2008

ASTEROID THREATS: A CALL FOR GLOBAL RESPONSE

A report on the need to develop an international decision-making program for global response to Near Earth Object threats. Submitted for consideration and subsequent action by the United Nations, its goal is to assist the international community in preventing loss of life and property resulting from an asteroid impact on Earth.

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Association of Space Explorers International Panel on Asteroid Threat Mitigation

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Executive Summary

Earth's geological and biological history is punctuated by evidence of repeated and devastating impacts from space. Sixty-five million years ago, an asteroid impact caused the extinction of the dinosaurs along with some 70% of Earth's living species. A more typical recent impact was the 1908 Tunguska Event, a 3-5 megaton explosion which destroyed 2,000 square kilometers of Siberian forest.

A future asteroid collision could have disastrous effects on our interconnected human society. The blast, fires, and atmospheric dust produced could cause the collapse of regional agriculture, leading to widespread famine. Ocean impacts like the Eltanin event (2.5 million years ago) produce tsunamis which devastate continental coastlines. Asteroid 99942 Apophis, which has a 1-in-45,000 chance of striking Earth in 2036, would generate a 500-megaton (MT) blast and inflict enormous damage.

Devastating impacts are clearly infrequent events compared to a human lifetime: Tunguska, thought to be caused by the impact of a 45-meter-wide asteroid, is an event that occurs on average two or three times every thousand years. However, when Near Earth Object (NEO) impacts occur they can cause terrible destruction, dwarfing that caused by more familiar natural disasters.

Advances in observing technology will lead to the detection of over 500,000 NEOs over the next 15 years. Of those several dozen will pose an uncomfortably high risk of striking Earth and inflicting local or regional devastation.

The Need for a Global Response

Faced with such a threat, we are far from helpless. Astronomers today can detect a high proportion of Near Earth Objects and predict potential collisions with the Earth. Evacuation and mitigation plans can be prepared to cope with an unavoidable impact. For the first time in our planet's 4.5-billion-year history, the technical capacities exist to prevent such cosmic collisions with Earth. The keys to a successful outcome in all cases are preparation, planning, and timely decision-making.

Efforts to deflect a NEO will temporarily put different populations and regions at risk in the process of eliminating the risk to all. Questions arise regarding the authorization and responsibility to act, liability, and financial implications. These considerations make it inevitable that the international community, through the United Nations and its appropriate organs, will be called upon to make decisions on whether or not to deflect a NEO, and how to direct a proposed deflection campaign. Because of the substantial lead time required for a deflection, decisions will have to be taken before it is certain that an impact will occur. Such decisions may have to be made as much as ten times more often than the occurrence of actual impacts.

Existing space technology makes possible the successful deflection of the vast majority of hazardous NEOs. However, once a threatening object is discovered, maximizing the time to make use of that technology will be equally important. Failure to put in place an adequate and effective decision-making mechanism increases the risk that the international community will temporize in the face of such a threat. Such a delay will reduce the time available for mounting a deflection campaign. Therefore, timely adoption of a decision-making program is essential to enabling effective action.

Within 10-15 years, the United Nations, through its appropriate organs, will face decisions about whether and how to act to prevent a threatened impact. To counter a threat of global dimension, information-sharing and communications capabilities must be harnessed to identify and warn society of hazardous NEOs. To prevent an actual impact, an international decision-making program, including necessary institutional requirements, must be agreed upon and implemented within the framework of the United Nations.

This report, prepared by the Association of Space Explorers and its International Panel on Asteroid Threat Mitigation, proposes the following program for action:

Proposed Program for Action

Because NEO impacts represent a global, long-term threat to the collective welfare of humanity, an international program and set of preparatory measures for action should be established. Once in place, these measures should enable the global community to identify a specific impact threat and decide on effective prevention or disaster responses.

A global, coordinated response by the United Nations to the NEO impact hazard should ensure that three logical, necessary functions are performed:

1. Information Gathering, Analysis, and Warning

   An Information, Analysis, and Warning Network should be established. This network would operate a global system of ground- and/or space-based telescopes to detect and track potentially hazardous NEOs. The network, using existing or new research institutions, should analyze NEO orbits to identify potential impacts. The network should also establish criteria for issuing NEO impact warnings.

2. Mission Planning and Operations

   A Mission Planning and Operations "Group," drawing on the expertise of the spacefaring nations, should be established and mandated to outline the most likely options for NEO deflection missions. This group should assess the current, global capacity to deflect a hazardous NEO by gathering necessary NEO information, identifying required technologies, and surveying the NEO-related capabilities of interested space agencies. In response to a specific warning, the group should use these mission plans to prepare for a deflection campaign to prevent the threatened impact.

3. Mission Authorization and Oversight Group

   The United Nations should exercise oversight of the above functions through an intergovernmental Mission Authorization and Oversight "Group." This group would develop the policies and guidelines that represent the international will to respond to the global impact hazard. The Mission Authorization and Oversight Group should establish impact risk thresholds and criteria to determine when to execute a NEO deflection campaign. The Mission Authorization and Oversight Group would submit recommendations to the United Nations Security Council for appropriate action.

The Association of Space Explorers and its international Panel on Asteroid Threat Mitigation are confident that with a program for concerted action in place, the international community can prevent most future impacts. The Association of Space Explorers and its international Panel are firmly convinced that if the international community fails to adopt an effective, internationally mandated program, society will likely suffer the effects of some future cosmic disaster—intensified by the knowledge that loss of life, economic devastation, and long-lasting societal disruption could have been prevented. Scientific knowledge and existing international institutions, if harnessed today, offer society the means to avoid such a catastrophe. We cannot afford to shirk that responsibility.

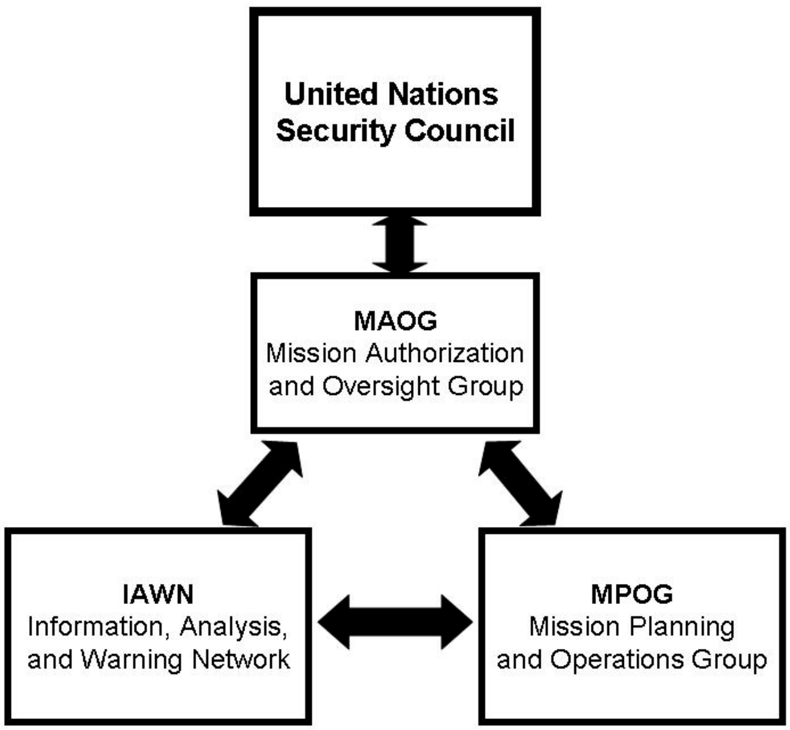

Figure 1. NEO Decision-making Functions

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Figure 2. Barringer Meteor Crater, Arizona, USA (1.2 km diameter)

Foreword

In 2005, the Association of Space Explorers (ASE) recognized the global nature of the asteroid impact hazard. It noted that future impacts from a Near Earth Object can occur anywhere on Earth, and the response requires the political will and technical capabilities to deflect a hazardous asteroid using the contributed expertise of all interested nations. Subsequently, the ASE formed a Near Earth Object (NEO) committee to consider the challenge of future asteroid impacts. Through its observer status on the United Nations' Committee on the Peaceful Uses of Outer Space (UN-COPUOS), the ASE developed a plan to draft a document on a NEO decision-making process. It was agreed that the document be submitted for consideration and subsequent action through the United Nations' relevant organizations.

The ASE assembled its international Panel on Asteroid Threat Mitigation, enlisting volunteer experts in science, diplomacy, law, and disaster management from around the world. That Panel, through the ASE, has over the past three years continually advised the UN-COPUOS Action Team 14 (NEO) about its work. The Action Team, aware of this progress in the drafting of decision-making procedures to respond to asteroid threats, has agreed to accept the report of the ASE's international Panel for further consideration and action.

This document, then, conveys the findings of the international Panel on Asteroid Threat Mitigation, established by the ASE, to the appropriate United Nations organs and programs. Its submittal begins the process of developing a global response to existing and future asteroid threats.

I. Introduction

The Association of Space Explorers and its international Panel on Asteroid Threat Mitigation submits this document, *Asteroid Threats: A Call for Global Response*, for consideration and necessary action by the United Nations on behalf of the international community, comprised of all the nations on Earth. The document's purpose is to urge the global community to establish necessary institutional decision-making capacities to prevent an asteroid impact with Earth.

International NEO decision-making should take the following factors into consideration:

- Damage caused by asteroids and other Near Earth Objects might affect the entire international community and/or major parts of the world. A truly global response is required.
- Capabilities (unevenly spread among the international community) are available to humankind to undertake responsive action against NEO threats, especially if the appropriate decisions are made sufficiently in advance.
- The discovery rate of NEOs posing a potential threat will increase significantly within the next 10-15 years.
- Because a substantial lead time is usually required to execute an asteroid deflection operation, the international community may have to act before it would be certain an impact would occur.
- Efforts to deflect a NEO could cause a temporary shift in the impact site from one populated region of the planet to another.
- Delays in decisions to undertake responsive actions will limit the relevant options. Such delays will increase the risk that the remaining options may cause undesirable political consequences or even physical impact damage.

For these reasons, the Association of Space Explorers and its international Panel on Asteroid Threat Mitigation consider it necessary that a decision-making program for global action in response to asteroid threats should be developed at the earliest opportunity. Such a program requires high level acceptance by the international community as a whole. Accordingly, the ASE and its international Panel on Asteroid Threat Mitigation believe that the United Nations is the most appropriate forum to begin addressing and implementing such a decision-making program.

II. Dealing with the Impact Hazard

II.1 The Impact Hazard

Our planet's geological and biological history is punctuated by evidence of repeated, devastating cosmic impacts. Since its formation 4.5 billion years ago, Earth has absorbed repeated impacts from asteroids and comets. These remnants of solar system formation delivered to Earth the water and organic materials which created a favorable environment for life. But as life emerged and developed here, cosmic impacts continued, sometimes with effects devastating enough to shift the course of evolution. Today, our complex and interdependent society is more vulnerable than ever to catastrophic disruption by a major impact.

Our planet orbits the Sun amid a swarm of hundreds of thousands of inner solar system objects capable of causing destruction on Earth. They range in size from 45-meter Tunguska-like objects to the extremely rare 10-kilometer objects which can cause a catastrophic mass extinction.

The Cretaceous-Tertiary (K-T) Extinction, 65 million years ago, was probably triggered by the impact of a 12-kilometer-diameter asteroid in what is now the Yucatan Peninsula of Mexico. The planet-wide effects of Chicxulub eliminated about 70% of all living species, including the dinosaurs.

Tons of cosmic material fall on the Earth every day, but nearly all disintegrates and burns during passage through the atmosphere. However, when objects larger than approximately 45 meters in diameter strike, the atmosphere cannot fully screen us. Even NEOs[1] which do not make it all the way to the ground can cause destruction through the production of a damaging fireball and shock wave. The most famous example occurred in 1908, when 2,000 square kilometers of Siberian forest were destroyed by a multi-megaton impact called the Tunguska Event (see Figure 3). When larger objects make it through the atmosphere and strike Earth's surface, they produce an explosion and crater.

Figure 3. Tunguska impact damage to forest

[1] The total of near-Earth asteroids and near-Earth comets. NEAs comprise the vast majority of all NEOs.

The human species has always been vulnerable to this cosmic impact process, which has often altered the course of life on Earth. But the advanced telescopes and technology available today provide us with the necessary early warning and deflection capabilities to prevent these infrequent but terribly devastating natural disasters. We need no longer remain passive victims of the impact process.

II.2 The Coming Wave of NEO Discoveries

As of late 2008, we know of approximately 5,600 Near Earth Objects, and some 967 of those are known as Potentially Hazardous Asteroids: objects 150 m or larger which come within 0.05 astronomical units (about 7.5 million km) of Earth. Current United States law directs the National Aeronautics and Space Administration (NASA) by 2020 to discover, track, catalog and characterize 90% of all near-Earth objects over 140 m in diameter. Advanced telescopes planned for operation within the next 5-7 years will greatly increase our ability to find more and smaller NEOs. Over the next 10-15 years, the NEO discovery[2] rate will increase dramatically.

Based on what we know about the statistics of the NEO population, search programs over the next 15 years will add to the NEO database[3] 200,000 to 400,000 potential impactors large enough to do substantial damage to Earth. Approximately 6,000 of these objects will have a “non-zero” probability of impacting Earth within the next 100 years. Generally these “non-zero” probabilities are very small, typically one in several hundred thousand or less, but it is likely that hundreds will have impact probabilities that are worrisome. Dozens of NEOs will likely be threatening enough that they will require a proactive decision about whether to take action to prevent an impact.

II.3 Impact Warning Scenarios and Reaction Time

The physical and orbital characteristics of near-Earth objects, the capabilities of the early warning systems, and the performance of deflection alternatives are presented in greater detail in the appendices of this document.

In describing these impact scenarios, we emphasize that of all the near-Earth asteroids discovered, only a very small fraction (3% or so) possess even a small possibility of impacting Earth in the next century. Of this small fraction, most will cease to be a threat[4] entirely once we obtain multiple tracking "apparitions"[5] for each NEO and better determine its orbit. Still, we must search for the rare case of an ultimately threatening NEO, for only by discovering it can we prevent or minimize what may be a disaster of unprecedented magnitude.

[2] A NEO discovery is the initial sighting of a NEO which, to be officially recorded, must be independently confirmed.
[3] The NEO database contains the orbital parameters of all NEOs discovered and tracked to date.
[4] The potential for a near-Earth object to impact Earth. NEO threats range from a few megatons of TNT-equivalent explosive energy up to infrequent, but devastating, impacts with millions of tons of TNT explosive energy.
[5] A period of time during which a NEO is visible to telescopes. NEOs are discovered on their first apparition, pass out of sight, and are seen again at second apparition.

Near Term Potential Impacts (Mitigation[6])

Asteroid impacts occur on both the daylight and night sides of the Earth in roughly equal numbers. While there are exceptions, asteroids impacting on the sunlit hemisphere appear to approach the Earth from the direction of the Sun, while those impacting at night appear to approach from the anti-Sun direction. As a result, while ground-based optical telescopes can observe the approach of night impactors, they cannot (due to solar glare), be used to detect and track those close to impact on the day side.

From the daylight hemisphere, NEO detection and tracking are restricted to radar telescopes[7], which are insensitive to the bright sky. Furthermore, while optical telescopes can detect and track the smallest NEOs of concern from 1 to 6 months before impact, radar systems with their limited range can only "see" objects this size within 3 to 6 days of impact, provided the operators know precisely where to look.

Thus, for an impactor approaching from the sunlit side, there will be a maximum of 3-6 days of warning time for the evacuation of a potentially large target zone. Even that minimal warning would be available only for those asteroids detected on a previous close pass by the Earth; that earlier tracking would provide us with the predicted impact time and direction of approach necessary for aiming our radar telescopes. Because radar observatories have small fields of view and cannot view the entire sky, an undetected asteroid approaching Earth from the daylight side will give us little or no warning.

For NEOs approaching from Earth's night side (about 50% of the cases), the situation is slightly better. Optical telescopes should detect both known asteroids and those not in our database a month or more prior to impact. This should be true even for the smallest (and most numerous) asteroids of concern. For those previously discovered NEOs headed for nighttime impact, a fairly precise impact point can be determined when they are first optically recovered a month or more pre-impact.

For "new" asteroids (those on their first apparition), astronomers cannot determine the specific impact point until a few weeks prior to impact, or perhaps until they come within radar range, 3-6 days from Earth. Although we can issue a general alert for the target region (perhaps 1,000 km across), we may not be able to give the precise impact point until a few days prior to the collision.

Long Term Potential Impacts (Deflection)

To discover and track near-Earth asteroids early enough to obtain accurate orbits and predict any possible impacts far in advance, a dedicated NEO search program is necessary. With good, early orbit knowledge, we can initiate a deflection campaign and avert an impact. This outcome, while entirely feasible, is highly dependent on possessing all three elements of an effective NEO defense, namely:

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[6] Generally, any action reducing the consequences of a threatened NEO impact. It usually refers to those actions short of physical deflection of a NEO (e.g. evacuation).

[7] A radio telescope which has the capability of active radio transmission, used to obtain precision tracking of NEOs. Radar tracking complements optical tracking and, when available, can significantly improve predictions of NEO orbits.

1. The early warning system must discover and track the entire cohort of sizeable near-Earth asteroids (approximately 500,000 objects) and establish accurate orbits for them a minimum of 15-20 years prior to any predicted impact.
2. Spacecraft deflection systems should be designed and tested in demonstration missions that validate and provide confidence in their capability.
3. The international community must be prepared to decide on a deflection campaign in a timely manner.

Failing to provide a decision-making framework before a threatening NEO is discovered will result in lengthy argument, protracted delays, and collective paralysis. Such delays will preclude a deflection and force the world to absorb a damaging – albeit preventable – impact. With the lead time for a decision typically needed at least 10-15 years ahead of a potential impact, we should now begin to forge that vital decision-making capacity.

II.4 Impact Prevention and Decision Frequency

There are many more small asteroids than large ones. Most asteroid impacts are caused by the smallest NEOs. Earth will be struck by a 40-meter diameter object (about the minimum size that will cause surface damage) will impact Earth every 700 years, on average.

If damaging impacts occur an average of only once every 700 years, why should the international community deal urgently with this issue? The simple answer is that far more NEOs will *appear* to pose a threat to Earth than will actually strike it. In many instances, we won't know with certainty if an impact will occur until after it is too late to prevent the collision—whether it actually occurs or not. As a result, the decision to deflect an incoming NEO will often have to be taken when the probability of impact is 1 in 10, or even 1 in 100. For example, if the actual impact rate is 1 per 700 years, but the decision to act must be taken when the probability of impact reaches 1 in 70 (about 1.5%), then the average frequency of decision-making is once every 10 years. Over the next 10-15 years, then, the process of discovering NEOs will likely identify dozens of new objects threatening enough that they will require proactive decisions by the United Nations.

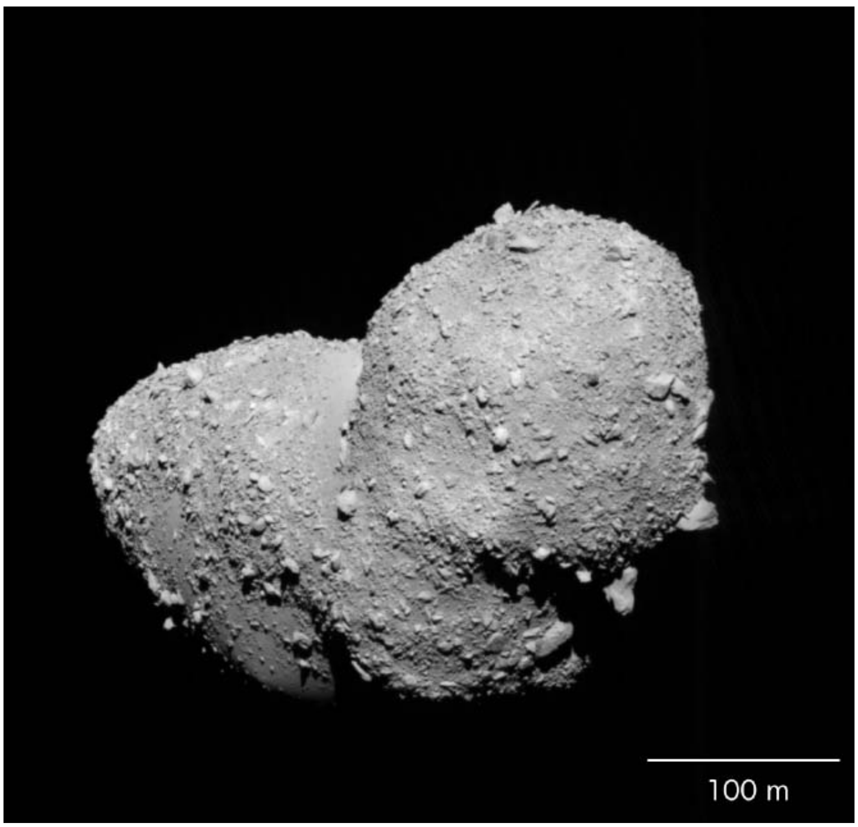

Figure 4. NEO 25143 Itokawa (500 m in diameter) imaged by Hayabusa spacecraft (2005).

III. Toward a Decision-Making Program for Asteroid Threats

Humankind possesses the first two of the elements necessary for impact prevention: search telescopes and a proven spaceflight technology. **The missing third element is the readiness and determination of the international community to establish decision-making capacities.** This commitment to trigger timely action must be embodied in the form of a coordinated, pre-established international NEO decision-making process.

This process must include deflection criteria and campaign plans which the international community can implement rapidly and with little debate. In the absence of an agreement on a decision-making process, we may lose the opportunity to act against a NEO in time, leaving evacuation and disaster management as our only response to a pending impact. A single such missed opportunity will add painful fault-finding to the devastating physical effects of an impact. The international community must begin work now on forging all three impact prevention elements (warning, deflection technology, and a decision-making process) into an effective defense against a future collision.

The purpose of this document is to initiate a process at the United Nations level leading to the establishment of a decision-making framework for prevention of an asteroid impact. The framework should include an agreed-upon set of criteria, policies, and responsibilities, which can be applied without delay in the case of a specific asteroid threat.

The rationale for such a pre-established, international set of decision-making criteria on NEO deflection and mitigation stems from a combination of: (1) the uncertainty in the specific impact point at the time a deflection decision must be made (i.e., the potential impact zone may extend entirely across one hemisphere of the Earth), and; (2) orbital mechanics considerations which dictate that action to deflect an asteroid will temporarily raise the risk to other regions and populations in the process of eliminating the risk for all.

This temporary shift in risk from one region and population to another during NEO deflection will include a choice as to which nations will face that heightened risk. Plainly, with a NEO impact and its proposed deflection affecting people and nations across the face of the planet, the decision criteria, policies, and practices must be determined by international agreement.

There is a strong derived benefit in having the international community grapple with these issues now, in the brief period before the incidence of specific NEO threats increases. Once a potential NEO threat arises, with a particular risk corridor[8] and/or identified impact point, the discussions concerning deflection actions, and which nations should bear the temporary increase in risk during the campaign, will inevitably become more political and difficult. We make our recommendations for the decision-making process on the basis of the value of human life and property, independent of national political power or influence. It is critical that the decision-making process be thoroughly deliberated and agreed upon prior to the advent of a specific threat.

[8] A virtual locus of points, unique to each NEO, within which a NEO may impact the Earth. Although extending across the entire planet, the corridor is often only a few tens of kilometers wide. Physical effects of the impact may extend well beyond the corridor. Also see Appendix II.3.

That process should begin now and reach a conclusion at the earliest possible time. Based on this reasoning, the ASE and its international Panel on Asteroid Threat Mitigation have submitted the present report for consideration and decision by the intergovernmental processes of the United Nations.

IV. Recommendations on a Decision-Making Program for a Global Response to Asteroid Threats

The need for a NEO decision-making program leads the Association of Space Explorers and its international Panel on Asteroid Threat Mitigation to make the following recommendations to the international community, represented by the United Nations.

Recognizing that Near Earth Object impacts represent a global, long-term threat to our collective welfare, we recommend that international preparations, under the umbrella of the United Nations, are the only way our society can identify a specific impact threat and decide on effective prevention or disaster response measures.

A global, coordinated response by the United Nations to the NEO impact hazard should ensure that three logical, necessary functions are performed (see Figure 5):

1. An Information, Analysis, and Warning Network should be established. This network would operate a global system of ground- and/or space-based telescopes to detect and track potentially hazardous NEOs. The network, using existing or new research institutions, should analyze NEO orbits to identify potential impacts. The network should establish criteria for issuing NEO impact warnings.

   Information, analysis, and warning encompass a logical flow of information beginning with basic telescopic observations of NEOs, both new and known, and progressing through orbit analyses enabling, in rare but critical cases, a hierarchy of warnings of an impending NEO threat.

2. A Mission Planning and Operations "Group," drawing on the expertise of the spacefaring nations, should be established and mandated to outline the most likely options for NEO deflection missions. This group should assess the current, global capacity to deflect a hazardous NEO by gathering necessary NEO information, identifying required technologies, and surveying the NEO-related capabilities of interested space agencies. In response to a specific warning, the group should use these mission plans to prepare for a deflection campaign to prevent the threatened impact.

   Whenever the probability of a NEO impact is high enough, and the projected impact is sufficiently far in the future, the international community should initiate preparations for a deflection campaign. Alternative mission designs, specific information needs, and coordination among the spacefaring nations (SFN) must proceed in an orderly way to achieve a deflection capability. This group should develop a set of coordinated threat responses (e.g. planning for threat verification missions) as well as plans for full deflection campaigns.

3. The United Nations should exercise oversight of the above functions through an intergovernmental Mission Authorization and Oversight "Group." This group would develop the policies and guidelines that represent the international will to respond to the global impact hazard. The Mission Authorization and Oversight Group should

establish impact risk thresholds and criteria to determine when to execute a NEO deflection campaign. The Mission Authorization and Oversight Group would submit recommendations to the United Nations Security Council for appropriate action.

The above functions encompass a myriad of judgments, criteria, thresholds and policies which ultimately should represent the collective will of the international community in responding to the global threat of NEO impacts.

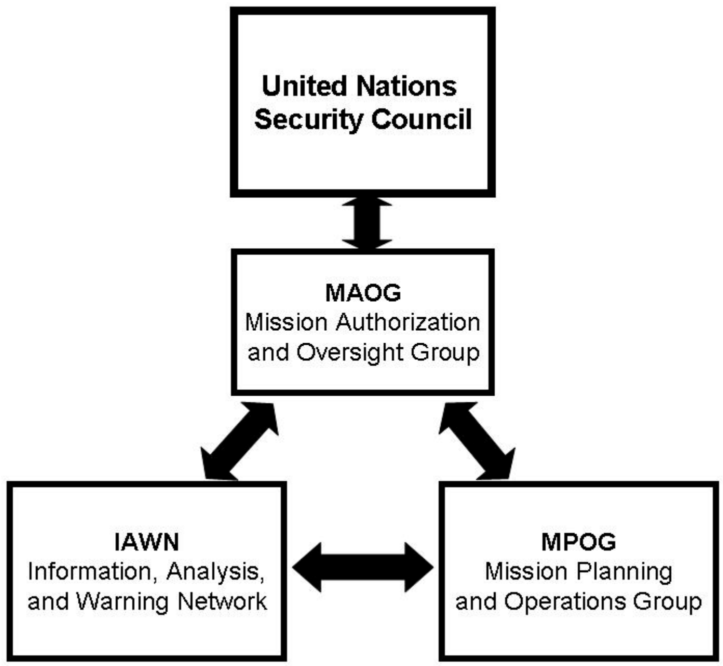

Figure 5. NEO Decision-making Functions

To safeguard humankind from future NEO impact threats, the United Nations, with its existing framework for international cooperation and decision-making, offers the best path toward implementing recommendations 1 through 3.

The following sections expand upon and describe in greater detail the group responsibilities summarized above. Greater detail and technical background for many of the issues addressed are contained within the report’s technical appendices.

V. Implementation of the Recommendations

V.1. Information, Analysis, and Warning Network (IAWN)

Recommendation 1 calls for establishment of an Information, Analysis, and Warning Network (IAWN). At the highest level, the responsibilities of such a network would be to:

a) Serve as the official source of information on the NEO environment.

There is today an international, informal, functional information system on NEOs. The information flow begins with the basic telescopic sightings of NEOs which are reported via the internet to a data clearinghouse, designation, and orbit determination center. From there, via open publication on the internet, information flows to two analytic centers which project NEO orbits into the future to forecast potential impacts. Institutions participating in this chain of information development include academic institutions, international scientific organizations, and government agencies. While the day-to-day performance of this informal structure is generally excellent, there is no overarching direction, nor is there a common or reliable funding source. Indeed the system functions well only because of the dedication and sense of purpose shared by the individuals and institutions involved.

The most integrated element of the current information system is the U.S. NEO Program run by NASA. Approximately $4 million/year is spent in support of the NEO discovery, tracking and cataloging system, popularly known as the Spaceguard Survey[9]. Four institutionally separate NEO discovery teams are each partially funded by NASA to conduct nightly sky surveys with the goal of discovering new NEOs and improving the accuracy of the orbits of known NEOs. Additional international NEO discovery efforts are underway in Korea, Japan, China, and Italy.

Each of these observational teams, and many amateur observers as well, report their nightly data collections to the Minor Planet Center (MPC) at the Harvard Smithsonian Center for Astrophysics in Cambridge, Massachusetts (USA). The MPC is primarily funded by NASA, with minor contributions from private sources. The MPC is largely self-directed, albeit some guidance is provided by the International Astronomical Union (IAU).

When the MPC NEO data are updated and made available on a daily basis, NASA/JPL's[10] Sentry and the University of Pisa's NEODyS[11] systems project the future trajectory of each of the NEOs in the database (now just over 5,600). To

[9] The informal name of the NEO discovery and tracking program that the U.S. Congress has directed NASA to perform. The initial Spaceguard goal (1998) was to discover by 2008, 90% of all NEOs larger than 1 kilometer in diameter. The recently revised goal directs NASA to discover, by 2020, 90% of all NEOs larger than 140 meters in diameter.

[10] JPL (Jet Propulsion Laboratory): The NASA center in Pasadena, California responsible for the design and operation of many planetary missions and for managing NASA's NEO Program.

[11] NEO Dynamic System: The University of Pisa's analytic office which analyzes and publishes information (including impact prediction) on all discovered NEOs. NEODyS performs a function similar to that done by NASA's JPL.

determine the possibility of impacts for 100 years into the future, each of these two analysis centers uses similar, but slightly different software. Each NEO with any possibility of an impact is listed in a risk table and for each potential impact (for some NEOs there are hundreds of specific impact possibilities), an impact probability[12] is determined and published on the web.[13]

While this semi-formal information system has functioned quite well to date, elements of it are stretched close to their capacity, and sources of funding are not secure. Critical questions therefore confront the international community when the likelihood of potential NEO threats emerging over the next 10-20 years is considered:

1) Should resolution be provided between any differing impact probability estimates of JPL, NEODyS, and other future NEO tracking entities?
2) Should there be an "official" single risk table and impact solutions database or are differences between the existing and future analytical centers acceptable?
3) How can the NEO data centers be provided a stable funding source? If funded by the United Nations, do national entities, and IAU (for the Minor Planet Center) retain control?

b) Designate and maintain the official clearinghouse for all NEO observations and impact analysis results.

A coordinated international response to perceived NEO threats suggests a single official source of information is desirable. Yet there are currently two primary sources of impact prediction and other national or academic sources may appear in the future.

Moreover, the basic observational data is collected worldwide and reported daily to the MPC, which is both financially insecure and capacity-limited. Given the anticipated increase in the volume of NEO data generated in the future, there is a serious question as to whether the MPC will be able to fulfill the clearinghouse role.

The IAWN should recommend solutions consistent with the international community's need to both speak with a single, authoritative voice and make critical decisions. Where such solutions raise fundamental policy issues the recommendations should be directed to the MAOG (see Section V.3). Recommendations should be based on scientific research, and developed and validated to ensure enabling systems are available to the international community.

[12] The probability that a specific NEO will actually impact Earth on a particular date. The astronomical community analyzes the orbit of each NEO for potential impact within the next century and assigns an impact probability, which is updated following each subsequent sighting of the NEO.
[13] JPL Near Earth Object Program, http://neo.jpl.nasa.gov.

Specifically, the IAWN should address the following questions:

1) Should an official NEO information source be created, serving as the sole basis on which the international community makes appropriate NEO threat decisions?
2) Alternatively, should the international community (IAWN? MAOG?) designate an existing national or non-national system as the official information source for NEO decision-making?
3) Should there be a single public "voice" of the international community for NEO threat information, providing unambiguous understanding of the status of NEO threats?
4) If the international community is to rely on independent national or non-national sources of information (e.g. NASA's JPL or Univ. of Pisa's NEODyS), is there an obligation to ensure that these sources of information are maintained on a firm financial basis? What form should such assurances take?

c) Review the existing NEO information set provided by JPL/Sentry and NEODyS and recommend possible modifications to them.

The current information sets contained within the NEODyS and JPL/Sentry systems were designed to inform the NEO community of the discovery, tracking, impact probability, and other NEO characteristics.

Data requirements for mitigation and/or deflection of threatening NEOs have not yet been systematically investigated or analyzed because currently, there is no institutional assignment of NEO responsibility beyond the "early warning process." Yet, it is clear that much critical information needed for understanding the timing of deflection decisions, total impulse requirements vs. deflection date, keyhole (see Appendix II.2.) passages between discovery and potential impact, and other mission planning requirements provided by the IAWN to the MPOG. Issues raising policy questions should be called to the attention of the MAOG along with any recommendations for improving the data sets.

Specifically, the IAWN should address the following issues:

1) Determination of the latest possible date for a deflection decision. For each NEO's potential impact date there is a corresponding final (latest possible) decision date for a successful deflection effort. Beyond this date, it is too late to accomplish the necessary actions leading to a successful deflection. If this date passes without a deflection decision, the only remaining option is to "take the hit."

2) Does a potentially hazardous NEO have an attractive close gravitational encounter with the Earth or other major body? Is there a much less challenging deflection opportunity provided by causing the NEO to miss a keyhole passage?

3) If so, what is the corresponding latest decision date for initiating a deflection campaign (see Appendix II.1) prior to this keyhole passage? What are the deflection requirements? (For Apophis with a potential keyhole passage in 2029, the decision date is ~2020.)

4) If a threatening NEO is headed for a keyhole passage prior to impact, are ground tracking capabilities alone sufficient to provide adequate information on which to base a deflection campaign decision? In the case of Apophis, the answer to this (based on NASA/JPL/Chesley) is no. A transponder mission would have to be initiated in 2013 if optical tracking shows the NEO remained a threat.

5) For each decision date (latest date for deflection initiation) there is a figure of merit characterizing the quality of the information available for decision-making. Below what quality threshold should a transponder mission be launched to obtain more precise tracking?

6) If it is too late (beyond the decision date) for a successful deflection, would better tracking rule out the potential impact?

d) Recommend policies to the MAOG regarding criteria for warning and, with MOAG approval, issue NEO warnings and "all-clear" notices.

While there are technical risk scales in use, criteria are needed for issuance of specific NEO warnings, alerts, or notices. The IAWN should work with established United Nations programs to develop a warning/alerting system for both NEO mitigation and deflection scenarios. Since this subject involves the global public, the IAWN should bring some key issues to the MAOG for consideration and resolution.

An example of such an issue is deciding what NEO minimum characteristics (size, mass, and energy) constitute a threat to Earth. Recent analysis at Sandia Laboratory appears to show that the 1908 Tunguska Event in Siberia was caused by the impact of a NEO of approximately 45 meters in diameter, having an explosive energy of 3-5 megatons of TNT. While the only known damage from this impact was the destruction of approximately 2,000 square kilometers of Siberian forest, the blast would have leveled a modern city (see Figure 6).

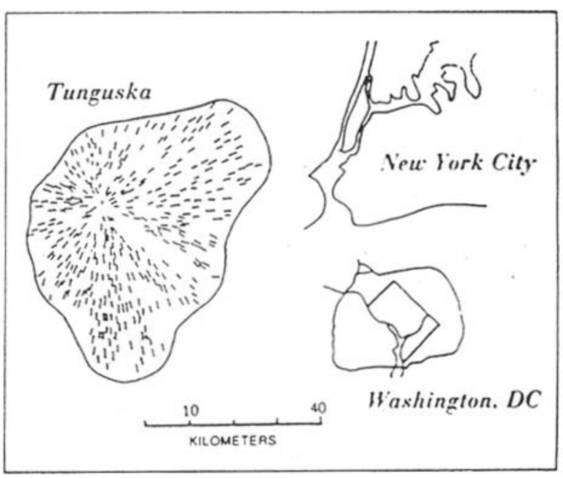

Figure 6. Tunguska in Perspective (Art courtesy of John Pike)

It has been suggested that a NEO of about this size or explosive energy might be considered the minimum NEO threat with which the international community should be concerned. NEOs below this threshold would then be allowed to impact without formal action (warnings would be issued as appropriate). Clearly, such a threshold definition is a matter of broad interest and to the IAWN, MAOG, and the public.

For objects above the minimum NEO threshold, mitigation and deflection operations will require that the IAWN define a number of specific alerts and warnings to provide timely notice for actions to protect life and property. The IAWN should coordinate with both mitigation experts and the MPOG to develop the appropriate warning requirements.

A notification system for issuing alerts and warnings should also be defined by the IAWN, in consultation with both MPOG and MAOG. Given the powerful impact such information will have on public perception and response, this issue deserves careful consideration. Ambiguous alerts, warnings, and "all-clears" must be avoided. The international community should designate a single authoritative voice to minimize anxiety, misunderstanding, and panic.

The IAWN should address the following questions:

1) Should the international community establish and/or designate a single entity to issue, update and clear all NEO alerts and warnings? If not, how are differences in perception or analysis to be resolved to support coordinated action and unambiguous information flow to the public?
2) Should the international community establish and/or designate a single entity for distributing NEO information to the public and media?

e) Consider and recommend to the MAOG a NEO threat public information policy, and explore what threshold should trigger release of information like the risk corridor, potential tsunami simulations, and other potential impact information.

Each potentially hazardous NEO's tracking history generates a broad set of descriptive information, including potential impact dates, impact probability, impact energy, and other technical details. JPL and NEODyS both publish this information in real-time on their websites.

The tracking data can furnish additional information more meaningful to the general public and the mitigation planning community, but it is not currently produced or published. Examples include the specific NEO impact risk corridor (see Appendix II.3) or the potential tsunami characteristics from an oceanic impact. Other derivable information useful to the mitigation planning and response communities, and to the general public, also exist.

The risk corridor (see Apophis example) is the locus of all potential impact points for a particular NEO, defining a narrow band stretching across the Earth. Once a significant tracking arc is obtained for a NEO, the set of potential impact sites is surprisingly well known. On a globe, the risk corridor extends slightly more than 180 degrees across the Earth's surface, and is only a few tens of kilometers wide.

Those countries and peoples crossed by the NEO risk corridor are subject to a potential impact. Over oceans, the radius of potential destruction extends considerably further from the centerline of the corridor due to coupling of impact energy into tsunamis. Along with the NEO's impact probability, the risk corridor provides immediately understandable information regarding the nature and bounds of the potential danger. Today, while the numeric data underlying the risk corridor is openly published, no one converts it into graphic form. Its value is so clear that making it available would be useful as advance notification to those institutions responsible for disaster planning and mitigation.

Because NEOs appear and are then subsequently eliminated from the risk tables, producing a detailed analysis and graphic presentation for each potentially hazardous object would be burdensome to the NEO analytic community (and of negligible value for mitigation planners). Therefore, the IAWN should work closely with designated national/international disaster response entities to define some criteria defining when such detailed NEO impact information should be developed and published. Publication too early will be burdensome and viewed as frivolous; . publishing too late will tend to cause panic.

f) Identify in cooperation with United Nations Member States a focal point to engage designated national/international disaster response entities.

If a specific NEO deflection is impossible, planning for evacuation or other mitigation actions must be considered. These preparations should utilize existing public and civil society disaster management capabilities. To this end, each Member State of the United Nations should identify a contact person to be informed about the status of the NEO threat. Each State should follow the process within the United Nations International Strategy for Disaster Reductions: Platform for the Promotion of Early Warning.[14]

g) Assist in mitigation response planning.

The IAWN should assist national/regional disaster management entities to develop a comprehensive NEO mitigation response plan, tailored to the unique characteristics of a potential NEO impact. The plan should capitalize on the existing structures and capabilities of disaster management and response systems among the United Nations Member States.

Because of the general lack of familiarity with the NEO threat, education, training and communication are critical elements of this plan. The potential magnitude of NEO impact disasters, the low frequency of and consequent lack of experience associated with impacts -- even the frequency of “all-clears” -- underline the importance of education.

[14] United Nations Inter-Agency Secretariat of the International Strategy for Disaster Reduction.
*United Nations/ISDR) Platform for the Promotion of Early Warning.

h) In cooperation with the Mission Planning and Operations Group, recommend to the Mission Authorization and Oversight Group the criteria for initiating the planning of a deflection campaign.

A decision to deflect a threatening NEO must be based on policy criteria established and agreed upon by the international community. The establishment of such criteria, dependent on detailed technical analysis (involving evaluation of launch capacity, total impulse and other deflection capability requirements) must be done cooperatively between the IAWN and the MPOG.

A successful NEO deflection must be completed well in advance of the anticipated impact. The particular lead time required will depend on a host of NEO physical and orbital characteristics and on the deflection capacity available to the spacefaring nations.

To complete a NEO deflection in time, deflection campaign preparations (see Appendix II.1) must be initiated years earlier. The total time, extending from the decision itself through design, assembly, testing, launch, rendezvous and execution of the deflection techniques may total 7-10 years or more.

For some long-period NEOs with (orbital periods of 2-4 years or more),the limiting space capability will be travel time to the asteroid rather than the actual deflection process. These NEOs may require mission design techniques, such as gravity assist fly-bys, in order to reach the asteroid. While these powerful techniques enhance mission performance, they usually come at the expense of adding, several years of flight time to the mission. The decision on when to act in the case of a long-period NEO is a difficult one, because in many cases, our knowledge of where or whether the NEO will impact is imprecise.

The MPOG must provide to the IAWN the timing requirements for the necessary mission planning and operations to enable the latter to define the decision date and complete their analytic work in time for a deflection decision.

For many potential NEO impacts, by the decision time we will know with certainty whether the Earth will be struck.. In many other cases we will not posses such certainty at the critical decision time. In those situations, the international community will face the decision to mount a costly deflection campaign while still uncertain that an actual impact will occur (an impact probability of 1 in 10, or lower). Taking no action, alternatively, means risking a future impact with no options but evacuation and disaster mitigation measures. For a given decision time, the IAWN must determine the level of confidence in tracking information needed to support the decision process.

That quality evaluation is determined by the object's tracking history, its specific orbital characteristics, and the precision of tracking telescopes, radars and other remote sensing systems. With sufficient time and better tracking systems, the quality of information will be high enough by decision time to enable clear-cut decisions. However, in many threatening NEO situations, ground-based tracking will be insufficient to permit an easy deflection decision. A transponder mission to the NEO may be justified to resolve the tracking uncertainties in time to enable a clear and timely deflection decision.

Many such factors must be explored and analyzed by the IAWN to establish a decision timeline for each potential NEO impact, one sufficiently precise to enable the international community to prevent a disastrous NEO impact.

i) Develop and recommend to the MAOG the threshold NEO characteristics that warrant international community attention.

A threshold set at 40 meters in diameter (~3 MT of explosive energy), implies that below this threshold no action will be taken; i.e. we'll "take the hit."

Impacting objects ranging from millimeters in size up to approximately 40 meters in diameter do not cause any damage on the ground due to screening provided by our atmosphere. Impacting objects with diameters of 100 meters or more cause considerable damage at the Earth's surface. The former should clearly be ignored by the international community; the latter must be dealt with responsibly. What defines the boundary between these two classes? The 1908 Tunguska Event, probably caused by a small asteroid approximately 45 meters in diameter with an impact energy of 3-5 megatons of TNT, might represent such a threshold.

In September 2007, an asteroid just one meter in diameter entered over Peru and struck the Earth's surface, resulting in a small impact crater about 14 meters in diameter. This event is quite puzzling to NEO experts in that such a small, rocky object was thought never to reach the Earth's surface with cosmic velocity (instead it would be slowed significantly by the atmosphere). This anomalous event will inform scientific analysis of what energy or diameter threshold will allow us to safely ignore an incoming NEO.

j) Develop and recommend to the MAOG a NEO impact public information plan.

Transparency in the development and handling of information associated with the global NEO threat is essential if the international community is to retain the confidence of the public.

With transparency, however, comes a proliferation of independent "experts" and unofficial analysts, all with predictions, warnings, and alarms. The IAWN should anticipate this development and counter it with the integrity, thoroughness, and openness of the official NEO information system. The international community must speak with a single voice, yet be responsive to reasonable questions and critiques from independent experts. The IAWN's public information plan should include NEO status update criteria, dissemination means, and a question-handling procedure.

V.2. Mission Planning and Operations Group (MPOG)

Recommendation 2 calls for the establishment of a Mission Planning and Operations Group (MPOG). The high-level responsibilities of such a Group would be to:

a) Determine specific decision and event timelines for all NEOs selected for preliminary deflection campaign analysis.

   Once a NEO exceeds the threshold that triggers initial deflection planning, the MPOG should begin development of a critical event timeline, working backward from the impact time to the decision date (the latest date by which a decision to deflect can be made and still achieve successful deflection). The timeline is a logical and necessary sequence of steps that must be taken to perform the NEO deflection.

   The first phase is the engineering sequence, from decision through mission design, manufacture, testing, and launch of the vehicle (or vehicles) involved in the deflection campaign.

   The second phase of the deflection campaign timeline is derived from the orbital characteristics of the target NEO and the total impulse required to execute a successful deflection. A key factor in this planning phase is the choice of deflection direction: whether to deflect the NEO ahead of or behind the Earth (increasing or decreasing the NEO's velocity). The time required to rendezvous with or intercept the NEO is strongly dependent on the deflection direction.

   The third phase is the time between the deflection maneuver and Earth impact. This phase must be long enough for the maneuver to displace the deflected NEO in its orbit enough and achieve the desired miss distance.

   Several components affecting the overall timeline will be part of the trade-space, including: the particular launch vehicle capability available, the NEO orbit, the deflection concept, total impulse available, and the desired miss distance chosen. Understanding the trade-offs and their cost and policy implications is essential to provide an accurate decision date (deflections attempted after the decision date are by definition unsuccessful).

b) Develop and recommend to the MAOG a process for assigning operational responsibility for a deflection campaign.

   The MPOG will develop and recommend to the MAOG a process for planning and managing a deflection campaign, drawing on the expertise of the spacefaring nations. The MPOG should consider both the planning and execution phases of the operation.

c) Evaluate and recommend to the MAOG alternative deflection concepts proposed by spacefaring nations (SFNs).

A campaign to deflect a NEO from an impact with Earth requires at least two coordinated space missions. The first is a rendezvous mission, utilizing a spacecraft capable of operating in close proximity with the NEO. Tracking of its radio transponder yields a precise NEO orbit and determines the likelihood of an Earth impact.

If a future direct impact is confirmed by the observer spacecraft, a second spacecraft would be deployed, capable of applying to the NEO a total impulse sufficient to avert an impact. Two deflection concepts are currently available to accomplish this primary deflection. A kinetic impact (KI) mission is one in which an intercepting spacecraft crashes into the NEO in a precise manner, changing its velocity enough to cause it to miss the Earth. Alternatively, a stand-off nuclear explosion mission can be employed: the intercepting spacecraft passes closely behind or ahead of the NEO and detonates its nuclear device at the point of closest approach. Explosive vaporization of the NEO surface facing the detonation will push the NEO in the opposite direction, causing it to miss Earth.

The KI and other non-nuclear concepts can provide sufficient total impulse to deflect the vast majority of possible NEOs from an impact. In the exceptional instance of a NEO greater than about 400 meters diameter, or in the equally rare case of a very late deflection attempt, the KI capability not provide sufficient total impulse. However, the frequency of NEO collisions where kinetic impact cannot accomplish deflection is low: approximately once every 100,000 years.

In more than 98% of projected collisions, a combination of kinetic impact and a precision impulse (e.g., a gravity tractor) will be sufficient to eliminate the threat. The effectiveness of the KI approach was demonstrated conceptually during the 2005 Deep Impact mission, when a robot probe deliberately rammed comet Tempel 1.

d) Develop the necessary information requirements for mission planning, and transmit them to the IAWN.

Planning a NEO deflection mission requires detailed knowledge of the factors critical to establishing a deflection timeline. These critical factors include both pre- and post-deflection timing issues, the anticipated NEO tracking opportunities, and the resultant uncertainty in NEO impact point.

Preceding any deflection maneuver is a sequence of events beginning with the deflection decision and ending with the successful application of the required NEO velocity change to guarantee a miss. While each situation will be unique, representative times for this mission execution interval may range between 7 and 10 years or more.

Any deflection effort must allow adequate time between the deflection encounter and the predicted impact for the necessary NEO displacement along its orbit to occur. In most instances of a direct impact, this time interval will be a decade or more. For certain keyhole impacts, however, this interval may be as short as 2 years.

Combining the deployment and deflection intervals yields a total time for the deflection campaign, the decision date for a successful deflection Delaying a deflection decision beyond this date either negates the possibility of a deflection or requires the use of a deflection technique with greater total impulse (to reduce the deflection interval). The shift to a new technique increases mission cost. Because, with current technology, the nuclear stand-off technique will deliver the greatest total impulse, any delay in the decision to deflect will drive the choice of deflection technology toward that option. If decision delays make the kinetic impact technique impractical, the choices remaining will be two: either utilize a nuclear stand-off explosion, or prepare for the NEO impact (i.e. “take the hit).

Although an early deflection decision will reduce many of the timing and cost challenges, it must grapple with increased uncertainty regarding the true impact probability. When a possibility of Earth impact is first detected, the probability of impact is always very small. Longer tracking of the NEO causes the probability to drop to zero, or, rarely, shows an increasing probability of impact. In the latter case, when a decision to deflect must be made, uncertainty will still remain as to precisely where the NEO will impact, or even if an impact will occur at all.

The MPOG should propose to the MAOG a decision logic which clearly identifies deflection timing constraints, addressing these relevant variables and their implications for cost, risk, and public policy.

e) Develop cost models for each approved deflection campaign concept, including each planning and mission operations event.

To support the international community in deciding between a full deflection campaign or a transponder mission, the MPOG should develop cost models for these operations. Because instantaneous force deflection alternatives (e.g KI or stand-off explosion) have a wide range of total impulse potential, and because delay will necessitate increasing the requirement for total impulse, the monetary implications of a decision delay must be clearly understood.

Conversely, early employment of a transponder-equipped mission applying a continuous force to the NEO may offer attractive cost-savings. Tracking from such a mission may provide early differentiation between a close approach and a future impact. The MPOG should make the cost models for precision threat determination missions available to the international community.

V.3. NEO Mission Authorization and Oversight Group (MAOG)

Recommendation 3 calls for the establishment and tasking of a Mission Authorization and Oversight Group (MAOG). The high-level responsibilities of such a group would be to:

a) Develop a policy to fund those United Nations Member States who conduct authorized NEO activities on behalf of the international community. Submit final recommendations on such a funding policy to the United Nations Security Council for adoption and implementation.

> In dealing with NEO threats, the use of specific national assets, such as space hardware and technical manpower, will be required. Using such assets (e.g., observational, computational, analytic, and management capabilities) will reduce the risk to people and property irrespective of national borders. However, knowledge of the specific geographic impact location will not be available In most cases until long after deflection expenditures have been made.
>
> Given the real cost of the described deflection activities, the ASE and it s international Panel recommend that the international community share the economic cost of bringing the most capable resources in the world to bear against the NEO hazard.

b) Consider and propose for adoption, by the appropriate United Nations organs, threshold criteria submitted by the IAWN concerning NEO alerts, warnings and actions .

c) Consider and decide those general policy questions presented and/or recommended by the MPOG.

> Numerous threshold limits must be identified and analyzed to address NEO threat mitigation and deflection preparations .
>
> For example, NEOs smaller than a meter in diameter (which strike Earth several times per year) pose no danger due to the protection provided by the atmosphere. However, NEOs 200 meters or larger cause substantial damage when they impact the Earth.
>
> Between these two obvious cases lies a threshold, yet to be defined, specifying a size or impact energy that triggers action by the international community. This threshold is of considerable import given the more numerous ,smaller, NEOs and the cost of searching, tracking and cataloging, the NEO population above this damage threshold.
>
> Another example of a critical policy decision confronting the the MAOG is deflection targeting. Conceptually the deflection of a threatening NEO means moving or dragging the nominal impact point from its pre-deflection location and across Earth's surface until it is the "impact point" is a safe distance in front of or behind the Earth.
>
> An unsuccessful deflection will shift the original NEO impact point from its original location and leave it at a new location along the risk corridor Hence, any deflection

attempt will shift risk temporarily from one region or population to another before the risk for everyone goes to zero. For a specific NEO threat, the MOAG must choose in which direction this risk shift will move.

The MOAG's choice must clearly be made on the basis of objective risk consideration to various populations, deflection campaign success probabilities, and the costs involved.

Using recommendations from the IAWN and the MPOG, the MOAG should establish policy for dealing with this and other difficult NEO issues.

d) Sit ex-officio on all IAWN and MPOG sessions.

Given the complexity and consequence to the global community of decisions for rotecting the Earth from NEO impacts, the ASE and its international Panel recommended that the MAOG sit ex-officio during deliberations of the IAWN and the MPOG, as the latter address those issues having clear policy implications.

VI. Conclusion

As previously pointed out, humankind now possesses the technology to provide the first two essential elements necessary to protect the planet from asteroid impacts. Early impact warning is already underway for the largest objects of concern and new telescopes will soon increase the capability to provide impact warning for more numerous smaller objects of concern. Asteroid deflection capability, while not yet proven, is possible with current spaceflight technology and is being actively investigated by several of the world's space agencies.

The missing third element is the readiness and determination of the international community to take concerted action in response to a perceived threat to the planet.

An adequate global action program must include deflection criteria and campaign plans which, can be implemented rapidly and with little debate by the international community. In the absence of an agreed-upon decision-making process, we may lose the opportunity to act against a NEO in time, leaving evacuation and disaster management as our only response to a pending impact. A single such missed opportunity will add painful fault-finding to the devastating physical effects of an impact. The international community should begin work now on forging its warning, technology, and decision-making capacities into an effective shield against a future collision.

Now that humankind has the scientific, technical and operational capabilities *both* to predict whether an asteroid will come too close for comfort, *and* to launch operational missions to deflect a potential impact, it is time for the international community to identify the decision-making institutions and begin the development of a coordinated decision-making process. This decision-making program proposed by the international Panel on Asteroid Threat Mitigation is only the first step in that direction.

We are no longer passive victims of the impact process. We cannot shirk the responsibility to prevent or mitigate impacts wherever possible.

Appendix I. Glossary of terms

Albedo
: A value between 0 and 100 representing the percentage of incoming light reflected by an object.

Aphelion
: For a solar-orbiting object, that point in the orbit farthest from the Sun, directly opposite the perihelion.

Apparition
: A period of time during which a NEO is visible to telescopes. NEOs are discovered on their first apparition, pass out of sight, and are seen again at second apparition.

ASE (Association of Space Explorers)
: The international professional organization of astronauts and cosmonauts.

Asteroid
: A small rocky and/or metallic primordial body orbiting the Sun. Most asteroids orbit in the main asteroid belt between Mars and Jupiter. Near-Earth asteroids (NEAs) follow paths that approach or cross the orbit of the Earth.

AU (Astronomical Unit)
: The average distance between the Earth and the Sun, about 150 million km (93 million miles).

Comet
: A small, rock-and-ice primordial body orbiting the Sun. Comets were formed in and largely orbit the Sun in the outer reaches of the solar system. Perturbations cause some to enter orbits which dip into the inner solar system.

Database (NEO)
: The NEO database contains the orbital parameters of all NEOs discovered and tracked to date.

Discovery (NEO)
: A NEO discovery is the initial sighting of a NEO which, to be officially recorded, must be independently confirmed.

IAWN (Information, Analysis, and Warning Network)
: One of the three primary international working groups whose formation the ASE and its international Panel on Asteroid Threat Mitigation recommend to address the NEO decision-making challenge.

Impact probability (NEO)
: The probability that a specific NEO will actually impact Earth on a particular date. The astronomical community analyzes the orbit of each NEO for potential impact within the next century and assigns an impact probability, which is updated following each subsequent sighting of the NEO.

Inner solar system
: Generally, that portion of the solar system inside the orbit of Jupiter.

JPL (Jet Propulsion Laboratory)
: The NASA center in Pasadena, California responsible for the design and operation of many planetary missions, and for managing NASA’s NEO Program.

Keyhole (NEO)

Small regions in space near the Earth through which a passing NEO may be redirected (due to gravitational effects) onto a path to impact Earth. For example, if a NEO passes through the 7:6 keyhole while passing Earth, it will travel 6 times around the Sun and impact the Earth in exactly 7 years.

Main Asteroid Belt

That region of space between the orbits of Mars and Jupiter within which the vast majority of asteroids orbit. NEAs are thought to be asteroids whose orbits have been perturbed (through collisions and gravitational interaction with Jupiter) such that they now approach Earth's orbit.

Mitigation (NEO)

Generally, any action reducing the consequences of a threatened NEO impact. It usually refers to those actions short of physical deflection of a NEO (e.g. evacuation).

MPC (Minor Planet Center)

The Minor Planet Center of the International Astronomical Union is responsible for the designation of minor bodies in the solar system and the efficient collection, checking, and dissemination of observation and orbits for minor planets and comets.

MPOG (Mission Planning and Operations Group)

One of the three primary international working groups whose formation the ASE and its international Panel on Asteroid Threat Mitigation recommend to address the NEO decision-making challenge.

NEA (Near Earth Asteroid)

An asteroid whose orbit approaches that of the Earth; defined as having a perihelion distance, q, less than 1.3 AU.

NEC (Near Earth Comet)

A short period comet whose orbit is indistinguishable from those of the near-Earth asteroids and is therefore treated in a similar manner.

NEO (Near Earth Object)

The total of near-Earth asteroids and near-Earth comets. NEAs comprise the vast majority of all NEOs.

NEODyS (NEO Dynamic System)

The University of Pisa's analytic office which analyzes and publishes information (including impact prediction) on all discovered NEOs. NEODyS performs a function similar to that done by NASA's JPL.

MAOG (Mission Authorization and Oversight Group)

One of the three primary international working groups whose formation the ASE and its international Panel on Asteroid Threat Mitigation recommend to address the NEO decision-making challenge.

Orbital elements

A set of six mathematical terms that fully characterize the orbit of an asteroid or other celestial body.

Orbital period

The time it takes an orbiting body to complete one revolution around the central body.

PATM (Panel on Asteroid Threat Mitigation)

The panel of international experts organized by the ASE NEO Committee to oversee and edit the development of this decision-making program for asteroid threat mitigation.

Perihelion

For a solar-orbiting object, that point in the orbit closest to the Sun, directly opposite the aphelion.

Radar telescope (NEO)

A radio telescope which has the capability of active radio transmission, used to obtain precision tracking of NEOs. Radar tracking complements optical tracking and, when available, can significantly improve predictions of NEO orbits.

Risk corridor

A virtual locus of points, unique to each NEO, within which a NEO may impact the Earth. Although extending across the entire planet, the corridor is often only a few tens of kilometers wide. Physical effects of the impact may extend well beyond the corridor.

Risk table

A table of NEOs, computed and published by both JPL and NEODyS, containing a list of NEOs which, in the next 100 years, may pose a risk of one or more possible impacts with Earth.

Spaceguard Survey

The informal name of the NEO discovery and tracking program that the U.S. Congress has directed NASA to perform. The initial Spaceguard goal (1998) was to discover by 2008, 90% of all NEOs larger than 1 kilometer in diameter. The recently revised goal directs NASA to discover, by 2020, 90% of all NEOs larger than 140 meters in diameter.

Threat (NEO)

The potential for a near-Earth object to impact Earth. NEO threats range from a few megatons of TNT-equivalent explosive energy up to infrequent, but devastating, impacts with millions of tons of TNT explosive energy.

Tunguska Event

An asteroid impact which occurred over Siberia on June 30, 1908, releasing the energy of approximately 3-5 megatons of TNT. Although the asteroid exploded in the atmosphere, it destroyed over 2,000 square kilometers of forest. The blast was capable of devastating a modern city.

Appendix II. Key concepts in Asteroid Threat Mitigation

1. Deflection Campaign

A successful NEO deflection must modify the orbit of a threatening NEO such that it misses the Earth at the predicted time of impact and that the deflection itself does not result in a subsequent impact within a few years. These two operations are referred to respectively as a primary deflection and a shepherding operation.

In general, the two conditions above require a combination of both substantial total impulse to avoid the direct impact, and precise orbit control to assure that the NEO passes between return keyholes (see Appendix II.2). Primary deflection causes the NEO to miss the Earth whereas shepherding guides the NEO such that it passes between all keyholes as it passes nearby the Earth.

If a threatening NEO passes close by the Earth in the decades prior to a potential impact, it will have to pass through a keyhole during that close encounter in order to subsequently impact Earth. If this scenario is seen to be developing sufficiently in advance of the potential impact, a shepherding mission can be launched to guide the NEO around the keyhole thereby avoiding potential impact. If, however, there is no close encounter with Earth between the discovery of a potential impact and the date of impact, then the NEO is on a direct impact path and a full deflection campaign (e.g., primary deflection plus shepherding) must be mounted to avoid the impact.

Primary deflection and shepherding requirements cannot be met with any single existing deflection technique. Available instantaneous force (IF) concepts (kinetic impact and nuclear explosion) can provide considerable total impulse, thereby meeting the primary deflection needs, but will result in a large uncertainty in the velocity change imparted to the NEO (up to 500% uncertainty).

Continuous force (CF) deflection methods, such as a gravity tractor, can provide only limited total impulse, but that impulse can be provided with high precision resulting in a well-determined (even a pre-determined) final NEO orbit, thereby being ideal for shepherding operations.

It is therefore the application of an instantaneous deflection followed potentially by a continuous force deflection which is necessary to assure a successful deflection, i.e. a primary deflection followed by a shepherding operation. These two deflection concepts, however, require two quite different mission designs, the deflection requiring an intercept trajectory, and shepherding requiring a full rendezvous with the NEO.

However, the requirement for two distinct missions in a deflection campaign is not limited to obtaining the magnitude and precision of the NEO deflection per se. There is also a requirement for a precise NEO orbit determination both before and after the deflection maneuvers. Furthermore, there is a high value in being able to observe and confirm the primary deflection by the shepherding spacecraft from a stand-off/observing location.

Precise NEO orbit determination by the shepherding spacecraft is required prior to the deflection (1) to confirm that the NEO is indeed headed for an impact with Earth, and (2) to reduce the size and pinpoint the location of the impact zone. Only if the impact prediction is confirmed would the primary deflection spacecraft be launched.

Following the primary deflection the shepherding spacecraft would again precisely determine the new NEO orbit to 1) confirm that the deflection has modified the orbit such that it misses the Earth, and 2) determine whether the new orbit will cause the NEO to pass satisfactorily between return keyholes. If the latter is not the case and the NEO threatens to pass through a keyhole, the shepherding spacecraft will utilize its continuous force capability to adjust the NEO orbit to avoid keyhole passage, thereby completing a successful deflection.

2. Keyhole

In this description, it is helpful to visualize the orbits of the Earth and the NEO creating an intersection as they cross one another. An impact occurs when the Earth and the NEO arrive at that intersection at the same time. If the NEO arrives slightly late at the intersection the Earth would already have passed through and the NEO will pass behind the Earth. Conversely, if the NEO arrives before the Earth it will pass in front of the Earth having arrived at the intersection early.

A NEO passing close by the Earth, or any large celestial body, is said to experience a close gravitational encounter. In any close gravitational encounter a NEO will pass through a field of hundreds of keyholes, small regions near the planet which, if the NEO passes through one, will cause the NEO to return some years later to impact Earth. The vast majority of actual and potential NEO impacts will have experienced a keyhole passage in the years or decades immediately prior to the impact.

The orbit of any object that passes near the Earth (or any large celestial body) will experience substantial modification due to the gravitational pull of the Earth. The orbital parameter of greatest significance regarding keyholes and NEO impacts is the period of the NEO orbit as it departs the Earth’s vicinity. If a NEO passes closely behind the Earth it will be pulled forward in its orbit by the Earth’s gravitational pull resulting in a longer period orbit than it had prior to the encounter. Conversely, if a NEO passes closely in front of the Earth its resultant period on departure from the close encounter will be shortened.

For example, if a NEO with an orbital period of 1.8 years passes closely behind the Earth, it would be pulled forward in its orbit and depart Earth with a period greater than 1.8 years. If it passes at a very specific distance behind Earth, its exiting period will be exactly 2.0 years. In this example, exactly two years after this close encounter, the Earth will again be located at the intersection, having gone around the Sun precisely 2 times, and the NEO will also return to precisely the same place, having gone once around the sun in the intervening 2 years. This is referred to as a resonant orbit, in this case, the 2:1 resonance.

There are many such resonant orbits which the NEO might enter depending on the specific distance it passes behind the Earth. For instance, if the NEO were to depart Earth on an orbit with a 2.25 year period (having passed slightly closer to the Earth than in the example above) then it would be on a 9:4 resonance, e.g., after exactly 9 years the Earth would have made 9 orbits of the Sun and the NEO 4 orbits and both return to the exact relationship as 9 years earlier.

An identical situation exists for objects passing in front of the Earth except that their departing orbits have shorter periods rather than longer. Nevertheless, there are a set of resonance points ahead of the Earth as well as behind it. In fact, there are hundreds of such resonance orbits for which, within 30 years, the Earth and the NEO will end up in the identical geometry as that of the initial close encounter.

An exact resonance exists only if the center of gravity of the NEO passes through a precise point either ahead of or behind the Earth. Such a hypothetical case is, of course, highly unlikely, and in any event is not of concern since the NEO will pass by the Earth precisely as it did on the first encounter. In the more general case however, the NEO might pass through a small region slightly further away from the Earth than the exact resonance, and its period would therefore be a few seconds or minutes different from the resonance case. If, for example, the NEO in the first example above were to pass very slightly further behind the Earth its period would end up not at 2.0 years but 2.0 years minus a few minutes. With this slightly shorter orbital period the NEO would arrive at the intersection slightly earlier which means that it would end up passing closer to the Earth than the precise resonance distance.

Clearly there is a situation where the NEO's orbital period would be shortened just enough that it would in fact arrive at the intersection just as the trailing edge of the Earth passes by. Orbital periods slightly shorter than this limiting case would result in the NEO impacting the Earth. Shortening the orbital period by another few seconds will ultimately result in the NEO passing through the orbital intersection just as the leading edge of the Earth reaches it. Between these two limiting cases, the NEO impacts the Earth. Returning to our original geometry, these two cases correspond with two points slightly further from the Earth than the exact 2.0 year resonance, the region between these two points defining the 2:1 keyhole. Any NEO passing between these two points slightly outside the 2:1 resonance (i.e. passing through the 2:1 keyhole) will impact the Earth 2 years after the initial close encounter.

Similarly, each resonance point behind and in front of the Earth has associated with it a small region, a keyhole, slightly further from the Earth which, if a NEO passes through will result in an impact with Earth some years after the initial close pass.

If one now imagines a NEO headed for a direct impact with Earth, and an instantaneous deflection changing the NEO orbit so that it just misses the Earth, it now must pass through this array of keyholes, whether behind or in front of the Earth, such that it does not pass through one of these many keyholes. Were this to be the case (it should be recognized that the space between keyholes is much greater than the space within keyholes) the NEO deflection would have caused the NEO to miss the Earth only to have it return several years later for an impact. For this reason it is important, in any deflection campaign, that the deflection cause the NEO to both miss the Earth and not pass through a return keyhole as it passes by Earth.

Keyholes are referred to variously as return keyholes, impact keyholes, resonance keyholes, etc. for descriptive purposes. In all cases a keyhole is a small region in space near the Earth (for our purposes) which, were a NEO to pass through it, would result in that NEO impacting the Earth a few years later.

3. Risk Corridor

If one imagines oneself riding on a NEO approaching an impact with the Earth, it is easy to visualize a point on the surface of the Earth where the imminent impact will occur. If one further imagines that the NEO has arrived at this point just a bit earlier, the impact point will be slightly displaced on the surface of the Earth toward its leading edge. Similarly, if the NEO were to arrive at the observation point just a bit later, the Earth would be slightly further along in its orbit and the impact point would now be displaced toward the trailing edge of the Earth.

Extending this image further in each direction, one would see a series of potential impact points tracing a line across the entire Earth between its leading and trailing edges. If one imagines this line in a left-right orientation, then it may be located horizontally (from the observer's point of view) anywhere between the top and the bottom of the Earth, but extending entirely across the planet in the left-right direction (see Figure 7).

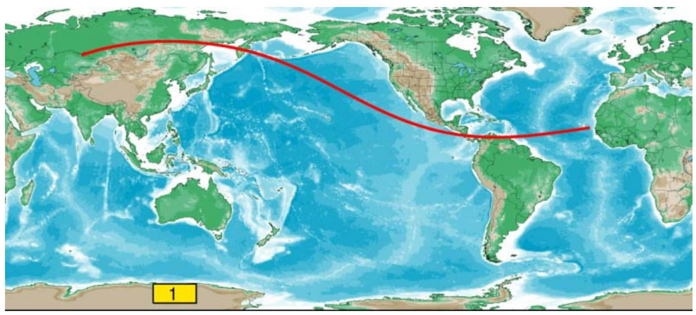

Figure 7. Risk Corridor visualization for a particular NEO

This line of potential impact points across the Earth is referred to as the "risk corridor." The left-right extent of the risk corridor is entirely dependent on the degree of precision with which we know the NEO orbit. If the NEO orbit is precisely known, then the risk corridor may well be a short line segment of only several 100 kilometers in length. Conversely, if the orbit is less precisely known, the risk corridor will extend entirely across the Earth and indeed for many Earth diameters ahead of and behind the planet. Where the length of the potential impact line is less than the width of the Earth but entirely superposed on the Earth, the probability of Earth impact is 1. If the line is greater than the width of the Earth but crosses part or all of the Earth the probability of impact is less than 1. In most cases where a NEO is known to have some probability of impacting Earth, this probability of impact may vary from 1 in 1,000 to 1 in 100 million, or more.

In all cases where the probability of impact is 1 in several 1,000 or greater, the risk corridor will extend (not necessarily symmetrically) across the planet and for many Earth diameters in each direction, but will nevertheless be very narrow. Typically, the risk corridor will extend entirely across the Earth's surface but be only tens of kilometers wide.

What can then be said about the risk corridor is that if a particular NEO is going to impact Earth it will do so somewhere within this narrow corridor. Every NEO with a non-zero (e.g., greater than zero) probability of impacting Earth has a unique risk corridor, generally extending across the entire planet (see Figure 8).

Figure 8. Risk Corridor visualization for multiple threatening NEOs

As our knowledge of the NEO orbit increases in precision, the extended risk corridor reduces in length until, if the NEO is going to impact, it reduces to a point: the point of impact. In general, as the extended risk corridor shortens (with increasing knowledge of the orbit) it reaches a point where the entire line segment no longer contains the Earth and the risk of impact drops to zero. It is the infrequent, but critical case where the Earth remains within the ever-shortening extended risk corridor that we are concerned with and must be prepared to react to.

An important characteristic of the risk corridor for any NEO headed for an impact, is that if a deflection is initiated, the NEO will end up passing by Earth (assuming a successful deflection) somewhere along the extended risk corridor, either ahead of or behind the Earth. In general, a deflection maneuver will cause the NEO to arrive in the vicinity of the Earth either earlier than or later than its prior time of encounter, thereby passing slightly ahead or behind the Earth respectively.

If an instantaneous force deflection is only partially successful, or more than one is required to shift the NEO impact off the Earth, then there will be a temporary or intermediate new impact point along the risk corridor in the direction of the intended deflection. Perhaps the case most easily visualized is that of a continuous force deflection where the original impact point is continuously “dragged” across the Earth’s surface along the risk corridor until it leaves the Earth either off its leading or trailing edge. In either the case of an instantaneous force or continuous force deflection, the impact point is shifted off the Earth, along the extended risk corridor, until it reaches a deflected miss distance and the deflection is terminated.

Should a failure of some kind occur in a deflection process causing a partial completion of the planned deflection, there will now be a new impact point on the Earth displaced along the risk corridor from the original toward either the leading or trailing edge of the Earth. While for a properly designed deflection campaign, the risk of such an interrupted deflection is small, there is nevertheless a slight and temporary increase in risk to populations and property in the direction of the deflection which must be accepted in the process of dropping the risk to the planet to zero. Clearly, there is a choice of shifting the NEO so as to pass either ahead of or behind the planet and this decision has substantial implications for people along the risk corridor.

4. Low Probability Mitigation Alerts

In each case that a NEO is discovered and its orbit determined, its future path is projected ahead 100 years and compared with the projected path of the Earth over the same interval. Due both to small uncertainties in the measurement of the NEO orbit and to future close encounters with the Earth or other solar system object, a NEO that has a non-zero probability of intersecting the Earth usually has more than one such possible impact. In many cases, especially for the smaller, more populous NEOs where tracking is limited, one or more of these low probability potential impacts will have an impact date too close to the present to mount a deflection campaign.

While these near-term potential impacts are generally of very low probability, that probability in each instance is not zero. Since there is no possibility in these instances of a deflection, the only available mitigation response is preparation and evacuation.

These near-term, low probability impact cases present a serious conceptual challenge. For example, if this is the one time in 100,000 when the NEO is indeed there and headed for an impact, then an evacuation would save many lives. However, the reality is that (in this example) there is a 99,999 chance out of 100,000 that the NEO will not be on an impact course. One would, and should be very reluctant to issue an alarm in such an instance only to have nothing happen as in the overwhelming majority of cases.

This situation can be considerably improved by specifically targeting optical and/or radar observations along the incoming approach path of the NEO if it is headed for an impact. In other words, we would be looking for this NEO "on final approach." While the odds of impact have not changed by this action, an optical search for even the minimum-sized NEO of concern, should enable two to three months of warning if indeed the NEO is on final approach to an impact. Therefore, in such an instance, an alert or warning would be issued only in those rare instances where a NEO is found to be on an impact path. Whether an "all-clear" would be issued in the overwhelming number of cases where no NEO is found in this search process is a matter to be determined by the world community.

Unfortunately, the above case of a two to three month warning of a pending impact only applies for the 50% of cases where the pending impact would occur on the night side of the Earth. For the other 50% of potential impacts occurring on the daylight side of the Earth, optical telescopes are of no use due to the proximity of the Sun to the point from which the NEO would approach. In these instances, the only advanced warning possible requires the use of a radar search directed out along the NEO's final approach path. However, while radar telescopes are not impeded by the proximity of the Sun, their range is considerably less than that available with optical telescopes and only a few days of warning would be available. While a well-planned evacuation could be executed, this short timeframe would be very challenging indeed.

Furthermore, in both the night and day instances, a specific impact point along the risk corridor (see Appendix II.3) would not be known until sometime after the initial sighting of the incoming NEO. In the night impact case, this may provide a nation or even a specific community with a month or more of warning, but in the instance of the daytime impact and the use of radar, the warning for a specific impact zone could be as close as 2 days to the event.

Clearly, the availability of such a last minute warning will depend on the continuing availability and frequent use of both optical and radar systems, with the overwhelming percentage of the final approach searches resulting in no NEO being found. The cost of such an ongoing last minute warning operation will have to be weighed against the very occasional life-saving benefit by the world community.

5. NEO Population, the Spaceguard Survey, and Discovery Rate

The information basis for much of what we anticipate about the NEO environment is illustrated in the statistical size-frequency distribution diagram (see Figure 9). The population estimates for NEOs of various sizes is obtained by several independent methods including crater counts on the Moon, extrapolation from actual NEO discoveries, and the frequency with which NEO searches produce new discoveries vs. re-discoveries. This process is described in detail in NASA's 2003 NEO Science Definition Team report.[15] The population diagram from that report was updated with more recent data and is shown below.[16]

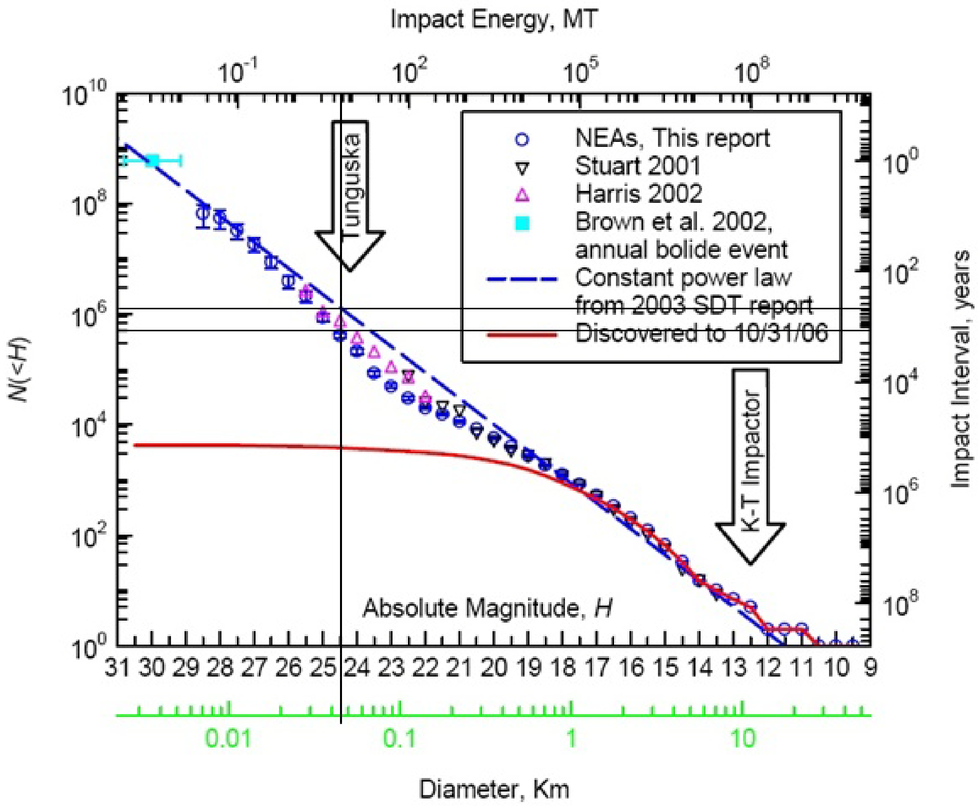

Figure 9. Size-Frequency plot of the NEO population. In this diagram, the left vertical axis is the number of objects of a given size, and the right vertical axis is the corresponding frequency of impacts at any given size object. The bottom (green) axis is the NEO diameter and the top horizontal axis is the explosive energy of the NEO. Specifically, the vertical line at 45 meters yields (at left) a potential population of 400,000 to 1,200,000 objects of this size, which cross the Earth's orbit and pose a potential hazard.

The two lines of primary interest on the diagram are the dashed blue line from upper left to lower right, representing the statistically expected population distribution, and the curved red line in the lower part of the graph showing the actual population distribution of those NEOs

[15] NASA: Near-Earth Object Science Definition Team. (2003). *Study to Determine the Feasibility of Extending the Search for Near Earth Objects to Smaller Limiting Diameters.* http://neo.jpl.nasa.gov/neo/neoreport030825.pdf
[16] Harris, A. Personal communication, 2007 (PDC07 report).

discovered to date. While there is a great deal of information on this chart, the important message is to recognize the much higher population of NEOs with decreasing size.

Three points on the dashed blue line are specifically identified to illustrate the dramatic change in our discovery of actual (not statistical) NEOs in the next 10-15 years. Farthest to the right, is the original 1 km target size for the first phase of the Spaceguard Survey (the official NEO search program). Projecting to the left from this point, we find the anticipated population of 1 km diameter NEOs to be about 950. Over 756 objects of this size have actually been discovered and are being tracked today, a completion of approximately 80%.

The goal for the second phase of the Spaceguard Survey (legal direction to NASA) is the discovery of 90% of NEOs 140 meters in diameter and greater by 2020. The second point on the line (140 meters diameter) projected to the left yields an anticipated population of about 15-60,000 objects. Finally, the farthest left point highlights the anticipated population of objects 45 meters in diameter, the estimated diameter of the NEO thought to have impacted at Tunguska, and the approximate minimum size that would cause significant damage at the Earth's surface on impact. The estimated total population of 45-meter NEOs is between 300,000 and 1,200,000. (It is unknown at this time whether the "dip" below the statistical population curve for 20 through 600 meter objects is real. Hence the quoted range in the expected population numbers.)

The curved red line on the diagram shows the distribution of NEOs actually discovered and being actively tracked. At sizes over 1 km in diameter, the numbers discovered at each size equate with essentially 100% of the statistically expected population. However, as the NEO sizes drop below 1 km in diameter, the percentage of the statistical population actually found drops below the dashed blue line, so that at 140 meters about 10% have been discovered to date, and at 45 meters only about 1% have been discovered to date.

Within the next 4-7 years, new, larger NEO search telescopes will become operational with the capability of meeting (or nearly meeting) the revised Spaceguard Survey 140-meter goal. As these telescopes become operational, the discovery rate of NEOs will dramatically increase and the 90% goal for the 140-meter NEOs will potentially be met between 2020 and 2025. In the process of increasing the completion of the 140-meter objects from 10% today to 90% by 2025, the completion of the 45-meter objects will also rise from the 1% found today to approximately 50% completion.

Given the much larger population of these smaller NEOs, the anticipated 50% completion of the 45-meter objects equates to 150,000 to 600,000 actual objects in the database being actively tracked. It is this rapid expansion of the inventory of these potentially dangerous NEOs that will inform us of the existence of many potential future impacts and ultimately necessitate decisions being made on whether or not to take protective action.

Appendix III. International Legal Framework

In view of the major international institutional and legal implications of a decision-making program for global action in response to asteroid threats, the realization of such decision-making in an effective and acceptable manner will partly depend on the extent to which it will take place sustained by as well as within existing legal parameters. In addition it will be important to consider to what extent amendments to existing elements of (especially international) law might be necessary or desirable.

In the present Appendix, a first effort is made to flag some of the most important of those issues and parameters, which may need to be tackled once the decision-making program comes closer to realization.

1. General Remarks

From a legal perspective, for the purpose of any decision-making program for global action in response to asteroid threats developed on the basis of the analysis and recommendations of the present report, the following phases need to be defined, each with the following general legal ramifications:

- **Detection, surveillance and threat assessment.** (See Appendix III.2)
    - There is no relevant law that could act as a barrier to detection, surveillance and threat assessment.
    - Because threat assessment is particularly critical and can trigger an overall political decision to take action, it is important to establish, by means of a clear legal structure, the parties who would be entitled to speak out with authority on the assessment, in order to leave minimum space for criticism or political fall-out. In view of the above, this should be taken on board by a decision-making program.
    - The main contribution of "the law" would lie in underpinning the broadest possible collection on an ongoing basis of relevant data, especially by creating/elaborating obligations to notify and inform relevant entities in the context of a decision-making program. This could be a flexible system, with the IAWN at its core, collecting any data that is relevant.
- **Threat response and mitigation**. (See Appendix III.3)
    - When action is necessary, it may come into conflict with existing legal obligations; the main part of legal analysis will be focused on this phase. This includes the establishment of transparent, effective, and internationally acceptable mechanisms for decision-making, mandating and action.

2. Detection, Surveillance and Threat Assessment

When focusing upon detection and surveillance, for the purposes of legal analysis, a distinction should be made between two options:

- **Detection and surveillance from earth**. The main legal issue here is to analyze the adequacy of existing obligations to inform; the principle that exploration and use should be for the benefit and in the interest all states (see above); and Art. IX, Outer Space

Treaty, which provides that exploration of outer space should be conducted "so as to avoid (…) adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter and (…) shall adopt necessary measures for this purpose",[17] which although not drafted with a view to asteroid threats, should be interpreted *a fortiori* to entitle measures to be taken to avoid serious and adverse changes to the environment of Earth stemming from an asteroid threat.

- **Detection and surveillance from outer space**. In addition to the issue above, which applies here as well, the regime of general space law applies to such activities in outer space. This also refers to a partly-analogous, partly *a fortiori* application of Principles X and XI of the United Nations General Assembly (GA) Resolution on remote sensing which calls upon states to promote by means of their remote sensing activities the protection of Earth and mankind, and share relevant information, whether it concerns a threat to "the Earth's natural environment" or resulting "from natural disasters".[18]
- As for **threat assessment**, as long as it does not result in any action – at least directed to, or in, outer space – its legal parameters do not fundamentally differ from those referred to above under detection and surveillance.

3. Threat Response and Mitigation

A. Three Technical Response Options

For the purpose of **threat response and mitigation**, three generic options are available, each with a partly different, partly overlapping set of attendant legal parameters to keep in mind. These generic options are summarized as follows:

- **Deflection essentially by gravitational and other non-kinetic forces** – 'the gravity tractor'.
    - From a legal perspective, to a certain extent there is a difference when two objects (a threatening asteroid and the threat-eliminator) crash into each other, or when the latter exerts its forces at a distance.
        - The chances of actual fragmentation are considerably less in the latter case than in the former, which is important for liability issues (see below).
        - Also, from a pragmatic perspective, the gravity tractor is most useful when the time-span between decision to mitigate and actual materialization of the threat would be long – in the range of years, if not decades. On the other hand, deflection by kinetic impact would be an option when that time-span is limited to a few months.
- **Deflection by kinetic impact** – see discussion above on the difference with deflection by gravitational and other non-kinetic forces.
    - Space Debris. Apart from the liability issue, the enhanced possibility of fragmentation also leads to a far more serious issue of secondary consequences (see Appendix III.3.I).
    - Military Concern. Moreover, some experience exists with kinetic interception, which makes it clear that issues of military usage of outer space, if not legally – then at least politically – are much closer at hand.

[17] United Nations. (1966). *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies*. http://www.unoosa.org/oosa/en/SpaceLaw/outerspt.html (Art. X).
[18] U.N. Doc. A/*Res*/41/65 (1987). http://www.un.org/documents/ga/res/41/a41r065.htm

- Deflection involving nuclear devices. The last resort-option, referred to by NASA, and therefore cannot be ruled out. The above formulation would also include the use of nuclear devices as propellant, but the focus obviously should be on the use of nuclear explosions to achieve deflection.
    - o Existing Space and International Law: Apart from once more raising issues of liability, space debris and general military concerns to yet a higher level, the nuclear option calls for due attention to relevant rules of space law and related regimes such as the Test Ban Treaties. The 1963 Partial Test Ban Treaty and 1996 Comprehensive Test Ban Treaty in principle prohibit nuclear explosions in outer space. The broader political implications require a flawless, beyond-reproach system for decision-making and action-taking on the international level.

B. The general legal framework – the Outer Space Treaty

The Outer Space Treaty provides for the following main legal principles of relevance, serving as the basis for any further legal analysis of (in particular) threat response and mitigation action, albeit sometimes to a different extent as between the three options.

- No national appropriation, meaning no territorial sovereignty in outer space (Art. II). The relevant regime for activities there can as a consequence at the highest level only be established at the international level (no state is able to view part of outer space as part of its legal territory and hence able to determine the law for that part).
- Freedom of exploration and use (Art. I).
    - o The point of departure is, roughly, that everything which is not one way or another prohibited, should be considered permissible. Hence, in line with the foregoing, limits to that freedom only exist if internationally agreed upon.
    - o Together with the phrase that activities in outer space shall be for the benefit of all countries and mankind (see below), this provides a good legal basis for a decision-making process. It means that any limits to action which may arise under literal interpretations of applicable legal texts should be interpreted in way that is as limited as possible because of the overarching aim of serving humankind.
- Activities in outer space should be for the benefit of all countries and/or all humankind (Art. I). This is a strong legal basis for any decision-making, as there is no doubt that asteroid threat mitigation can be strongly defended on this basis.
- The application, under the Outer Space Treaty, of general international law to space activities (Art. III), which also provides limits to the “freedom of exploration and use” (Art. I). Such limits can stem from general international law, which inter alia calls for peaceful cooperation as much as the Outer Space Treaty does itself, and provides the United Nations – under specific reference to the United Nations Charter in Art. III – with a special assignment in that area.[19]
    - o Examples of applicable international law:
        - ▪ Test Ban Treaties
        - ▪ General rules on the use of force
- State responsibility and liability for damage (Artt. VI & VII).

[19] United Nations. (1945). *United Nations Charter.* http://www.un.org/aboutun/charter/

- International responsibility for compliance with the space treaties lies with (a) state(s) (Art. VI). Similarly, responsibility for compliance by private actors also lies with the state (Art. VI).
- Similarly, international liability for damage caused by space objects lies with (a) state(s) (Art. VII, as elaborated by the Liability Convention).
- *Compliance, Liability, and State Responsibility must be properly dealt with in the context of any decision-making in order to conform to these provisions of the Outer Space Treaty.*
- The case of intergovernmental organizations. OST Art. VI provides here: "When activities are carried on in outer space (…) by an international organization, responsibility (…) shall be borne both by the international organization and by the States Parties to the Treaty participating in such organization", although in practice this requires some further development.

C. Four categories of issues in the legal area

Further to the general framework provided by the Outer Space Treaty as discussed above, four categories of legal issues may generally be discerned.

- The extent of a right to respond and mitigate: In view of the potentially catastrophic impact, in international law, an analogous right of 'self-defense' can be implied to conform with the requirements within which 'use' of outer space has to take place (Art. I, Outer Space Treaty). Any rule to the contrary could effectively be struck down by the fundamental principle of law that if application of a legal rule leads to 'manifest absurdity or unreasonableness', it should not be applied.
- The principle of the responsibility to protect: This responsibility is to protect citizens and should be taken into consideration in the decision-making process regarding threats from NEOs to human welfare and survival.
- The extent of obligations to respond and mitigate: Here, general humanitarian obligations as well as the adoption of appropriate measures (Art. IX, Outer Space Treaty; see above) calls for such a form of 'Good Stewardship', subject to precise parameters – which in the present case should be part of a decision-making process to be established.
- The legal parameters applicable in case of response and mitigation activities: Among those legal parameters, the most self-evident one is that such activities should be in conformity with any applicable law. These legal parameters need to be further elaborated: they concern the issue of liability (see Appendix III.3.D), the definition of a space object, the issue of 'space debris' (see Appendix III.3.I) and the institutional parameters (see Appendix III.3.J).

D. Legal parameter #1: the issue of liability

Further to Art. VII, Outer Space Treaty, the Liability Convention[20] provides for the following principles of liability:

- Liability arises under these provisions for damage caused by a "space object."
- Liability is absolute when the damage occurs on Earth, i.e. the establishment of a causal link is sufficient to establish liability.
- Liability is fault-based if the damage occurs in outer space.
- Liability is triggered only by damage caused by (man-made) space objects. That damage could refer either to that caused by a gravity tractor, kinetic or nuclear impactor directly, or – arguably – by pieces of a fragmented or only partially deflected asteroid if such fragmentation or deflection clearly resulted from the gravity-operation (unlikely) or impact itself.
- Liability is allocated to the 'launching State(s)', which is determined according to four self-standing criteria: the state that launches the space object concerned, the state that procures its launch, the state whose territory is used for its launch and the state whose facility is used for its launch.
- Compensation of the damage is without limit (in principle).
- There are certain exculpatory clauses, which do not seem to be relevant here.

It should be noted, furthermore, that the concept of liability has a different impact in law as well as in practice as between the three options for response (see Appendices III.3F, G, and H).

E. Legal parameter #2: the derivative issue of the definition of 'space object'

In the context of liability issues, the definition of 'space object' is of key importance for application of the liability regime under the Liability Convention.

F. Liability in the case of deflection by non-kinetic impact

Further to the general outline of the concept of liability above, in the case of deflection by gravitational and other non-kinetic forces liability would work as follows:

- In respect of such activities undertaken from Earth, since no space object is involved the Liability Convention would likely be considered not to apply, though principles of general international law can be applied, which according to case law (Trail Smelter[21]; Corfu Channel[22]) provide for the obligation for a state not to knowingly allow damage to be caused to other states. Although the obligation – at the time – referred to damage caused from the first state's territory, the mirror side to this obligation could be, if interpreted analogously and in conjunction with general humanitarian principles. That awareness of impending impact of an asteroid without warning the state(s) in harm's way may lead to a violation of international law.

[20] United Nations. (1972). Convention on International Liability for Damage Caused by Space Objects. http://www.unoosa.org/oosa/en/SpaceLaw/liability.html

[21] Trail Smelter Arbitration, 33 AJIL (1939).

[22] International Court of Justice. (1948). United Kingdom of Great Britain and Northern Ireland v. Albania ("Corfu Channel").

- In respect of such activities undertaken from space, the Liability Convention *may* apply, wherever as indicated above the damage is caused *by* a space object, and damage actually caused by the remains of the fragmented or partially deflected asteroid would likely through a slightly extended causal link be allocated to the launching state. As stated above, this is however not very likely, assuming that deflection by gravity or other invisible forces is a precision operation with ample time available, starting many years in advance.

G. Liability in the case of deflection by kinetic impact

Once again, in the case of deflection by kinetic impact, the application of the Liability Convention would need to be analyzed.

H. Liability in the case of using nuclear devices

The third option for deflection and mitigation is the use of nuclear devices. Here, the Liability Convention also applies along the same lines as discussed above, including the question of Electro-Magnetic Pulse (EMP) effects. An additional question however is whether nuclear fall-out (reaching Earth) as such would constitute 'damage'.

The specific legal parameters of the nuclear option follow, firstly, from the prohibition to orbit, install or station in outer space or on celestial bodies weapons of mass-destruction (Art. IV, Outer Space Treaty), which certainly includes nuclear weapons.

The requirement, in addition, for the Moon and other celestial bodies to be used for 'peaceful purposes' (Art. IV, Outer Space Treaty), does not pose legal obstacles here, as long as such a transparent and internationally acceptable decision-making process is in place.

Then, both the Partial Test Ban Treaty of 1963 and the Comprehensive Test Ban Treaty of 1996 in principle prohibit nuclear explosions in outer space (Art. I(1.a), 1963 Treaty resp. Art. I(1), 1996 Treaty). There is an escape clause making withdrawal possible if supreme interests of the state party are concerned, however, that takes effect after three months (Art. IV, 1963 Treaty) respectively six months (Art. IX, 1996 Treaty) which may not be short enough in the case of a decision to use a nuclear device against a threatening asteroid.

Thus, a need may arise to carefully phrase exceptions to the regime, backed up by 'confidence-building measures' or a transparent and internationally mandated decision-making process to establish confidence that such exceptions will not be abused.

I. Legal parameter #3: the derivative issue of 'space debris'

In addition to the issue of liability, the relatively much larger likelihood of fragmentation in cases of deflection by kinetic impact and/or the use of nuclear devices by definition also leads to a considerably enhanced chance of 'space debris' resulting. Simply put, under current international law, there is no fundamental prohibition of the creation thereof, only general duties of warning, consultation and cooperation (Art. IX, Outer Space Treaty). It might be worthwhile, however, for the purpose of political sensitivities, to include a general reference to such general duties of, essentially, 'Good Stewardship' into a decision-making program.

J. Legal parameter #4: the institutional structure

As to the institutional structure for any decision-making program, as well as the legal character of any international agreements on the subject (Protocol, Treaty, United Nations Resolution) to some extent discussions took place at the Strasbourg workshop of May 2007; presently it seems to be premature to go into further detail on this other than flagging it as the ultimate (legal parts of) the outcome of the present process.

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