Killer Asteroids
Feasibility of Using the IRTF to Track Near-Earth Objects

by

Kaya Shah

Submitted to the Department of Earth, Atmospheric and Planetary Sciences in Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science in Earth, Atmospheric and Planetary Sciences at the Massachusetts Institute of Technology

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The possibility of an asteroid or comet impact necessitates the tracking and cataloging of all such objects which could potentially impact Earth. Currently, no comprehensive catalog of Near Earth Objects (NEOs) exists which contains information on the physical properties of the objects. Spectroscopic observation of NEOs must be carried out in an efficient and timely manner in order to determine the physical properties of NEOs for this catalog. The cumulative fractions of objects visible at certain magnitudes were examined and compared for the NEOs discovered in 2005 at discovery, those at the first quarter moon following discovery, and all known NEOs in 1, 3, 5, and 10 year forecasted surveys to determine the best combination of Infrared Telescope Facility (IRTF) instrumentation, telescope observation time, and survey length. This thesis finds that the IRTF instrumentation should be improved to at least 19.5 to spectroscopically observe 57% of the objects discovered in 2005. Furthermore, spectroscopic observation of the objects should not occur at the first quarter moon immediately after discovery, as is currently the case, because as much as ~15% of the objects discovered in 2005 cannot be observed at this time. As survey length is increased, the fraction of objects that can be observed at the IRTF's current limiting magnitude also increase; thus it is best to conduct the survey as long as possible. Additionally, spectroscopic observation of the objects should be carried out every 7 days in order to gather the most information. Lastly, it is best to spectroscopically observe the objects within 7 days of discovery because the objects are generally discovered when they are at their closest possible approach to the Earth.

Thesis Supervisor: Richard Binzel
Title: Professor of Planetary Science

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I am indebted to three people for their generous help and advice as I worked on this thesis: Professor Binzel, my academic advisor, instructor, and thesis advisor; Dr. Susan Kern, my TA for 12.410 and 12.409; and Jane Connor, my writing coach for this thesis.

First of all, I would like to thank Professor Binzel for helping me find this thesis topic as well as helping me to understand the background of the project. His help and advice in understanding my data and results were invaluable. Professor Binzel remained patient with me throughout the project—even when I mixed together results that should not have been put together. Throughout the years that I have been in the EAPS department, Professor Binzel has always helped me find the best way to think about and accomplish a goal. His help with this thesis project was certainly no exception.

Secondly, I would like to thank Dr. Susan Kern for her generous help in structuring and revising my thesis. Dr. Kern stayed late many evenings to help me look over the logic and flow of my paper and to think through many crucial concepts. I could not have presented my thesis as I did without Dr. Kern's invaluable comments. Additionally, Dr. Kern helped me to understand concepts that I was unclear on; I learned a great deal from our discussions. When she was my TA in 12.410, I remember that she often stayed past midnight with students, even though she lives about an hour away. Dr. Kern is truly a stellar instructor, and the help she has given me with this thesis is just one example of her expertise and dedication to teaching.

Third, I would like to thank Jane Connor for her help with the entire thesis-writing process. Ms. Connor has been extremely busy juggling all of the EAPS seniors' theses. Despite her packed schedule, she has always found time to help me understand the general requirements of a thesis, the process of putting everything together, and finalizing the smallest details. Furthermore, she came to campus on days when she normally does not work to meet with me at the last minute. I would not have been able to put this paper together without her knowledge and help.

Finally, I would like to thank my family and friends; I credit them with helping me make it *to* and *through* MIT.

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1. Introduction

Approximately sixty-five million years ago, scientists believe that an asteroid impact caused a mass extinction of life on Earth (Binzel, 1995). More recently, astronomers have catalogued nearly 4,000 Near Earth Objects (NEOs), and people are likewise concerned that another such impact could occur within their lifetimes. In order to address this concern, numerous groups are making observations on a regular basis to catalogue NEOs and to understand both their orbital and physical parameters. This project seeks to determine the usefulness of the Infrared Telescope Facility (IRTF) to address the later set of observations with both its current instrumentation, SpeX, and to make recommendations for improved instrumentation. It presents the scheduling requirements for such observations and the improved detection capability if the IRTF detector's sensitivity could be increased.

In Section 2, I give a summary of the scientific and political drivers for this project, in Section 3, I describe my methods, in Section 4, I describe my results, in Section 5, I draw conclusions.

2. Background

NEOs are characterized as objects with orbital perihelia less than 1.3 AU. They may have rocky or icy compositions (extinct comet) and some of them could currently or in the future be on a collision course with the Earth. If an icy body were to hit the Earth, there is a good chance that much of it could burn up in the atmosphere, whereas if the body is rocky, then the impact effect on the surface of the Earth would be much greater. While the IRTF as a facility is not designed to discover large numbers of NEOs, it is extremely useful for determining their compositions since SpeX, a spectroscopic instrument, is well suited for collecting spectra of these objects. Currently when new NEOs are discovered by surveys such as the Lincoln Near-Earth Asteroid Research (LINEAR) project (Stuart, 2001), they are tagged for compositional analysis through a joint MIT and University of Hawaii program run at the IRTF (Binzel *et al.*, 2006).

In an effort to put the importance of categorizing the orbits and compositions of these objects in context, we consider the implications of NEO impacts along with the implications of everyday threats to human life. Table 1 lists the probabilities associated with dying from various causes, where those related to NEOs are noted in bold text. Though the chance that a person will die from a large NEO impact which could possibly cause global extinction is 1 in 20,000, the upper and lower limits of NEO impacts range from 1 in 250,000 to 1 in 3,000. This range is extremely large, and the lower limit is especially troubling. Even the chance of dying from a global mass extinction is comparable to the chance of dying in an airplane crash.

Table 1. Chances of Dying From Selected Causes in the US. This table lists the probabilities of dying in the United States of America from selected causes. The lower limit asteroid or comet impact refers to smaller but more frequent impacts which can cause localized fatalities. The upper limit impact refers to more destructive but less frequent events which cause mass extinction. It is interesting to note that the probability of dying from a medium asteroid or comet impact is the same as that of dying in a passenger aircraft crash. (Chapman and Morris, 1994).

Cause of Death	**Probability**
Motor vehicle accident	1 in 100
Murder	1 in 300
Fire	1 in 800
Firearms accident	1 in 2,500
Asteroid/comet impact (lower limit)	**1 in 3,000**
Electrocution	1 in 5,000
Asteroid/comet impact	**1 in 20,000**
Passenger aircraft crash	1 in 20,000
Flood	1 in 30,000
Tornado	1 in 60,000
Venomous bite or sting	1 in 100,000
Asteroid/comet impact (upper limit)	**1 in 250,000**
Fireworks accident	1 in 1 million
Food poisoning by botulism	1 in 3 million

Additionally, Table 2 lists the consequences of impacts as a function of NEO diameter. If an object is less than one hundred meters in diameter, it poses no threat to humanity. However, if an object has a diameter between two hundred and five hundred meters, it is likely to create impacts such as tsunamis and craters which would be dangerous for local populations. Any object between one and two kilometers in diameter would be disastrous for people across the globe, and an object ten or more kilometers in diameter would result in global extinction.

Table 2. Consequences of Impacts of Increasing Size and Decreasing Frequency. This table lists five categories of impact object diameters. As object diameter increases, the energy of the impact increases as well. Moreover, the larger the impact energy, the more infrequent the event. Though an impact with a very large impact energy can cause global extinction and kill everyone, it only happens every 100 million years; thus, the average number of deaths per year from such an event is 65 (Harris 2006).

Diameter	Energy	Primary damage	Interval, years	Expected fatalities	Deaths per year
<50 m	<1 MT	None	Tens	0	0
60-100 m	10-100 MT	Air burst	1,000	25,000	25
200-500 m	1,000 MT	Crater or tsunami	10,000	2 million	200
1-2 km	100,000 MT	Global climate	2 million	1-2 billion	1,000
10 km	100 million MT	Global extinction	100 million	Everyone	65

The consequences seem even more disastrous when Table 3 is considered. This table lists some of the largest NEOs that are currently known. Three of these objects have diameters greater than ten kilometers, and would surely cause global extinction. One such scenario is depicted in Figure 1. The rest of the objects listed in the table have diameters well over two kilometers and would wipe out entire populations if they were to impact the Earth.

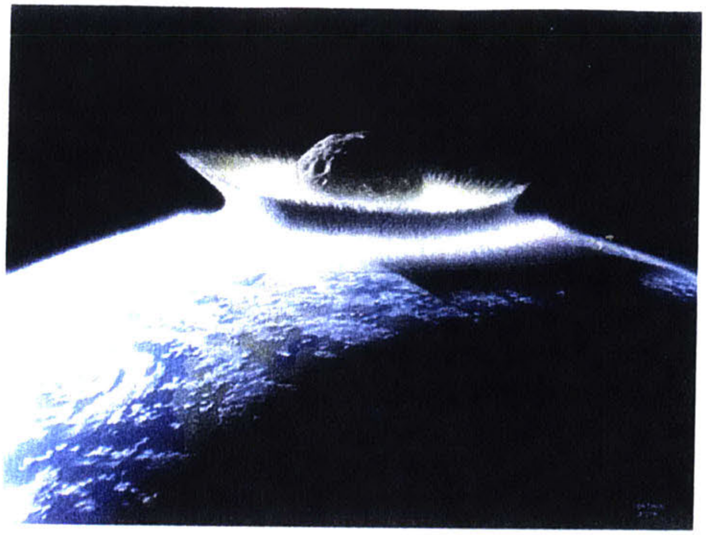

Figure 1. Rendering of a massive asteroid impact by artist Don Davis. If an asteroid were to impact the Earth, it would eject material into space and the atmosphere, cause the generation of shock waves, tsunamis, and affect the global climate (NASA Near Earth Object Program).

Table 3. The Largest Known Near-Earth Objects. This table contains a list of the currently known NEOs which have a diameter larger or equal to 8 km. Perihelion is the closest approach of the object's orbit to the sun, and all NEOs have perihelia less than 1.3 AU. The H-magnitude of an object is its absolute magnitude. In other words, the H-magnitude is the magnitude the object would appear at 1 AU from the Earth and from the sun. H-magnitude is related to object diameter by a logarithmic function (Binzel 2004).

Provisional Designation	#	Name	Diameter (km)	Peri-helion (AU)	H-magnitude (H)[a]
	1036	Ganymed	41	1.23	9.45
	433	Eros	23	1.13	11.16
1990 SQ	4954	Eric	12	1.10	12.6
1972 XA	1866	Sisyphus	8	0.87	13.0
1983 SA	3552	Don Quixote	8	1.21	13.0
1929 SH	1627	Ivar	8	0.99	13.2
1990 DA	5332		8	1.18	13.9
1990 SB	5587		8	1.08	13.6

[a] H-magnitude values (H) obtained from the Minor Planets Center. Absolute magnitude, H, and object diameter D are related in a logarithmic function: $d=10^{0.5[\log \rho-6.259-0.4H(v)]}$ where ρ is the albedo of the object in the wavelength of the absolute magnitude, the V filter in the given equation. ρ ranges from 0 to 1, for icy bodies it is generally around 0.5 or higher, for rocky bodies it is more around 0.1-0.3 and for dark bodies such as comets it is around 0.04. H(v) is the visual magnitude of the object with all geometry removed from the observations. The equations for this calculation can be found in the appendix of Bowell et al. 1989.

The task of predicting both the probabilities of impacts as well as their consequences on the Earth is daunting and spans both science and politics. Scientifically, NEOs can be tracked precisely, and their physical properties can be studied. While a number of facilities exist for spectroscopic measurements of these bodies, the IRTF is known as a facility that can do this well for bright objects and is being considered for survey status in the future. In order to optimize such a survey, the fraction of the NEOs at given magnitudes that the IRTF is sensitive to must be determined. Once this fraction is estimated, we can predict the effectiveness and scheduling requirements of the IRTF for future survey observations. Another consideration would be to upgrade the instrumentation to improve the sensitivity.

Politically, governments can address the problem of cataloguing NEOs by passing laws to mandate the actions they feel should be taken. One such law is the NASA Authorization Act of 2005, which was passed on December 22, 2005. It states that NASA should develop a survey program to detect, track, catalog, and characterize the physical characteristics of NEOs that are larger than 140 meters in diameter. Furthermore, the survey should aim to complete 90% of its catalog in fifteen years. Additionally, Congress expects NASA to put together a full report on ways to carry out the survey program by December 2006. Please see Appendix C for additional text from the NASA Authorization Act of 2005.

3. Methods

Constraints from the IRTF telescope with SpeX, ephemeris calculations from an online service, and results from a forecasting program were all utilized in order to study the 2005 NEO discoveries to make recommendations for IRTF improvement. We compare the magnitudes of the 2005 discoveries at their discovery date and at the following first quarter moon in order to determine if observing at the latter date is an effective strategy. Next, we compare the brightest magnitudes of all known NEOs in 1, 3, 5, and 10 year forecasts in order to determine how long the survey should run. Additionally, we compare magnitude changes at 3, 7, and 14 days in order to determine how often objects should be observed, and finally we compare the magnitudes of the 2005 NEO discoveries at their discovery date and the magnitudes of objects in the 10 year forecast to determine when an object should be observed relative to its discovery date. Figure 2 illustrates the analysis pipeline described in more detail in the following paragraphs.

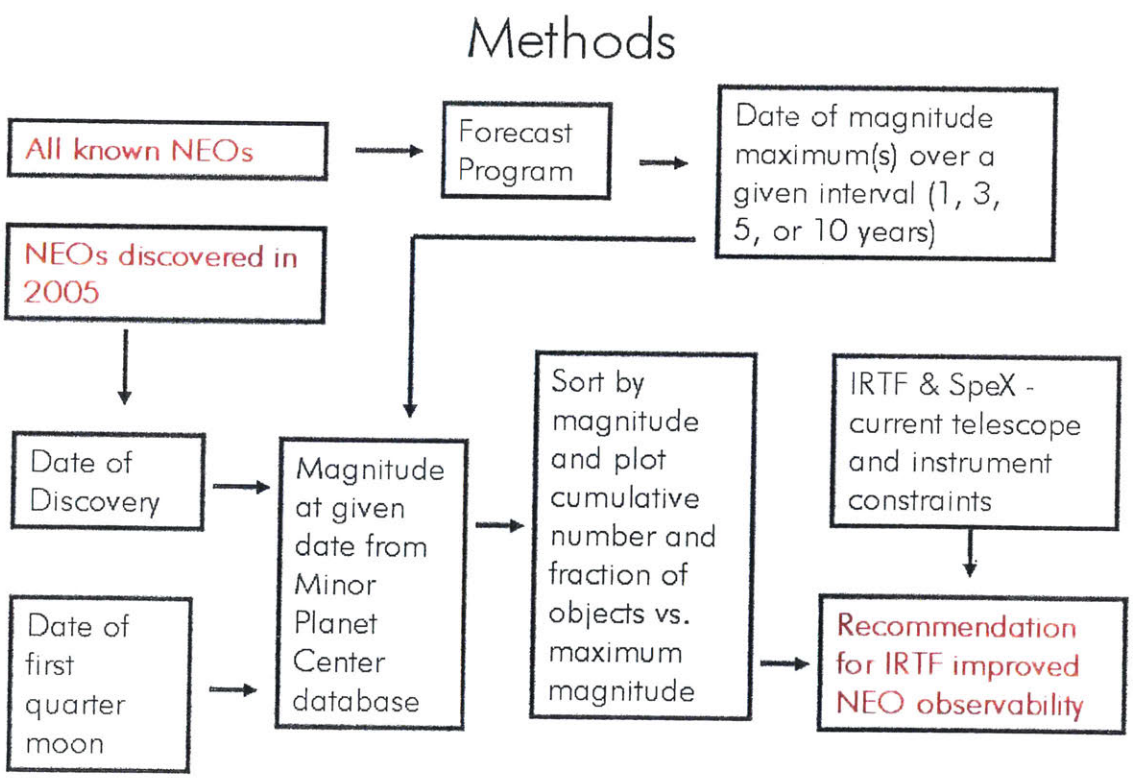

Figure 2. Methods outlined in this thesis. First of all, object magnitudes were determined at the date of discovery and at the date of the first quarter moon immediately following the discovery through use of the Minor Planet Center (MPC) database. Next, a forecasting program was utilized to calculate the dates of maximum magnitudes of a 1, 3, 5, or 10 year interval, and the MPC database was used to calculate the object magnitudes at these dates. The cumulative fraction of objects visible at certain magnitudes were then determined and compared. Constraints and requirements of the current Infrared Telescope Facility (IRTF) and its instrumentation were considered in order to make a recommendation for improving the IRTF's NEO observability.

A comprehensive catalog of NEOs should include the physical properties of each object. In order to determine whether or not a telescope and instrument combination can adequately contribute to such a catalog, the observing constraints for individual systems should be evaluated. In this paper we consider the IRTF with SpeX as one example. The IRTF is a 3.0 meter telescope located on Mauna Kea, Hawaii, and it is depicted in Figure 3. The telescope is optimized for infrared observations, and it is operated by the University of Hawaii for NASA. NASA provides operational costs, while the NSF provides funds for new instrumentation. Currently, half of all IRTF time is reserved for solar system observations. The director of the IRTF is currently looking for a survey project for the facility is willing to optimize the instrumentation in order to make it better suited for observing NEOs.

Figure 3. The Infrared Telescope Facility (IRTF) in Mauna Kea, Hawaii (IRTF Facilty Photos).

The current system, SpeX, is a 0.8-5.4 micron medium-resolution spectrograph and imager depicted in Figure 3. It provides a resolution of R~1000-2000 across 0.8-2.5 micron and 2.0-5.5 micron bands using a prism cross disperser. It utilizes a Raytheon 1024x1024 INSB array in the spectrograph with a scale of 0.12 arcseconds/pixel (Rayner et al 2003). This instrument was built specifically for the IRTF to provide simultaneous wavelength coverage at a spectral resolving power that is appropriate for planetary, stellar, and galactic features. SpeX was also built to have a resolving power that can separate sky emission lines and can disperse sky continuum. This system currently works well for spectroscopic observations of NEOs brighter than 17.5 magnitudes (d~1.5 km), but improvements could be made to optimize its effectiveness for an NEO survey.

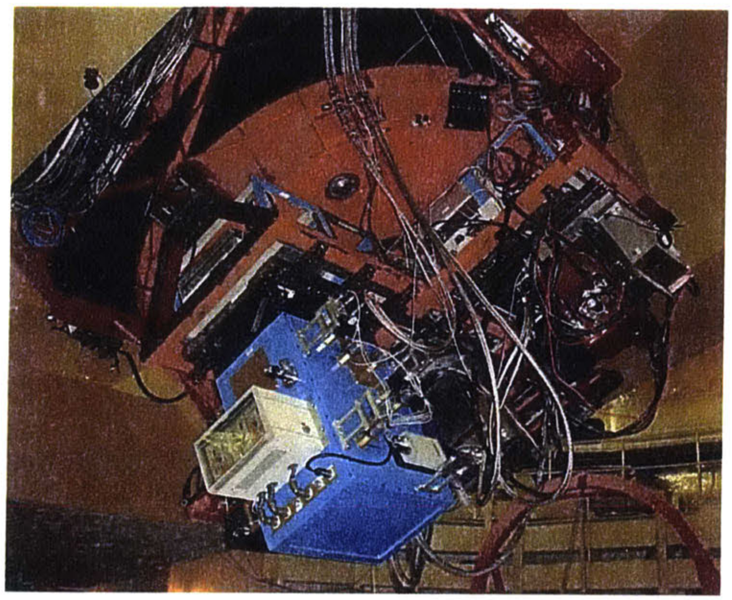

Figure 4. SpeX, the IRTF's spectrograph (IRTF Facility Photos).

In order to determine the observing ability of NEOs in the current database and to make predications for the future, the Minor Planet and Comet Ephemeris Service was utilized to obtain ephemeris calculations with the most currently updated information. The ephemeris service is provided courtesy of the IAU's Minor Planet Center (MPC). A forecast program, written by S. Slivan and R. Binzel, was used to calculate daily ephemeris and to select the date of best observing ability for all known NEOs. For any input interval, the Forecast program gives the best dates for when an object may be observed.

In order to make recommendations for improvement of the current IRTF instrumentation and observation strategies, the magnitudes of the objects discovered in 2005 were inspected. First of all, the MPC ephemeris service was utilized to determine the magnitudes of the objects at discovery. Second, the ephemeris service was utilized to determine the magnitudes of the objects at the first quarter moon immediately after each object's discovery. From these magnitudes, the cumulative fractions of objects visible at certain limiting magnitudes were taken at intervals of 0.5 between magnitudes of 15.0 and 24.0.

The fractions of the objects discovered in 2005 were then inspected in order to make recommendations for improvement of the IRTF's instrumentation and current observation strategy. In particular, the cumulative fraction of objects currently visible at magnitudes of 17.5, 19.5, and 21.5 were considered in order to determine the fraction of objects that would become visible if the limiting magnitude of the IRTF instrumentation were improved.

Furthermore, the cumulative fractions of the objects discovered in 2005 were compared to the cumulative fractions of the same objects at their first quarter moons. Most NEOs are discovered between the last quarter moon and the first quarter moon because they are easiest to discover when the moon is faintest. Currently, an object's spectral properties are measured at the first quarter moon after the object's discovery. A comparison of these cumulative fractions was conducted in order to determine if spectral observation of objects at the first quarter moon immediately after discovery is an effective strategy.

Next, forecast predictions for all known NEOs were considered in order to determine how long a cataloging survey should run. First of all, the Forecast program was used to produce the maximum magnitudes over 1, 3, 5, and 10 year spans for all the NEOs thus discovered. The brightest magnitude of each object for a given span was then determined. The cumulative fraction of objects visible at certain magnitudes were then determined at magnitude intervals of 0.5 over a range from 15.0 to 24.0. The fractions for the one, three, and five year surveys were compared in order to determine which survey would be able to observe the most number of objects.

Next, the magnitude changes of objects in the ten year survey at ±3, ±7, and ±14 days were considered in order to determine how often objects should be observed. The apparent magnitudes of each object with a discovery magnitude between 19 and 19.5 from the ten year forecast were referenced from the MPC at each of these intervals. Next, the differences between these magnitudes and the object's brightest magnitude were determined. Histograms were then plotted to compare these differences. Negative magnitude changes or magnitude changes with an absolute value greater than or equal to 1.0 were placed in the last bin. The negative magnitude changes may have occurred because the Ephemeris data changed between the first reading of the object's brightest magnitude and the reading of the magnitudes around this date. They might also have occurred because the object became unobservable as it passed behind the sun.

In order to determine when an object should be observed relative to its discovery date, the cumulative fractions of the 2005 NEO discoveries at their discovery date were compared to the cumulative fractions of objects in the 5 year forecast.

4. Results

The extent of improvement that the IRTF needs to undergo can be determined from the cumulative fractions of the objects discovered in 2005. These results are graphed in Figure 5 and a corresponding table of values can be found in the table in Appendix A.

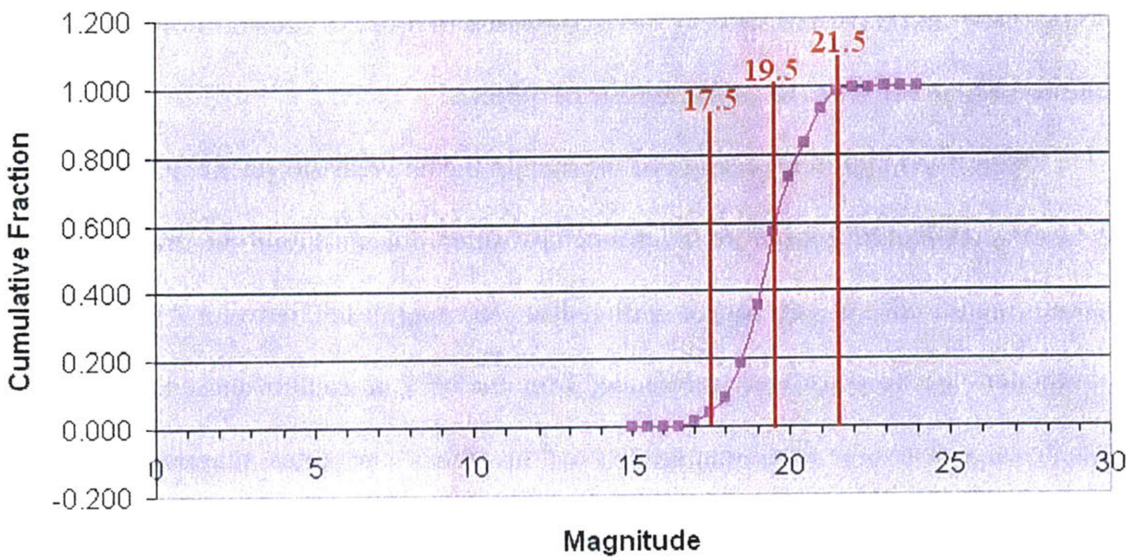

Figure 5. Cumulative fraction for NEOs discovered in 2005. This figure describes the cumulative fraction of objects visible at certain magnitudes. At the IRTF's current limiting magnitude of 17.5, ~4% of all NEOs discovered in 2005 are observable. The IRTF's limiting magnitude should be raised to an acceptable level, such as 19.5 (57% of objects observable) or 21.5 (98% of objects observable).

The magnitudes limits of interest, 17.5, 19.5, and 21.5, have been marked on the graph for reference. It is interesting to note the number of objects that could be observed at each of these limits. In particular, the IRTF with SpeX currently has a limiting magnitude of 17.5, and therefore it can detect only ~4% of all objects discovered in 2005. If it were somehow possible to increase the limiting magnitude of the instrumentation to 19.5, then

~57% of these objects would be detected. Finally, if the limiting magnitude were increased to 21.5, ~98% of these objects would be detected.

Next, the discovery magnitudes of objects discovered in 2005 were compared to the objects' magnitudes at the first quarter moon immediately after discovery in order to determine whether or not observing at first quarter moon is an effective strategy. The cumulative fractions can be found in the table in Appendix A, and the results of plotting the resulting cumulative fractions can be found in Figure 6.

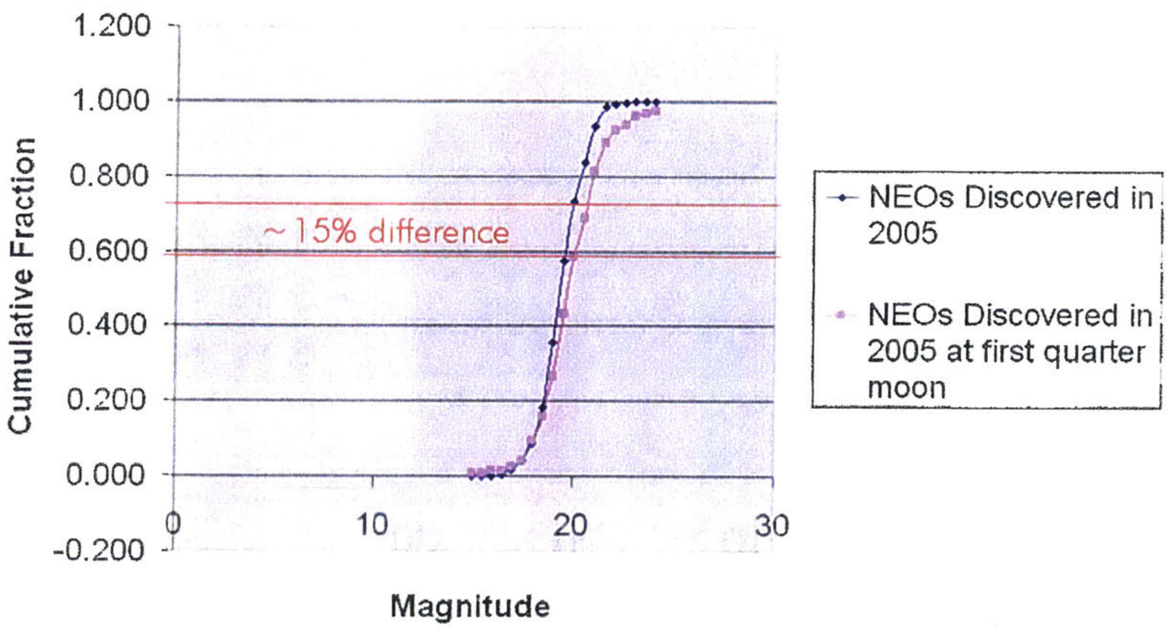

Figure 6. Cumulative Fraction of 2005 NEOs at Discovery Date and First Quarter Moon. At the first quarter moon following object discovery, fewer objects are visible. For example. at a limiting magnitude of 19.5, the IRTF would be able to spectroscopically observe ~15% fewer objects at the first quarter moon following discovery than at the discovery date. This means that spectroscopic observation of objects at first quarter moon, which is currently the case, is not an effective strategy.

Overall, the number of objects that can be observed at first quarter moon is much less than the number of objects that can be observed in the period between last and first quarter moon, when most objects are discovered. The greatest difference between the two fractions occurs at a magnitude of 19.5. However, the two curves continue to remain divergent at fainter magnitudes. At a magnitude limit of 19.5, this plot also shows that

~15% fewer objects will be observed at the first quarter moon than at the discovery date of the object. Therefore, it is best if one can observe the object closest to discovery.

In order to determine how long the survey should run, the cumulative fractions of the 1, 3, and 5 year surveys were compared. The cumulative fractions can be found in the table in Appendix A, and the results of this comparison can be found in Figure 7. As one might expect, the five year survey detected more objects than the three year survey, which in turn detected more objects than the 1 year survey. From this one would conclude that the longer a survey runs the more complete the catalog of the observations.

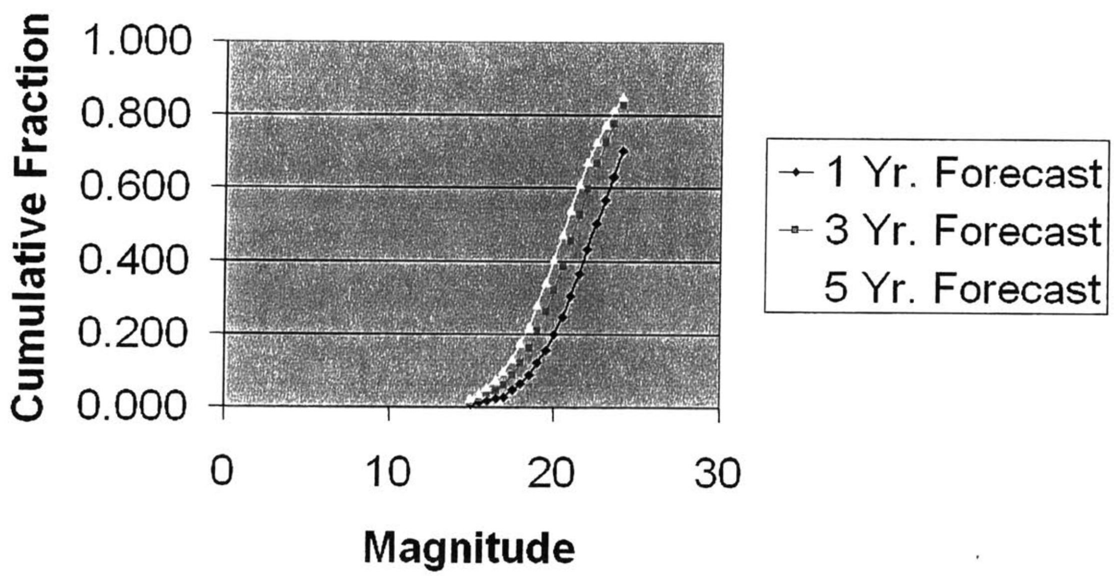

Figure 7. Cumulative Fraction of All Discovered NEOs, 2006-2011. Plotted is the cumulative fraction versus the magnitude at forecast intervals of 1, 3, and 5 years. This shows that the longer a survey operates, the greater the cumulative fraction of objects that can be observed.

To determine how often observations of NEOs should be made in order to gain the most complete spectroscopic data, the magnitude change between an object's maximum brightness and its brightness fourteen, seven, or three days in the future or past were considered.

The magnitude changes that occurred in plus or minus 14 days from the maximum brightness for NEOs between 19 and 19.5 in the ten year forecast were graphed. The results are depicted in Figure 8. The overall distribution is relatively broad and is centered at a magnitude change of 0.0. This means that over the course of plus or minus 14 days, most objects exhibited some change in magnitude. Additionally, many objects exhibited significant change in magnitude. Table B.1 in Appendix B lists the fraction of objects found within a given magnitude change for objects plus or minus 14 days from the day of their peak magnitude.

From table B.1, it appears that most objects can be accounted for within a magnitude that is plus or minus 1.0 of their peak brightness. Over 75% of all of the objects can be accounted for by a magnitude change of 0.6. As is also the case for the plus or minus seven and three day results, the largest increase in the number of objects that exhibit a magnitude change greater than 1.0 or negative can be explained by the large total number of outliers. A magnitude change of 0.3 would be considered reasonable for observing NEOs, but at this range, just over fifty percent of all objects exhibit a change within this limit. Therefore it is determined that observing an object within fourteen days of its maximum brightness would not be sufficient.

The magnitude changes that occurred in plus or minus 7 days from the maximum brightness for NEOs between 19 and 19.5 in the ten year forecast were graphed. The results are depicted in Figure 8.

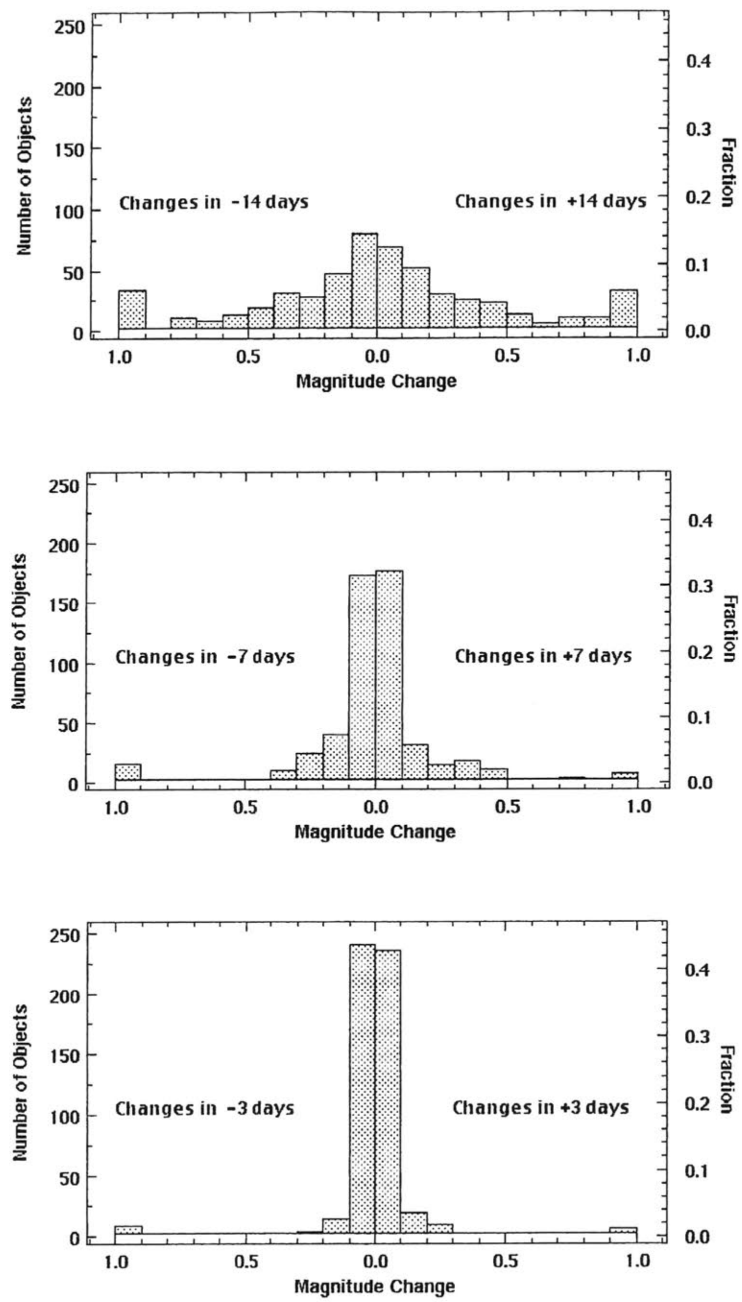

Figure 8. Magnitude changes for NEOs. All changes are referenced to the brightest magnitude the object reaches, indicated by "0.0" on the abscissa. (top) Plus or minus 14 days., (middle) plus or minus 7 days, and (bottom) plus or minus 3 days. This demonstrates that the best spectroscopic observations of objects will occur within 7 days of discovery. Furthermore, observing within 3 days of discovery is even better. In other words, spectroscopic observation of newly discovered NEOs should occur at least every seven days.

The overall distribution is also centered at a magnitude change of 0.0, but the distribution is far less broad than that for the fourteen day distribution. Though most objects exhibited some changes over the course of plus or minus seven days, few objects exhibited a significant change in magnitude. Table B.2 in Appendix B lists the fraction of objects found within a given magnitude change for objects plus or minus seven days from the day of their peak magnitude.

From the table, it appears that most objects can be accounted for within a magnitude that is plus or minus 0.8 of their peak brightness. It is significant that 60% of all objects lay within a change of 0.1, and nearly 75% of objects can be accounted for by a magnitude change of 0.2. This distribution also exhibits an increase in the number of objects due to outliers, but the increase is much smaller. A magnitude change of 0.3 would be considered reasonable for observing NEOs, and at this range, just over eighty percent of all objects exhibit a change within this limit. Therefore it is determined that observing an object within seven days of its maximum brightness would suffice for a survey of NEOs.

The magnitude changes that occurred in plus or minus three days from the maximum brightness for NEOs between 19 and 19.5 in the three year forecast were also graphed. The results are depicted in Figure 8. The overall distribution is extremely narrow compared to the seven and fourteen day distributions. Over the course of plus or minus three days, most objects exhibited very little change in magnitude; very few objects exhibited a significant change in magnitude. Table B.3 in Appendix B lists the fraction of objects found within a given magnitude change for objects plus or minus three days from the day of their peak magnitude.

From the table, it appears that most objects can be accounted for within a magnitude that is plus or minus 0.2 of their peak brightness. Over 75% of all of the objects can be accounted for just within a magnitude change of 0.1. As is also the case for the plus or minus seven and fourteen day results, the increase in the number of objects that exhibit a magnitude change greater than 1.0 or negative can be explained by the significant total number of outliers. Surprisingly, this increase is larger than that for the seven day distribution. A magnitude change of 0.3 would be considered reasonable for observing NEOs, and at this range, just over eighty-five percent of all objects exhibit a change within this limit. This percentage is greater than that for the seven day distribution by five percent. Therefore it is determined that observing an object within three days would not significantly increase the observing ability of the total number of objects.

If observation is conducted every seven nights, this means that spectroscopic observation of objects discovered in the previous week can be undertaken while the objects are still close to their brightest magnitudes. This would mean that four nights a month, or one night a week, would be the required telescope time for the survey.

In order to determine if spectroscopic observation of objects should occur immediately after discovery or can occur at any time after discovery, the cumulative fractions of the objects discovered in 2005 were compared to the cumulative fractions of the objects in the ten year survey. The results of this comparison are shown in Figure 9. The sharp difference in slopes of the two profiles suggests that many more objects would be visible immediately after discovery as opposed to at the next maximum brightness of the objects over a given period. Furthermore, from results given earlier in this paper, it becomes apparent that objects should be observed within seven days of discovery.

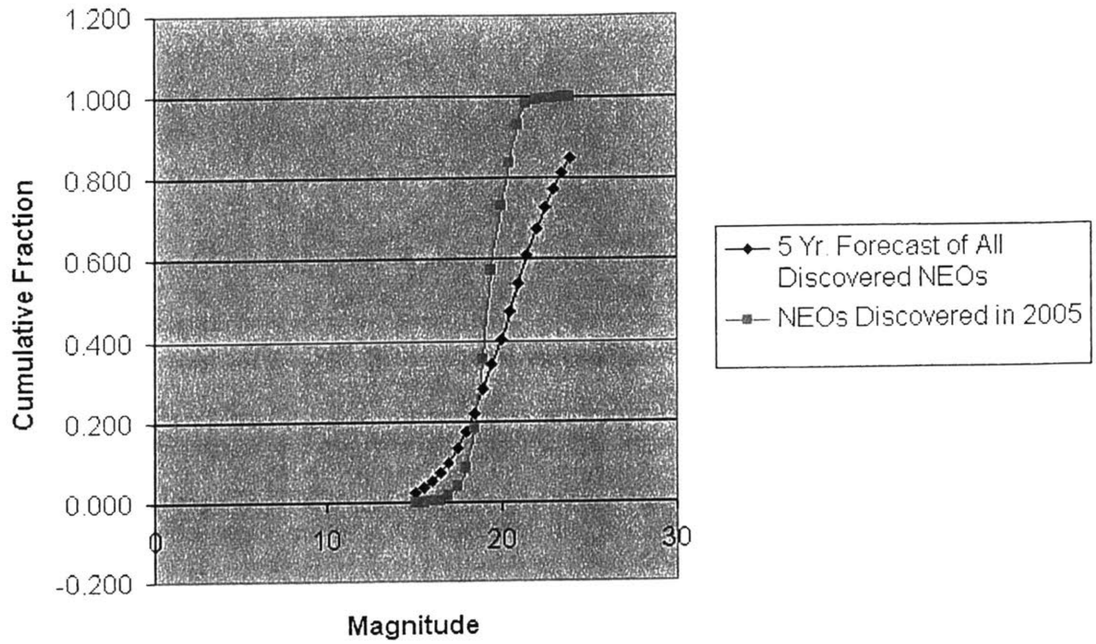

Figure 9. Cumulative Fraction Comparison, 2005 & 5 Year Forecast. This figure depicts the difference in profiles of all discovered NEOs at their maximum magnitudes in a 5 year forecast and the NEOs discovered in 2005 at their discovery dates. The difference in profiles demonstrate that IRTF observation of objects immediately after their discovery dates would result in far greater spectroscopic observability than observation at the maximum brightness in the next 5 years.

The objects should be observed immediately after discovery because objects are usually discovered when they are at their closest possible approach to the Earth. This usually occurs when the perihelia of the NEO and the Earth are aligned. After a period of time, an NEO's orbit will misalign with that of the Earth. One possible scenario is depicted in Figure 10.

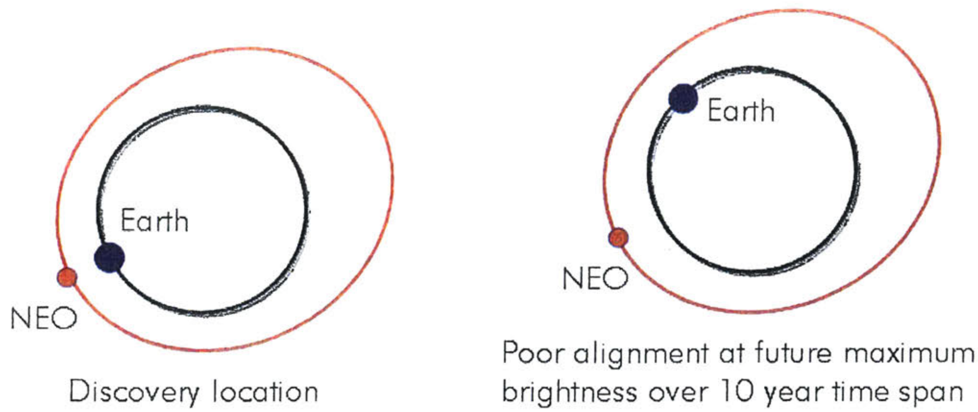

Figure 10. Possible scenarios for the location of an NEO relative to the Earth at its discovery and then later at its maximum brightness over a ten year span following discovery. This figure demonstrates how the alignment of the maximum brightness of the NEO in a given time span after discovery does not necessarily replicate the alignment of the NEO and the Earth at the discovery of the NEO. This is because NEOs are usually discovered at their closest possible approaches to Earth.

5. Analysis and Conclusions

It was the goal of this thesis to determine if the IRTF could be used to conduct an extensive NEO survey and if so, how the current IRTF instrumentation and survey strategy could be optimized.

In order to address the optimization of the IRTF's instrumentation to conduct spectroscopic observation, the NEOs discovered in 2005 were considered. At a limiting magnitude of 17.5, it was possible for the IRTF to detect approximately 4% of all objects discovered in 2005. If the IRTF's limiting magnitude were increased to 19.5, approximately 57% of these objects would be detected. Furthermore, if it were possible to increase the limiting magnitude of the IRTF to 21.5, approximately 98% of these objects would be detected. From these results, it can be concluded that the IRTF's limiting magnitude must be improved to at least 19.5 for it to be useful to detect the NEOs already discovered in 2005. An increase in limiting magnitude to 21.5 would be even better.

Further, the cumulative fractions of the 2005 discoveries and their magnitudes at the first quarter moon immediately after discovery, the cumulative fractions of 1, 3, 5, and 10 year surveys, the magnitude changes over a ten year span, and a comparison of the cumulative fractions of the 2005 discoveries and 5 year survey were consulted in order to make recommendations for IRTF observing time. Because the IRTF is used to observe objects between last quarter moon and first quarter moon for most of the studies, it is important to determine if time at the end of this period can be allotted to the NEO survey, as is currently the case. Over all, fewer objects can be observed at the first quarter moon following discover than at the actual discovery time. Additionally, the greatest difference between the two surveys is approximately 15%, which is a large difference. Thus, observing at first quarter moon would not be acceptable. From the cumulative fractions of the one, three, and five year surveys, it is apparent that more objects can be detected for a longer survey length. It is projected that a ten year survey would provide even more observing ability, and for this reason it would be best to conduct a ten year survey of NEOs. From the relative distributions of magnitude change for plus or minus three, seven, and fourteen days, it seems that a large gain is obtained by observing an object within seven days, as opposed to fourteen days, of its maximum brightness. However, there is little gain, as compared to the seven day distribution, from observing the object within three days. For these reasons, it is concluded that the IRTF can be used to detect NEOs every seven days. In comparing the cumulative fractions for the NEOs discovered in 2005 and the objects in the ten year survey, it is clear that many more objects can be observed immediately after discovery. This result means that greater spectroscopic observation will occur immediately after discovery as opposed to some later magnitude maximum in a given time frame.

To conclude, the result of this project was to determine that the IRTF instrumentation should be improved to have a limiting magnitude of at least 19.5. Furthermore, objects should be observed within seven days immediately after discovery and not at the first quarter moon following discovery, as was previously the case. Additionally, the survey should run as long as possible in order to observe the greatest number of objects.

Appendix A

Table 4. Cumulative fractions at certain magnitudes. This table gives the cumulative fractions of objects at certain magnitudes for the NEOs discovered in 2005 at discovery, the NEOs discovered in 2005 at first quarter moon, all known NEOs during a 1 year forecast, all known NEOs during a 3 year forecast, all known NEOs during a 5 year forecast, and all known NEOs during a 10 year forecast. The reference magnitudes used in this thesis are marked in bold. The current limiting magnitude of the IRTF is 17.5, but the IRTF limiting magnitude should be improved to 19.5 or 21.5 (Binzel 2005).

	Magnitudes									
	15	15.5	16	16.5	17	**17.5**	18	18.5	19	**19.5**
NEOs Discovered in 2005 at Discovery	0.000	0.000	0.002	0.003	0.017	**0.041**	0.086	0.184	0.355	**0.574**
NEOs Discovered in 2005 at First Quarter Moon	0.006	0.008	0.013	0.014	0.024	**0.043**	0.093	0.158	0.266	**0.434**
1 Year Forecast of All Known NEOs	0.008	0.012	0.018	0.022	0.028	**0.047**	0.065	0.089	0.120	**0.157**
3 Year Forecast of All Known NEOs	0.015	0.022	0.036	0.045	0.061	**0.089**	0.122	0.161	0.208	**0.261**
5 Year Forecast of All Known NEOs	0.025	0.037	0.054	0.073	0.097	**0.132**	0.175	0.221	0.280	**0.342**
10 Year Forecast of All Known NEOs	0.008	0.012	0.021	0.029	0.038	**0.058**	0.080	0.106	0.140	**0.182**

	Magnitudes								
	20	20.5	21	**21.5**	22	22.5	23	23.5	24
NEOs Discovered in 2005 at Discovery	0.733	0.836	0.933	**0.984**	0.994	0.995	0.998	1.000	1.000
NEOs Discovered in 2005 at First Quarter Moon	0.584	0.687	0.812	**0.888**	0.925	0.939	0.960	0.968	0.976
1 Year Forecast of All Known NEOs	0.198	0.247	0.303	**0.366**	0.432	0.504	0.566	0.633	0.703
3 Year Forecast of All Known NEOs	0.320	0.385	0.455	**0.527**	0.598	0.668	0.725	0.778	0.826
5 Year Forecast of All Known NEOs	0.404	0.472	0.539	**0.610**	0.673	0.727	0.773	0.814	0.852
10 Year Forecast of All Known NEOs	0.225	0.275	0.338	**0.402**	0.472	0.545	0.605	0.668	0.730

Appendix B

Fraction of Objects Within Each Magnitude Change, Plus or Minus 14 Days		
Magnitude Change	Number of Objects	Fraction of Objects
0.1	151	0.274
0.2	244	0.442
0.3	303	0.549
0.4	356	0.645
0.5	403	0.730
0.6	429	0.777
0.7	448	0.812
0.8	463	0.839
0.9	476	0.862
1.0	489	0.886
>1.0 or negative	552	1.000

Table B.1. Objects within certain magnitude changes at plus or minus fourteen days from their maximum brightness. This table shows that the cumulative fraction of objects spectroscopically observable within a reasonable magnitude change, 0.3, is ~55%. Thus it is determined that observing the object 14 days before or after discovery is unacceptable.

Fraction of Objects as a Function of Magnitude Change, Plus or Minus 7 Days		
Magnitude Change	Number of Objects	Fraction of Objects
0.1	331	0.600
0.2	406	0.736
0.3	444	0.804
0.4	468	0.848
0.5	483	0.875
0.6	486	0.880
0.7	492	0.891
0.8	497	0.900
0.9	501	0.908
1	504	0.913
>1.0 or negative	552	1.000

Table B.2. Objects within certain magnitude changes at plus or minus 7 days from their maximum brightness. This table shows that the cumulative fraction of objects spectroscopically observable within a reasonable magnitude change, 0.3, is ~80%. Thus it is determined that observing the object 7 days before or after discovery is acceptable.

Fraction of Objects as a Function of Magnitude Change, Plus or Minus 3 Days		
Magnitude Change	Number of Objects	Fraction of Objects
0.1	425	0.769
0.2	458	0.828
0.3	472	0.854
0.4	476	0.861
0.5	478	0.864
0.6	480	0.868
0.7	481	0.870
0.8	481	0.870
0.9	481	0.870
1	484	0.875
>1.0 or negative	553	1.000

Table B.3. Objects within certain magnitude changes at plus or minus 3 days from their maximum brightness. This table shows that the cumulative fraction of objects spectroscopically observable within a reasonable magnitude change, 0.3, is ~85%. Thus it is determined that observing the object 3 days before or after discovery is acceptable. However, because there is only a 5% difference between the percentage of objects observable at 3 days as opposed to 7 days before or after discovery, observing at plus or minus 7 days is acceptable.

Appendix C

The following text became law as part of the NASA Authorization Act of 2005 passed by the Congress on December 22, 2005, and subsequently signed by the President. The following text became law as part of the NASA Authorization Act of 2005 passed by the Congress on December 22, 2005, and subsequently signed by the President.

> The U.S. Congress has declared that the general welfare and security of the United States require that the unique competence of NASA be directed to detecting, tracking, cataloguing, and characterizing near-Earth asteroids and comets in order to provide warning and mitigation of the potential hazard of such near-Earth objects to the Earth.
>
> The NASA Administrator shall plan, develop, and implement a Near-Earth Object Survey program to detect, track, catalogue, and characterize the physical characteristics of near-Earth objects equal to or greater than 140 meters in diameter in order to assess the threat of such near-Earth objects to the Earth. It shall be the goal of the Survey program to achieve 90% completion of its near-Earth object catalogue (based on statistically predicted populations of near-Earth objects) within 15 years after the date of enactment of this Act.
>
> The NASA Administrator shall transmit to Congress not later than 1 year after the date of enactment of this Act an initial report that provides the following:
> (A) An analysis of possible alternatives that NASA may employ to carry out the Survey program, including ground-based and space-based alternatives with technical descriptions.
> (B) A recommended option and proposed budget to carry out the Survey program pursuant to the recommended option.
> (C) Analysis of possible alternatives that NASA could employ to divert an object on a likely collision course with Earth.

(Sec. 321. George E. Brown, Jr. Near-Earth Object Survey, 2005)

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