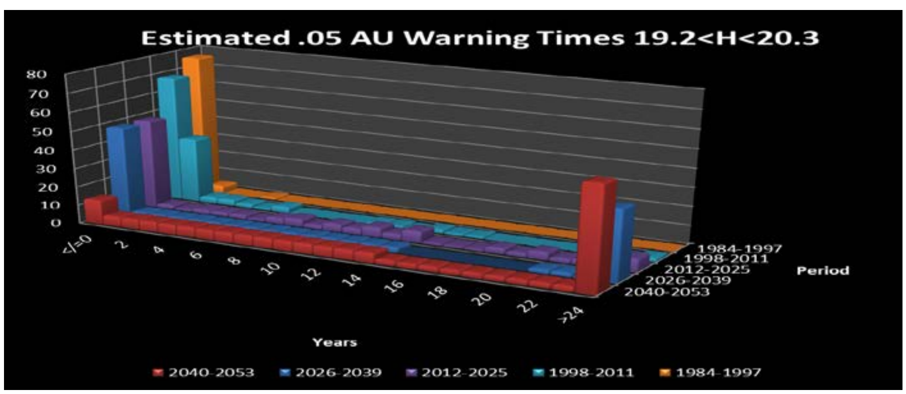

Figure 28. 3-D 0.05 AU Approach Warning Times 1984-2039, D= 300-500.

In the first period, penetration warning times were below 0, and moved to below 1 in the period since the 1998 congressional mandate. In the next period (2012-2025) 38% of penetrations will provide over 10 years warning time. 63% of penetrations from 2040-2053 will provide over 10 years warning time, and 33% will provide over 24 years.

The delay in having reliable warning times comes from the high uncertainties in trajectories of 48.5% of PHAs (see table 8) in this size range. This uncertainty, accompanied by the high number of PHAs in this size range, has the potential to delay completion for several decades. If the uncertainty level can be reduced through greater funding, the length of time until completion can be cut significantly, giving more warning time for penetration of this early layer for planetary defense. The reduction of uncertainties may require re-observation, re-discovery, and observation over long arc lengths for new discoveries. Uncertainty in the orbital trajectory plays an even greater role in the 100-300 m bin, which is addressed next.

PHAs ~100- 300 m

PHAs in this size bin are more numerous than all of the PHAs larger than 300 m combined. Table 5 shows the estimate of total PHAs in this size range at 3,807, whereas there are only an estimated 478 PHAs in the 300-500 m range. Because progress is much slower in this size bin, only every other period is shown in the graphs below. In the first period, over 500 missed penetrations of 0.05 AU occur. In the 2026-2039 period, there are still 500 projected missed penetrations and 168 approaches by newly discovered PHAs. Even as late as 2054-2067, there are 463 missed penetrations and still some 168 approaches by newly discovered (or re-discovered) PHAs. Because the population is so large, and uncertainty so high, completion will take a very long time for this size bin, and warning times will remain very low for the majority of approaches.

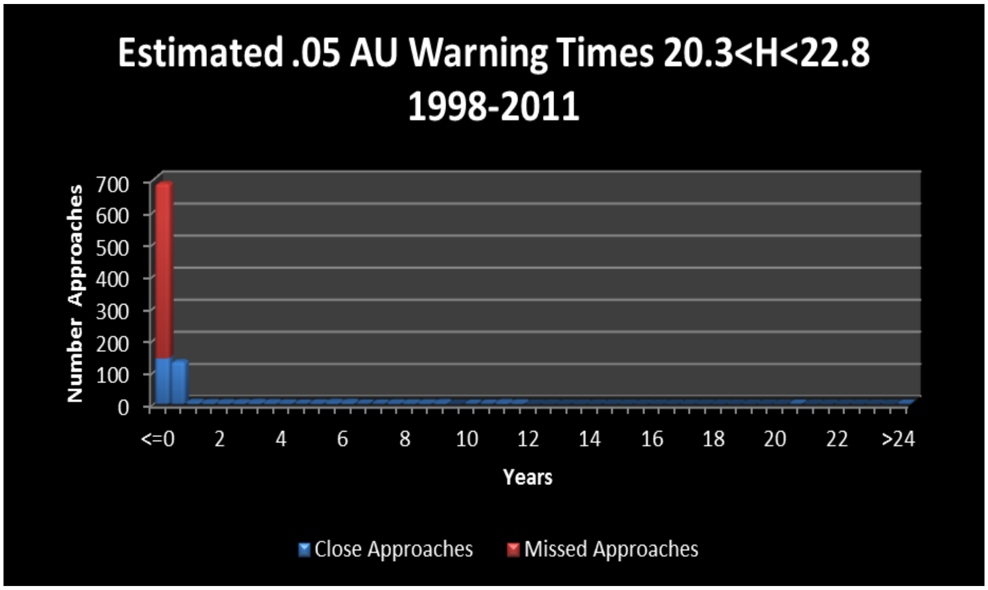

Figure 29. Close Approach Warning Times 1998-2011 D= 100-300 m.

Note the high number of missed approaches, because so many PHAs in this size bin remain to be discovered. Warning times for a only few approaches are greater than 1 year, barely discernible compared to the number of approaches with less than 1 year warning time.

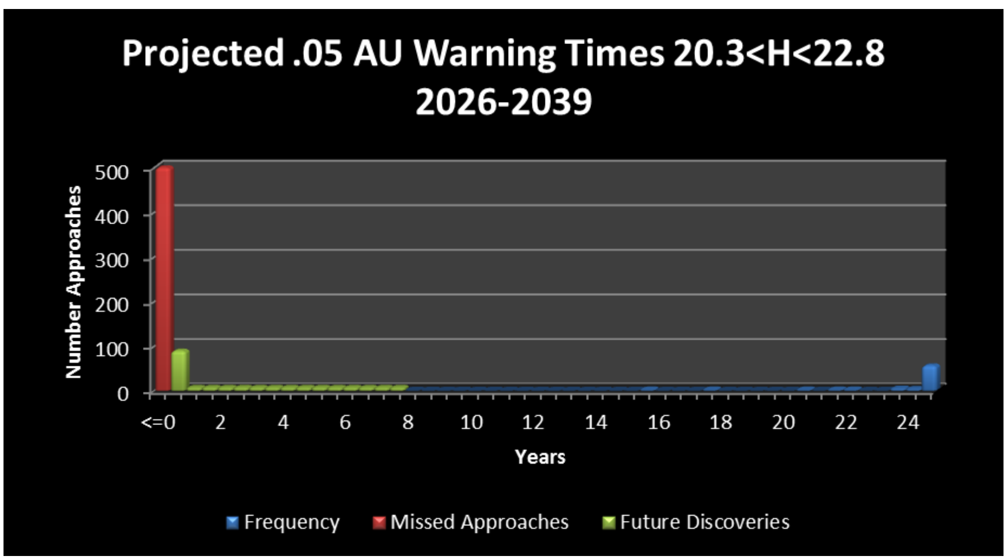

Figure 30. Close Approach Warning Times 2026-2039 D= 100-300 m.

Missed approaches are still high, overshadowing the also high number of approaches by newly discovered PHAs. Many newly discovered PHAs in this size bin have high uncertainties to their orbital trajectories, requiring them to be re-discovered.

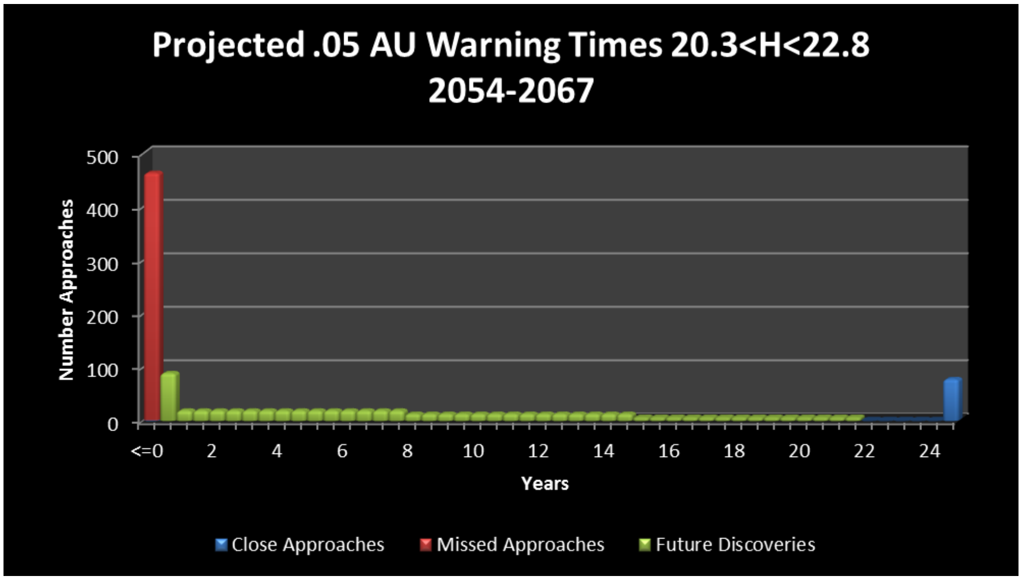

Figure 31. Close Approach Warning Times 2054-2067 D= 100-300 m.

By this time period there are slightly fewer missed penetrations, and penetrations by newly discovered PHAs continue. The number of approaches with warning times over 24 years, at 78, is fairly high compared to other size bins, but the percentage is very low.

Projections were only carried out to 2067 for this project. However, as discussed regarding table 5, if average rates of discovery continue for the foreseeable future, it would take 86.3 years (past 2011) to reach completion, without taking into account trajectory uncertainties. Because uncertainties are high in this size bin, it could take several hundred years to reach completion of the population. However, even before completion is reached, a great many objects will be discovered, yielding a good chance of finding an EI among them. For this reason, the 100-300 m size bin may yield both a surprise strike by an EI and an EI with well over 30 years of warning time.

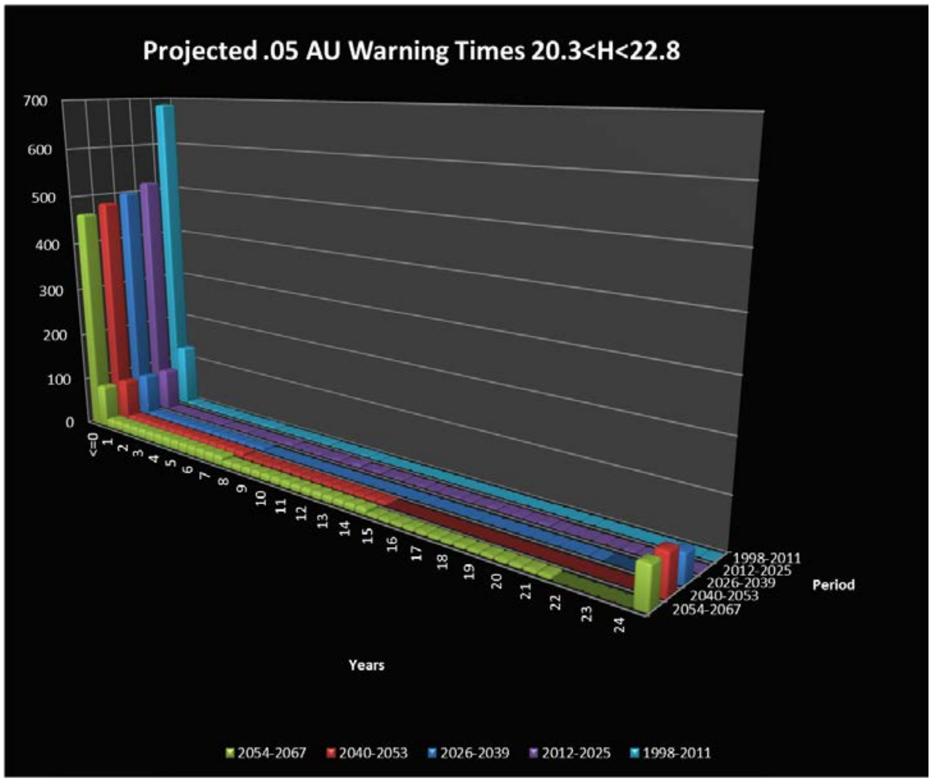

Figure 32. 3-D 0.05 AU Approach Warning Times 1984-2039, D= 100-300.

This graph shows that progress will be slow for warning times in this size range. On the left side, the total of missed approaches and new discoveries remains high well into the period of 2054-2067. Most approaches even in 2054 will have less than 1 year of warning time. If one of these turned out to be a potential EI, there would be little opportunity to employ the rest of the layers of defense. However, this population also provides some opportunity for discovery of an EI with over 30 years warning time, due to the high discovery numbers relative to other size bins.

Very Small PHAs ~ 25- 100 m

Because projections were only accomplished out to 2067, the Very Small PHAs of 25-100 m in diameter (~22.8< H<25.7) did not show any progress in terms of warning time for MOID penetration. The number of missed approaches in each period is over 1,700, and the new and lost detections so high that it will take potentially an order of magnitude improvement in finding and tracking NEOs to consider this size viable for early warning. Yet this is also the bin containing the next most likely surprise EI (no warning) to cause damage somewhere on the Earth.

It may take over a millennium to reach completion for this size bin, and to therefore have reliable warning for every penetration of the MOID. However, counter intuitively, this size bin may still provide an EI with over 30 years of warning, simply because there are so many PHAs being discovered in this size range all the time, as discussed in the following section.

The Next Known EI versus the Next Surprise Strike

Several of the graphs for the smaller objects previously shown have bimodal distributions, displaying both high number of MOID penetrations with under 1 year warning, and a high number with over 30 years warning time. This illustrates the reality of the PHA targeting problem: there is a reasonable chance that the size bin will yield both an EI with over 30 years warning time as well as a surprise EI that strikes with very little, if any, warning.

It is well known that the smaller the object is (down to 25 m), the more likely it will strike the Earth, because of the high numbers in the lower diameter populations. Our PHA population estimates in table 5 show over ~19,400- 400,000 PHAs in the 25-100 m range, with over ~18,260-399,000 left to detect. In the 100-300 m range, there are over 3,800, with over 3,300 left to detect. This means that there is over an 83-99% chance that the next EI to strike without warning will come from the 25-100 m population of PHAs, followed by a 1-15% chance it will come from the 100-300 m bin. There is an exceedingly small chance (<<1%) that the next surprise EI will be greater than 300 m, and this chance will continue to decline as the remaining population is discovered.

However, determination of the size of the next EI to strike with over 30 years of warning time is more complex. These must come from the population of discovered objects. Small PHAs are discovered frequently. Yet, as discussed in depth in Chapter II, a great number of small PHAs have too few observations to reliably predict their orbits for more than a couple of decades, and generally not out to 30 years. The following table considers our previous estimates of discovery rates and uncertainty rates.

Table 14. Probability of Next EI with 30 Years Warning Time Coming from a Size Bin.

2012-2025	> 1km	500m-1km	301-500m	100-300m	25-100m	Total
Est. PHA Discovery rates (14 yr)	9	47	193	539	1661	2448
Est. Level 2 PHAs	0%	0%	48%	80%	95%	
Level 1 PHAs	9	47	100	109	84	349
% next known EI:	2.5%	13.5%	28.7%	31.2%	24.1%	100%

Note: This table, with data pulled from previously explained tables 5 and 8, shows that three times as many PHAs are currently discovered in the 25-100 m bin as in the 100-300 m bin. And almost three times as many PHAs are discovered in the 100-300 m bin as in the 300-500 m bin. Yet objects whose trajectories have high uncertainty are more common in the 25-100 m range (95%) than in the 100-300 m range (80%). Once all objects with high uncertainty are removed from the discovery population, the 100-300 m bin is left with 109 objects whose trajectories can be projected out to 2200. Only 84 objects have such certainty among the 25-100m size bin.

Estimates in the above table are discussed in the “Detection Rates for New Objects” section and the “Level 2 PHAs: High Orbital Uncertainties” section in Chapter II. The main conclusions drawn from this analysis is that the next EI with over roughly 30 years of warning time has a fairly equal likelihood of being drawn from the 100-300 m, 300-500 m, or 25-100 m size bins, with the most likely to be found in the 100-300 m size bin (31%). This probability distribution will change in future periods, as the larger size bins reach completion. Currently, if an EI with over 30 years warning time is discovered in the next period, there a reasonable chance it could come from the 300-500 m bin (28%). It should be emphasized that this does not mean there is a high chance of an impact for objects 300-500 m in diameter. As Don Yeomans, manager of NASA's NEO program office at the Jet Propulsion Laboratory explained to Space.com, for 500 meters (1640 feet), this is a mean interval of about 100,000 years.

> When you get down to 50 meters, the mean interval is about 700 years, and for 30 meters, about 140 years or so, but by then you're getting down to a size where you won't expect any ground damage, as they burn up in the atmosphere at about 25 meters in diameter and smaller, probably for an impressive fireball event. (Choi, 2009, p. 1)

Dr. Yeoman's statement above underscore that if an object is less than 25 meters, there is little need to be concerned about the risk. For this reason, this lower threshold was used throughout this analysis. Objects above 25 m may, with the right composition and trajectories, make it through the atmosphere to cause impact the Earth. Clearly, objects in the 25-100 m and 100-300 m size ranges have a higher chance of containing an EI than the population above 300 m. However, when looking purely at the chance for finding an EI with over 30 years of warning time, the outlook changes somewhat. The 100-300 m range may very well have the highest chance of yielding an EI with warning time over 30 years, but only slightly greater than the chance of such an EI coming from the 25-100 m range or the 300-500 m range.

The uncertainty in these answers lies principally in the estimates for the total number of PHAs in each size bin. While the total number of NEOs have been estimated through simulation, the number of PHAs is still unknown, though there are some estimates stating that the total number of PHAs should be 21% of the number of NEOs (L. Johnson, personal communication, Feb 12, 2012). Further refinement of these estimates would help reduce the error levels of this thesis. However, the answer will still involve a high number of very small objects along with a high uncertainty in the trajectories of their orbits, yielding a low number of objects discovered with predictable orbits.

One assumption in this analysis is that observation technology, techniques, funding, and focus of the scientific community will remain the same. If the community decides that focusing on the small objects is not worthwhile, the time for survey completion could remain quite a long period. However, if technology continues to increase rapidly, completion of even the 25-100 m objects might be conceivable.

CHAPTER IV

APPLICATION OF RESULTS: MISSION CAMPAIGNS

Subsequent Layers: The Importance of a Transponder Mission

Within the layered defense approach, our results show distributions of the time between detecting an object and its next close approach to the Earth as a parallel to impact warning times and as a time frame within which a decision must be made for further action. As discussed in our overview at the beginning of this thesis, possible decisions to be made within the early warning period for each close approach include, in order of necessity:

1. Ignore the NEA.
2. Focus additional ground based telescopes at the NEA.
3. Focus RADAR assets on the NEA if possible.
4. Launch a precursor characterization/transponder mission.
5. Launch near-simultaneous observation and deflection missions.
6. Evacuation.
7. Recovery operations.

Beyond the initial layer of knowing that an object is coming within the 0.05 AU MOID, the probabilities of impact must be further refined. Additional ground observations, radar, and a precursor mission are the next layers. Possibly the most significant single piece of information that a precursor mission would need to determine would be the answer to the questions "What are the odds of the object hitting us?" There is a great deal of uncertainty in orbital refinements. Several passes of a NEO may be required before ground observations can tell if a NEO will have a high probability of being an EI. Chesley and Spahr (2004) accomplished a case study of the "rate at which the probability of an impending impact increases after discovery" (Chesley & Spahr, 2004, p. 34). In their simulation, an object discovered in 1983 and destined to hit in 2000 is determined to be harmless after initial observation. Years later, when the object is again observable, the future impact is confirmed, leaving less time for deflection attempts (Chesley & Spahr, 2004, p. 35).

A recent example of the application of this concept is 2011 AG5, an object which currently has the highest known chance of impacting the Earth (on its pass in 2040). The chance is estimated at 1 in 625. "Processing additional observations in the 2013-2016 time period," Don Yeomans told space.com, "will almost certainly see the impact probability for 2011 AG5 significantly decrease." (David, 2012, p. 1). In this case, enough observational opportunity will exist for 2011 AG5 well prior to 2040 to ease the pressure on decision-makers. However, if the next chance for observation was not until 2030 or 2035, the US government would have to decide if a 1 in 625 chance of impact merits launching a precursor transponder mission to the object.

For this reason, the author advocates a multi-layered approach with defined probability levels past which the next stage is activated. For example, a potential EI whose probability of impact reaches above some predefined amount should become the immediate subject of a global observation campaign, including RADAR observations. Once uncertainties are further resolved, if the NEA still provides a sufficient probability of threat and enough time, the next stage should be implemented- that of an immediate, inexpensive and uncomplicated precursor transponder mission. As the transponder mission is flying to the NEA, more expensive long-term transponder-observation and deflection missions could be designed and assembled as necessary.

Tens of billions of dollars could be spent to deflect or destroy a PHA presumed, incorrectly, to be on a collision course with the Earth. For this reason, sending a transponder mission to a PHA with a reasonably high chance of being an EI might be essential for determining if the NEO is indeed an EI. However, it is a difficult and politicized decision to determine the best minimum probability before such a mission is deemed necessary. For example, if a PHA in the 140 m size range has a 1 in 625 chance to strike, how long are NASA, congress, the President, and other nations likely to wait before taking action? In our current fiscally constrained environment, if added ground observations are soon possible, clearly the proper decision is the wait. However, what if the same odds applied and no more ground-based observations would become available prior to the threatening flyby? What level of risk are we willing to tolerate, and at what level do we make the hard decision to send a precursor mission? Decisions currently take place on a case by case basis, and no known NEO represents sufficiently high probability of near term impact to justify an expensive mission. But more ideally, there would be some minimum parameters above which the government would fund and mandate action, first in the form of a low-cost precursor observer-transponder mission, and secondly in a more expensive campaign of observer and deflection missions.

Purpose of a Transponder/Observer Mission in the Targeting Cycle

As discussed, a precursor transponder mission could determine orbital parameters to such a degree that the EI is determined to no longer be a threat, potentially saving the international community from large expenditures related to deflection attempts. Moreover, if the trajectory of the NEA is shown to be on a near miss with the Earth, deflection techniques might be better avoided, so as to not disturb the object and turn it into an EI. And if deflection is necessary, a transponder would likely be required for any deflection attempts and for post-deflection observation to find out the level of success. In the Air Force, this sort of post- impact assessment is analogous to "Battle Damage Assessment," an essential part of the Air Force's targeting cycle.

Time-Sensitive Target Considerations

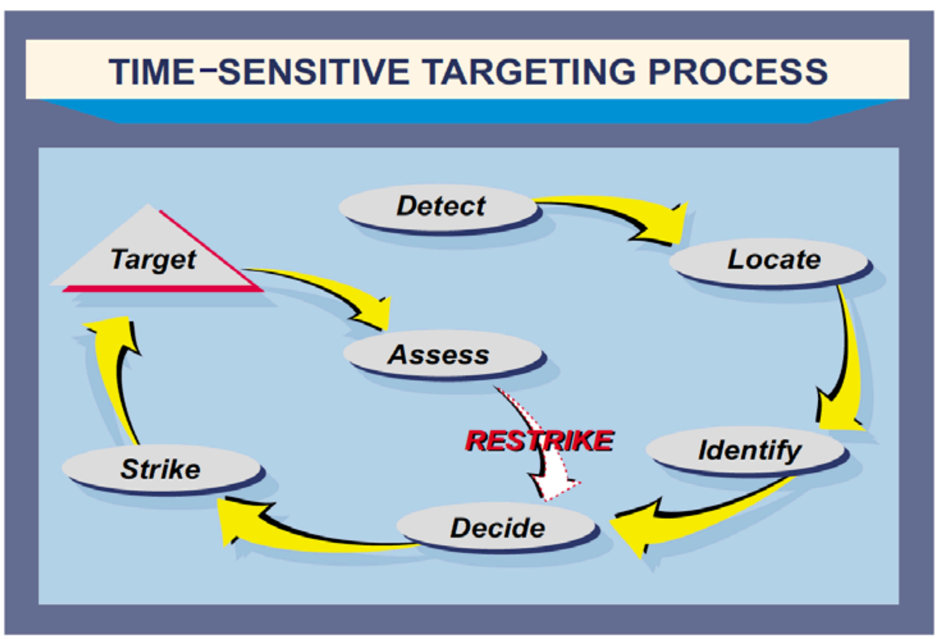

Figure B-1. Time-Sensitive Targeting Process

Figure 33. Joint Publication 3-60 "Joint Doctrine for Targeting".
This Time-Sensitive Targeting Process can easily apply to the NEA target set.

Figure 33 contains a typical example of the unclassified joint targeting cycle. In my professional career, I was part of this targeting process during the intense Afghanistan bombing campaign in the months after 9-11, and also in weaponeering prior to the second Gulf War. What is striking is how relevant this targeting cycle is to the NEA problem set. Detecting, locating, and identifying NEAs is currently being carried out by Spaceguard, and would be further carried out by the precursor observer-transponder mission. The decision point in the target cycle, one would presume, must lie with the President and/or Congress with (currently) recommendations from NASA for funding a campaign of missions to the NEA. Once deflection is attempted, assessment of the target would be required through the still active observer/transponder mission, after which a new decision for retargeting would take place.

The first key element in any targeting cycle is to gain as much detailed information about the target as possible. During the targeting of potential Weapons of Mass Destruction (WMD) going into the second Gulf War, a widespread assumption was that there was, indeed, WMD in Iraq. This assumption, however, was not supported by all in the targeting community. During subsequent congressional inquiries, it became apparent that no considerable amount of WMD existed, and an investigation began to find out how the error was allowed to propagate (Senate Select Committee on Intelligence, 2006, p. 4). A critical series of informational errors had taken place, causing or allowing immense resources to be allocated towards a lengthy war. This serves as an example of how the early stages of targeting- ascertaining the true nature of the target- are without a doubt the most critical.

Subsequent important stages of the process include developing targeting packages that address the most likely characteristics of the target. After adequate characterization, an attempt to destroy the target takes place, followed by another important process, assessment of the target after impact. All of these must take place in the targeting of an EI.

Characterization Data Necessary for Mitigation

Most importantly, a precursor observer- transponder mission could supply precise orbital parameters and mass/density distribution, due to the fact that these are required to determine whether the NEA is an EI, and if so, how much damage it can inflict. Other important data needed include shape models, rotation rates, gravity distribution, moment of inertia, chemical composition, and internal structure. Prior to embarking on a precursor mission to obtain this data, all attempts from ground-observation to yield as much data as possible should be carried out, both to determine the necessity of the precursor mission and to assist the mission, in the event that it must take place.

Prior to sending a precursor mission, it is important to have a general idea of the size and mass of the threatening NEA. The most likely size will be in the 100-300 m range, with possibilities in the 300-500 m and 25-100 m ranges. Close-proximity operations around small bodies such as these are complex. Scheeres (2004) states that orbits about small bodies can become rapidly destabilized and result in impact or escape velocity in a matter of hours, rather than thousands to millions of years (Scheeres, 2004, p. 2). He emphasizes that small bodies, with their large range of physical parameters, will merit very different concepts in terms of close-proximity operations. He discusses a case study of the NEAR approach to Eros versus Hayabusa's approach to the smaller Itokawa. These missions required substantially different designs due to vast differences in the bodies, particularly the mass difference. This meant that for Itokawa, the spacecraft used more station-keeping, in essence almost hovering around the object, which meant differences in terms of fuel, placement of instruments, and more (Scheeres, 2004, pp. 1-2). Therefore, radar imaging and precise optical imaging of a NEO would be ideal prior to embarking on a threat mitigation mission or a precursor to that mission.

Alternatives and Mission Times for a Precursor/Transponder Mission

A precursor transponder mission could involve placement of a device onto the surface of the NEO, or simply conducting long term close-proximity orbits of the object using a radio science package for distance measurements from Earth. The mission could be designed for a direct short term stay near the body (a few years) using already developed technologies for costs that would be low relative to a deflection mission, which might be determined to be unneeded due to the refinement of the orbit. Or it could be designed for more sophisticated, long-term stay for pre- and post- deflection purposes, which would likely cost more. The design and test of an inexpensive, rapidly deployable precursor transponder mission would be a step in the right direction. The precursor mission should be designed for objects in the 100-300 m range, based on this analysis. Another recommendation is continued design of a robust suite of observation and deflection missions that would follow the initial precursor mission. Finally, testing of a kinetic deflector against a benign NEO in the 100-300 m size range would provide real world experience for planetary defense.

Charania, Olds, and Koenig of Spaceworks carried out recent work on Foresight, an inexpensive precursor mission designed as an Apophis mission. The Planetary Society's Apophis Mission Design Competition awarded first prize to the Foresight mission for its "low-cost, conventionally propelled orbiter with only two instruments and a single band [X-band] radio tracking system" (The Planetary Society, 2008). Spaceworks wrote a mission design document for a transponder mission that would co-orbit the sun with Apophis. NASA scientists at JPL initially thought Apophis, a roughly 270 m object, had a reasonably high 2.7% chance of impacting the Earth in 2029 (Brown, 2009). With additional observations, they were able to rule out the 2029 impact, but will be watching it closely as it passes very close to the Earth to the Earth at around 31,000 km (Brown, 2009), which is inside the orbit of our geosynchronous satellites. Initially, scientists were also concerned that in 2029, "if Apophis passes through a several-hundred-meter-wide 'keyhole' in space during this approach, it will impact the Earth in 2036" (Charania, p. 1). However, "updated computational techniques and newly available data indicate the probability of an Earth encounter on April 13, 2036 for Apophis has dropped from one-in-45,000 to about four-in-a million" (Brown, 2009). Nevertheless, Apophis' close passes to the Earth make it ideally suited for testing a transponder precursor mission.

Wertz breaks down a spacecraft into the following subsystems: propulsion, control systems, on-board processing, communications and power, and structures and thermal, as well as payload, ground system, and launch operations (Wertz, 2011, pp. vi-vii). Looking at the Foresight mission for these elements, Charania uses "a single bi-propellant chemical main engine and a number of small thrusters" for Foresight's propulsion (Charania, p. 2). Ion propulsion has recently matured enough to where this might be the preferred mechanism (M. Gaffey, personal communication, 18 Apr, 2012).

On-board processing includes a central processing unit (PowerPC 750FX), a solid state drive, and an electronics module. Control systems include four reaction control system thrusters, several sun sensors, two star trackers, and an inertial measurement unit. Foresight uses both high and low gain antennas for communications, and it has two solar arrays as its primary power source, augmented by batteries (Charania, p. 1). For the payload design, Charania et al. felt that a laser altimeter and camera were "the minimum suite of instruments one would need in order to provide the data to reduce future orbital uncertainty (A. Charania, personal communication, December 4, 2012). All of these fit into an 85 cm X 85 cm X 70 cm box, with a total mission cost estimate of only $131 M (FY2007 constant U.S. dollars) , including the $22 M stated for the Minotaur IV launch vehicle. For the launch, Charania used a Propulsive Transfer Vehicle (PTV), "a simple bi-propellant chemical stage, to assist in achieving the necessary Earth departure velocity", after initial launch on an Orbital Sciences Corporation (Orbital) Minotaur IV launch vehicle from Wallops Flight Facility in Virginia (Charania, pp. 1-2).

The Foresight would, if launched on May 9, 2012, take 310 days to transfer from Earth to Apophis, followed by a 10 day Initial Survey period and a 30 day Observation period during which it would orbit Apophis to determine its shape, rotation, and gravity model. It would then retreat from orbiting Apophis and enter a trailing orbit 2 km behind the asteroid's center of mass, for the modeled minimum of 300 days required to reduce the error ellipse down to 6 km (Charania, pp. 3-4). Added together, this would yield 650 days for mission success, plus a waiting time for the window of approximately 5 years after the initial design, for a total of approximately 7 years' time to mission success after the proposal.

This 7-year time to mission success provides a direct link in to the warning time estimations. After ground –based instruments determine some minimum chance of a NEA being an EI, we can see that the precursor transponder mission alone will consume a sizeable chunk of time. Bruce Willis would age perhaps a decade or more before being able to board the Space Shuttle and rocket off with a nuclear weapon. Early warning is vital.

The second (A-Track) and third-prize (APEX) competitors estimated their costs at $387.2 M and $497.8 M respectively. A-Track proposed a payload of 2 cameras, a thermal radiometer, a visual and near-IR spectrometer, and a dual band (Ka and X) tracking system. It was larger and more massive than Foresight (540.2 kg versus 100.2 kg), with a correspondingly larger solar panel size (6 m^2 versus 1.2 m^2). A-Track proposed a 2013 or 2014 launch on a Boeing Delta II 7926, with rendezvous at Apophis 10-15 months later. Like Foresight, it would orbit Apophis for a preliminary period (5 months, longer than Foresight's 30 days). However, in lieu of leaving orbit to trail behind Apophis, Deimos Space, the creators of A-Track, proposed having the spacecraft withdraw to a stable orbit, well-away from Apophis, further out for a six-month tracking period (The Planetary Society, 2008). Again, with the waiting time for an appropriate launch window, the total time would be on the order of 6-7 years to mission success.

APEX, the most expensive of the three winners was a solar-electric propelled spacecraft that would be theoretically launched on a Soyuz Fregat between 2012 and 2015, to arrive 9 to 21 months later. Like the other two, it would arrive and accomplish a preliminary study of the asteroid's parameters, with added capabilities due to its extensive sensor suite of six instruments: 2 cameras, a laser altimeter, a visible and near-IR spectrometer, and an accelerometer, along with a dual band (KA and X) tracking system. With this more sophisticated instrument suite, EADS can accomplish a thermal mapping campaign for what it argues are essential estimates of the Yarkovski effect and Solar Radiation Pressure (SRP) on both Apophis and the spacecraft. APEX would track Apophis for at least an Apophis year after its initial observation period, with a potential additional year under some conditions (Allouis, et al., 2007, pp. 1-5). The total time to mission success for APEX is on the order of 5-7 years when adding launch window wait time to transit time and mission completion time.di

Proposed Campaign Architecture

For a 100-300 m object with warning time of over 30 years, the use of a mission similar to one of the above Planetary Society winning proposals for an inexpensive rapidly deployed precursor mission would be desirable. Secondly, a more robust observation mission to follow is advocated, should the initial precursor mission demonstrate conclusively that a NEA is indeed an EI. This mission would be required to loiter near the NEA, providing similar transponder and other characterization data as the above missions, with the potential addition of an observation role during and after a potential mitigation attempt. This follow-on precursor campaign would either require a more robust power source to keep it active for a longer period, or it would need to involve of a series of inexpensive observer spacecraft that would be launched periodically to replace and/or augment previous observer missions.

Rather than orbit the NEA, or after doing so for a period of time, the spacecraft would pull back and co-orbit the sun in close proximity to the NEA, far enough from it so that a deflection mission would not adversely affect it. This might not be too complicated if the deflection method chosen were a kinetic strike or the use of a gravity tractor. However, the use of a nuclear bomb as a deflection device may create complexity in terms of the radiation effects on the spacecraft. The degree of hardening and distance from the center of mass of the NEA might require modeling, likely based on models used within the Department of Energy and DoD for modeling nuclear blasts. A solution for preparing for such an environment might be to have the observation mission positioned on the opposite side of the NEA from the blast. Because there is no atmosphere involved, this could very well be enough to protect the spacecraft (M. Gaffey, personal communication, 18 Apr 2012).

Alternatively, a new transponder mission could be launched to arrive shortly after the mitigation mission. The campaign would include a means of initial scouting (the precursor), a follow-up long term observation mission, the mitigation, and the critical post-mitigation assessment-observation mission. After deflection attempts, a critical period would ensue to re-measure the orbit of the NEA, with the hopes that it shifted enough.

If warning times are less than 30 years, the multiple spacecraft in this campaign might be sent near simultaneously. For this reason, an already designed, inexpensive precursor mission, ready for rapid launch would be an important part of such a campaign architecture. With 10 years warning time, for example, the precursor would launch as soon as a certain probability for impact threshold is reached, and as soon as a window became available, completing its mission within the next 7 years. The follow-on observer mission and mitigation missions would be built in a crash program similar to the Apollo program to get to the moon, and might be sent while the precursor is still enroute.

The Most Likely Target

Such a transponder mission and/or campaign of several spacecraft, if launched within the next few decades to centuries, would most likely be sent to an object in the 100-300 m range, as the research in this thesis points to. If observation technology advances significantly, so that uncertainty rates for smaller objects decline significantly, then the most likely object for a transponder mission would move to the 25-100 m range. With the high frequency of discoveries in this very small object range, the only thing preventing an EI from being discovered is the uncertainty in its trajectories. Until these uncertainties are overcome, the next detected EI giving any time for a transponder mission will most likely come from the 100-300 m range, followed by the 300-500 m range, and then the 25-100 m range. Therefore, close-proximity operations may be designed around these three general size ranges, and the corresponding likely mass. While the mass range between 25 m and 500 m is significant, it is far better constrained than trying to design for larger NEAs. This means that the mission designs for Apophis, if tested, would provide proven technology in the range of objects considered.

CHAPTER V

DISCUSSION

The next EI with actionable warning times (greater than 30 years) will most likely come from the 100-300 m size bin, followed by the 300-500 m size bin, and lastly the 25-100 m size bin. This conclusion came from a combination of estimates of approach warning times, missed approaches, rates of occurrence of highly uncertain orbits, and projected detection rates. Possible campaigns for dealing with potential EIs discovered with enough actionable warning time to launch a precursor mission were discussed. Examples of mission designs for the initial precursor transponder mission were discussed, as well as a proposed campaign for follow-on observation and deflection missions, using the Department of Defense Joint Targeting Cycle as a model for carrying out such a deflection mission. A discussion of some technologies that should probably be improved over the next few decades follows, along with a synopsis of recommended paths forward to prepare for the different threats the Earth will face.

Future Technologies Essential to Spaceguard

This analysis has attempted to help focus the planetary defense efforts on current capabilities and help identify gaps in them. One such gap comes from the high uncertainties for the orbits of most objects less than 300 m, which, if overcome, will rapidly ramp up the warning time for these objects. Until this is rectified, there will be a substantial threat of little to no warning for many objects in the 100-300 m size-bin for several decades. For objects 25-100 m, this threat will remain for several centuries, unless several order of magnitude improvements take place in observation technology (ground and space-based). The following technologies should be maintained, and improved if possible.

Radar Observations

Arecibo, at 300 m in diameter, is the most sensitive radar system in the world, although it cannot be steered as well as the runner-up, NASA's Deep Space Network 70 meter antenna in California. The Arecibo radar has carried out 65% of all radar observations of NEOs, discovered 47% of known binary NEOs, and provided data for higher precision orbit determination for a significant number of NEOs (Campbell, 2007, p. 2). But even with these impressive statistics, Arecibo faced the prospect of being closed down, until Congress allocated funds to NASA with the charge to keep it running.

New Methods of Surveying

Detection methods have advanced greatly in recent years. Chesley and Spahr (2003) noted that "surveys will most readily detect impactors . . . in two fairly small 'sweet spots' situated within 15° of the ecliptic and 90-120° from opposition. Fainter objects will be preferentially found in the opposition region" (p. 36). This has heralded a new focus on observing in areas outside of opposition, yielding great results.

Dr. Spahr states that what we need is a "consistent survey to visual magnitudes (V) of 23 or 24, or a dedicated follow-up system that can get us to V = 24 quickly." (T. Spahr, personal communication, March 1, 2012). He and other scientists involved in Spaceguard have a wealth of understanding of the potential for improvements in existing technology. Surveying methods also need to work well with the overall goal of finding objects that might strike Earth. Spahr explains that we need a way to flag the NEAs that we are interested in and focus observations on them "at the discovery apparition. Then key objects won't ever get lost" (T. Spahr, personal communication, March 1, 2012).

Diversion of just a few percent of funds from a major DOD or DHS program, which may provide only marginal increases in national security considering our large lead in that area, could enable huge dividends in planetary defense and inspire more scientists to pursue space-related research.

New Space-Based Observations

Scientists such as Dr. Mainzer at JPL have made efforts for more space-based observations in the IR, with proposed projects such as NEOCAM. NEOCAM will, if approved, attempt to observe at low solar elongations. (A. Mainzer, personal communication, September 26, 2011). With such technology, current efforts might more quickly lead to a precursor mission to a small EI destined for impact decades to centuries from now. A space-based constellation added to increased ground-based technology, with automated target recognition and tracking technology, might also be a means to handle the tremendous number of objects in the smallest of size bins, which contains most likely next surprise impactor. Space-based assets can provide more precise orbits of objects, due to being above atmospheric distortions and potentially positioned better for observations. This would be a valuable addition for detection of small objects, in the 25-100 m and 100-300 m range. As astronaut Rusty Schweickart stated in a 2007 testimony to congress:

> It is an unfortunate reality that ground-based telescopic tracking produces, for many challenging NEOs, discontinuous information; data dropouts may last for several years at a time. . .The orbital phasing responsible for this interrupted tracking can be eliminated by selecting any of several space-based search options in NASA's analysis to augment the ground-based systems. While NASA reports that overall costs for space and ground tracking are comparable (a controversial claim), the tracking quality provided by a telescope in a Venus-like orbit, in particular, is vastly superior. The dual-band IR telescope is especially preferable since it also improves greatly our estimates of NEO mass (and thus impact energy) (Schweickart, 2007, pp. 57-58) .

Recommendations

The following two charts represents our conclusions and recommended actions for possible scenarios occurring out to 2200. The top entry (Highest, High, Medium, Low, Negligible), gives their general estimate for the likelihood of that scenario taking place within this time frame. Recommended actions after the discovery of the impending EI are provided. Finally, recommendations for what to do to prepare for each eventuality are provided, to include recommendations against preparing for negligible chance events. For example, the highest probable scenario is that of a 25-100 m object striking with no warning. The only actions available are recovery, and potentially an attempt at last minute evacuation. Recommendations for reducing this danger include improvements to detection and tracking technologies (through space- and ground-based technologies), and preparations for recovery from such an event within the emergency management system. Objects in this size range have a low probability of being detected long in advance because of the difficulties in resolving their orbits. In the 100-300 m range, there is a lower total chance of a surprise EI within this smaller population. However, the number of discoveries in this size bin is quite high, so if an EI is in this population, there is a moderate chance of finding it well in advance of its strike. Objects in this size range are numerous enough and pose enough damage potential to merit recommending an on-call pre-built precursor mission ready to deploy to the object quickly, followed by more long-term planning of a host of pre- and post-observing missions and deflection missions. Another strong recommendation is for the testing of a live deflection mission against such a small NEA, albeit one that could not be deflected such that it would later hit the Earth!

Table 15. Actions and Preparatory Recommendations by Size, Warning Times (<300 m).

Warning → → Size/Danger	0- 1 year warning	1- 30 years warning	30- 1000 years warning
25-100 m: -Large thermo nuclear blast - .3% high death toll & damage in air burst (3-8,000/km^2) - 12% Sparsely populated land (0-50/ km^2) - 17% Lightly to Moderately populated - 71% water strike- no death/ damage	Most likely size group <u>Action:</u> 1. Trajectory calculations 2. Warning 3. Evacuation 4. Recovery <u>Recommend:</u> -Improve detection/ tracking for precision impact location	<u>Action:</u> 1. RADAR ground observation 2. Precursor mission 3. Quick Follow-up observation/ mitigation missions <u>Recommend:</u> - - On-call precursor mission pre-built - Design observation/ mitigation missions - Conduct kinetic deflection tests in space	<u>Action:</u> 1. Extended RADAR/ ground observation 2. Precursor mission 3. Observation/ mitigation missions <u>Recommend:</u> - Conduct space mission design for precursor missions to small PHAs - Conduct kinetic deflection tests in space

Table 15. Cont.

Warning → → Size/Danger	0- 1 year → → warning	1- 30 years → → warning	30- 1000 years warning
100-300 m - 71% water strike- tsunami with coastal death/ damage - 26% significant land strike (excludes Antarctica)- local/ regional destruction	Action: 1. Evacuation 2. Post-strike recovery Recommend: -FEMA evac/ recovery prep - Augment space-based and ground based observation technology - Improve interplanetary lift capabilities	Action: 1. RADAR/ground observation 2. Immediate precursor mission 3. Quick follow-up observation/ mitigation missions Recommend: - On-call precursor mission built - Design & Test observation mitigation missions	Most likely size group Action: 1. RADAR/ ground observation 2. Precursor 3. Observation + mitigation msn Recommend: -On-call precursor mission -Design Observation/ mitigation missions

Note: The first column contains PHA size and estimate of damage levels. The second contains, at the top, a ranking of this event occurring within the next several centuries, and actions to take if it does occur. It also contains recommended advanced preparations to take to prepare for and prevent such an event. The third and fourth columns contain the same, for longer warning time periods. The highest chance event is a surprise EI under 100 m. A medium probability event is a 100-300 m EI with a very long warning time (30-1000 year).

Events in the 300 m and larger size bins have low to negligible chances of occurring; however, damage/death rates become so high projecting out all current orbits for several millennia would be a very good step to allow for very long term observation and mitigation planning.

Crash mitigation- observer missions (missions designed with urgency and very little time) should be designed for objects in the 100-300 m range and the 25-100 m range, in that order of precedence. Such crash missions would include near-simultaneous low-budget solar-powered precursor missions accompanied by higher-budget observer and mitigation missions. Emergency management agencies such as FEMA should design evacuation plans and post-impact recovery plans for objects in the 25-100 m and 100-300 m range, in that order of precedence. For objects greater than 500 m, emphasis should be on continuing to accelerate the discovery and orbital prediction for this limited population of NEAs out several centuries, to allow adequate time for several deflection attempts.

Table 16. Actions and Preparatory Recommendations by Size, Warning Times (>300 m).

Warning → → Size/Danger	0- 1 year warning	1- 30 years warning	30- 1000 years warning
300-500 m - Regional destruction with land or water strike	Action: 1. Evacuation 2. Post-strike recovery Recommend: -Evac/ recovery prep - Augment space-based and ground based observation technology	Action: 1. RADAR/ground observation 2. Immediate precursor mission 3. Quick follow-up observation/ mitigation missions Recommend: - On-call precursor mission built - Design & Test observation & mitigation missions	Action: 1. Extended RADAR/ ground observation 2. Precursor 3. Observation/ mitigation missions Recommend: - On-call precursor mission built - Design observation/ mitigation msn
500-1000 m - Regional/ hemisphere destruction with land or water strike	Action: 1. Evacuation 2. Post-strike recovery Recommend: - Increased observation technology	Action: 1. RADAR/ground observation 2. Immediate precursor mission 3. Quick follow-up observation/ mitigation missions Recommend: - Refine trajectories	Action: 1. Extended RADAR/ ground observation 2. Precursor 3. Observation/ mitigation missions Recommend: - Refine trajectories
>1000 m - Global chaos, long term struggle to survive	Very low chance Action: 1. Evacuation 2. Post-strike recovery Recommend: - Increased observation technology	Very low chance Action: 1. RADAR/ground observation 2. Immediate precursor mission 3. Quick follow-up observation/ mitigation missions Recommend: - Refine trajectories	Very low chance Action: 1. Extended RADAR/ ground observation 2. Precursor 3. Observation/ mitigation missions Recommend: - Refine trajectories

Summary and Conclusions

Throughout this analysis, the Department of Defense targeting cycle was applied to the EI challenge. This application began with characterizing early warning times for different size objects. An attempt was made to measure the success of the Spaceguard efforts in increasing warning times for different size bodies, and along with projections for future warning times for penetration of the 0.05 AU MOID. In doing so, a multi-step method to build a model consisting of aggregated differences in the dates of first discovery and close approach was carried out, along with estimates for missed approaches, projections of new discoveries, and estimates for high uncertainty trajectory rates. Conclusions for PHAs of different sizes were provided. The most significant of these conclusions was that the 100-300 m size range contains the most likely EI we will discover with enough warning time to take some form of action. Also provided were time frames as to when populations would reach enough completion that a high percentage of 0.05 AU MOID warning times would grow to greater than 30 years.

In the second half of the analysis, mission campaigns based on the results of the first were discussed, to include specific focus on use of a precursor transponder mission against small objects, likely in the 100-300 m size range. Recommendations against different EI scenarios were provided, given different warning times and sizes. Overall, the recommended campaigns included additional observation technology; an inexpensive short-termed precursor transponder mission; a long-term observation mission; and a suite of simultaneous observation and mitigation missions. A conclusion is that additional resources should be allocated toward more robust survey technology, the first layer of defense, with continued development of precursor characterization-transponder mission technology, the second layer of defense.

Another conclusion is that the Spaceguard effort has brought about the beginnings of a true targeting process that could either be maintained within NASA or spread out among the Department of Defense and Department of Homeland Security in some ways, against the day that mitigation of an EI becomes a real necessity. NASA began a process in 1998 that could result in an eventual successful mitigation of an EI. However, without “finishing the job”, by far the most likely scenario, that of a small object penetrating and striking with negligible warning time, will still occur. It is quite possible, in fact that two situations will occur within the next few centuries. It is quite possible that we will find and attempt to mitigate the threat of an EI with decades to centuries of warning time (100-300 m diameter), and in the meantime have another smaller EI (25-100 m diameter) hit us without warning. Now that the technology is viable and the effort is expanding, the President and Congress would best serve our country by allocating additional resources towards finishing the job.

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