Mitigation: Interfaces between NASA, Risk Managers, and the Public

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Summary: Threat mitigation, in the disaster management community, is treated in a systematic "all-hazards" manner, addressing readiness, response, and recovery. Deflection is only one element of response to an NEO threat. As the early warning system, NASA's Spaceguard search programs must go beyond finding threatening objects and calculating impact probabilities. Uncertainties must be calculated properly and sound risk communication practices must be employed, to inform the public, officials, and disaster management agencies; strategic planning must guide response. NASA must establish interfaces with national and international agencies that would lead response and recovery efforts if a NEO were to impact without warning, or if deflection is impossible or attempts to deflect fail. We outline basic elements of a NEO threat mitigation plan, emphasizing elements that are or should be NASA's responsibility.

I. NEO Threat Mitigation: All-Hazards Disaster Management Strategy

The Congressional mandate for this NASA Workshop was made "in order to provide warning and mitigation of the potential hazard [of NEOs]." The NEO impact hazard cannot be addressed in isolation from the national and international protocols established to deal with other natural hazards. Both national policy and professional practices in the disaster management community mandate employment of a systematic, integrated, end-to-end "all-hazards" management strategy to address natural (and man-made) hazards. While few natural disasters can be forecast and totally prevented (which is the 100% mitigation goal of deflecting an oncoming NEO), the impact hazard nevertheless has many features in common with other hazards. The consequent effects of an impact (falling debris, fire, wind, etc.) are identical to those of common natural disasters. In addition, there are many scenarios in which it is either impossible to deflect/destroy a NEO, or cases in which an attempt to do so may fail. It is therefore obligatory that any national or international agency or agencies that seek to address mitigation of the NEO hazard consider "threat mitigation" broadly and employ the "all-hazards" strategy, when appropriate. Therefore, our purpose in this White Paper is to urge this Panel to evaluate and recommend other elements of an integrated NEO mitigation strategy beyond deflection technologies.

Since this Workshop is being conducted by NASA, we emphasize what we consider to be both obligatory responsibilities that the space agency *already has*, in connection with its mandate to conduct the Spaceguard Survey, and to a lesser degree those responsibilities that NASA might assume if it undertakes broader responsibilities for the NEO hazard. Of course, other agencies (especially elements of the Dept. of Homeland Security) are currently chartered to handle the later phases of disaster mitigation (implicitly, but apparently not explicitly, including NEO impacts). Therefore we also briefly address broader NEO mitigation issues for which other agencies should take more explicit responsibility; of course, NASA must interface cleanly with these other agencies.

The NASA-funded Spaceguard Survey is the early warning system for the United States and the world concerning potential NEO impact disasters. This is an atypical role for astronomers and for space agencies. Since the impact hazard is newly recognized and unusual, it has generally not been included in the national "all-hazards" risk management and disaster reduction plans. NASA and the international astronomical community have so far taken only minor steps toward interfacing with disaster management agencies like FEMA or developing risk communication tools like the Torino Scale. What has been done has often been with little awareness of standard principles and methods adopted by other early warning practitioners, such as seismologists and hurricane meteorologists.

As NASA and the Congress wrestle with deciding what asteroid deflection technologies are appropriate, deciding with what priority they should be developed, and deciding which agency should take responsibility for such deflection, little attention has been paid to much more probable NEO impact scenarios where traditional risk management approaches are appropriate. Since the vast majority of NEOs 140 - 500 m diameter (and many larger ones) will remain undiscovered for at least another decade, it is more likely that one will strike without warning than that we will know an impact is coming. In this case, disaster response and recovery measures may resemble traditional approaches, but there will also be differences due to the unique characteristics of impacts. In addition, there remains a significant possibility, even in the case of a NEO impact forecast years or decades in advance, that evacuation, storage of food and medical supplies, and other disaster planning will be required, even as deflection is being attempted. There are many cases in which diversion or destruction of a NEO is beyond our technological capabilities or, in the case of using nuclear bombs to destroy a NEO, too dangerous to attempt. Other cases may prove sufficiently challenging that deflection attempts may fail and the impact disaster may actually happen, anyway. (This raises issues of international liability, which is a separate legal issue to be resolved, hopefully, by treaties enacted before an actual deflection attempt is made.) Neither NASA scientists nor disaster management agencies have yet given attention to the unique attributes of NEOs that must govern NEO disaster planning. We outline elements of a mitigation plan in this White Paper.

II. Minimal Obligatory Responsibilities of NASA in NEO Threat Mitigation

There are three canonical phases to disaster mitigation: readiness (planning), response, and recovery. Most disasters happen with little or no specific warning, so the "response" phase begins when the disaster is happening, or has happened. In the case of NEOs, there are two very different kinds of response: (1) response once a threatening NEO is found (e.g. by trying to deflect it) and (2) response to an impact disaster if it occurs. Responsibility for the latter, and for all of the recovery phase, lies with public and private disaster management entities and is beyond NASA's purview. This Panel will presumably make recommendations about the first kind of response (deflecting a NEO that has a good probability of striking the Earth). But the first phase of disaster mitigation -- readiness -- already lies squarely in NASA's lap, although elements of readiness could also be undertaken by other entities, as well.

Since NASA undertakes the early warning system for NEOs, it has several responsibilities beyond simply conducting an astronomical search for NEOs. It must, and does, evaluate the search data in order to discover potential impact threats during the next century. Thus its JPL office (in cooperation with an equivalent entity in Italy) makes predictions of specific impacts and specifies the frequently changing estimates of impact probabilities (just as the National Hurricane Center does for approaching tropical storms). These are only the first steps of many that are necessary for developing "readiness," but this is where nearly all the funding and activity currently ends within NASA. NASA must develop a multi-faceted risk management strategy to complete its responsibilities.

Since NASA astronomers and officials are first in the line of defense against a potential impact disaster, they must act throughout in ways that would seem proper from the perspective of survivors of the catastrophe if it were actually to happen. While NASA must caution the public not to worry about very small impact probabilities, its professional responsibility is to otherwise behave counterintuitively *as if a possible impact is going to happen*...until it becomes known that it will not happen. As hurricane Katrina was approaching Florida, the chances that it would directly strike New Orleans were low. But officials are now smarting from criticism that they did not act as they should have during the days when the threat was growing until Katrina actually struck. This maxim of acting as if the disaster will happen goes without saying for professional risk managers, but it is a lesson that New Orleans officials needed to know beforehand and that NASA needs to learn now.

Measurement and Understanding of Uncertainties. “Error bars” (including many diverse sources of uncertainty) have not been treated or thought about properly when dealing with the impact hazard. From the notorious case of 1997 XF11 until the present, one can think of many public statements about possible impact probabilities that turned out to be wrong *not* just because we obtained better data but because the uncertainties had not been properly understood in the first place. A well-known example is the case of Apophis (then 2004 MN4), which was announced on 27 December 2004 as likely to miss the Earth in 2029 by 5 Earth *diameters*; subsequent radar detection by Arecibo changed that estimate to a miss distance of just over 5 Earth *radii*, far outside plausible uncertainties of the 27 December calculation. After-the-fact, we understood why; but we need to approach NEOs in ways that would anticipate things we are now more commonly learning after-the-fact.

Consider a less-known aspect of Apophis. On 27 Dec., data were on hand from the previous night that would have raised the chances of a 2029 impact to 1-in-20, but then the pre-discovery observations were reported that ruled out an impact altogether. Yet the Torino Scale value of 4 (which was wholly unprecedented) was based not only on the impact probabilities >1% calculated between 24 Dec. and 27 Dec. but also based on a *nominal* value for the size/mass of Apophis derived from its H magnitude. Until several weeks later, when R. Binzel *et al.* measured Apophis' reflectance spectrum, the inherently bimodal albedo distribution for NEOs meant more nearly that there was a 25% chance of it being about 1 km in diameter (with a typical C-type albedo of 0.035) and a 75% chance of it being about 400 m diameter (albedo = 0.25). That was (for a brief time on 27 Dec.) a 1-in-80 chance of a 1 km body striking, which plots as Torino Scale = 7! The official wording describing TS=7, which was widely available on the web (although officially tweaked in an earlier technical publication) was: "A close encounter with an extremely significant threat of collision capable of causing a global catastrophe." But the uncertainty in size was ignored, so Apophis never officially exceeded TS=4.

In a framework where the typical probabilities of occurrence are so tiny, sources of error that are usually ignored by physical scientists can assume dominant importance. In most situations in life, we can simply ignore outcomes with extremely low probabilities, so we are unaccustomed to dealing with errors in estimates of such low probabilities. But when the consequences are great, we must deal with the low probabilities... and we often go astray. In our practical and professional lives, we may strive to be right 99% of the time, but hardly 99.999%. Many other sources of potential error, beyond human fallibility, exceed the formal errors (whether 1 or 3 sigma) that we typically employ.

Consider the remarkable case of AL00667 (later named 2004 AS1). The day before President Bush's "Vision" speech, which has shaped NASA priorities ever since, this asteroid was reported by the Minor Planet Center (based on the previous night's discovery positions) to have a nominal path that would impact Earth – somewhere in the northern hemisphere – the very next day, shortly after Bush's speech. Independent analyses by two experts in orbit calculation and impact predictions yielded extremely high probabilities (20% - 40%) that the impact would, in fact, happen. Because of bad weather in Europe and much of the U.S., hours passed by with this ominous possibility being taken very seriously by people at NASA's NEO Program Office, for example. By good luck, observations acquired later that night, before the fateful day, showed that the impact would not happen. But it was very plausible that no observations at all would have been obtained that night, so NASA could have been faced with the choice of (a) reporting the potential impact hours before Bush's speech or (b) withholding the report because of the hunches (described as "judgments based on experience") of a couple of crucial people in the ad hoc chain-of-command. With hindsight, we can see that choice (a) would have had bad consequences...but it might have been the proper action to take based on the knowledge on hand.

The asteroid turned out to be nowhere near the Earth and the independent calculations of a high likelihood of impact were not correct. But they were incorrect not because of "mistakes" but because of failure to consider larger, more qualitative sources of uncertainty. Such sources of uncertainty perhaps subconsciously fed the skepticism of those who rejected the results based on "judgments based on experience." But we need a less subjective, more rigorous and formal way to evaluate impact probabilities. We should use "meta-error-bars" (Chapman 1999) and

Bayesian statistics to deal with such issues. NASA should develop and then routinely use a more sophisticated approach to understanding uncertainties in NEO impact predictions.

The next step, of course, is to communicate impact predictions and their uncertainties in useful and understandable ways.

Risk Communication Plan. A prime responsibility under "readiness" is to undertake effective "risk communication." It is vital that the output of the Spaceguard search (and any successor) be articulated in effective, responsible, and useful ways to a wide variety of "consumers" of such knowledge. Officials in national and international disaster management agencies (like DHS/FEMA), technological agencies (e.g. operational parts of NASA or the Air Force) that might undertake a NEO deflection mission, members of the news media, policy makers and politicians, and the general public all need to be intelligently informed. It is notoriously difficult for the scientific community to communicate effectively with policy makers, as detailed in the book *Prediction: Science, Decision Making, and the Future of Nature* (Sarewitz *et al.* 2000). One of the book's case studies involved the break-down in communications between weather forecasters and public officials in Grand Forks, N.D., over uncertainties in storm predictions, resulting in great damage from the 1997 flood of the Red River of the North – all because the dikes were built to *exactly* the height of the predicted flood, taking no account of the "error bars".

An example of a special issue in NEO risk communication, which arose in the case of Apophis, is whether to announce or keep secret (or other intermediate options) the locations that would be impacted by a NEO if it were to hit. Because of the extremely small errors in the orbital parameters that define the plane of the NEO, it is generally known quite precisely what places on Earth are in the "path of risk", even if the chances of impact with the Earth are very small. For example, on 24 Dec. 2004, it was calculated by a centrally placed NEO scientist where Apophis would hit in 2029, if in fact it were to hit: somewhere along a line that would have crossed Central Europe, critical parts of the mid-East, the most populated district on Earth (the Ganges River valley), and on out across the Philippines. That scientist declined to tell even his colleagues where that path-of-risk lay. His withholding of this knowledge has been endorsed by many other NEO scientists. But it dramatically counters the risk communication policies of many experts and agencies far more accustomed to dealing with these issues (e.g. U.S. Dept. of Health and Human Services "Risk Communications Guidelines, 2002"; U.S. Centers for Disease Control, 2003; U.S. Nuclear Regulatory Commission "Guidelines for External Risk Communication," 2004). They say, *"Communicate early and often: failure [to do so] breeds mistrust and gives others the opportunity to frame the issues."*

Fig. 1 shows the approximate path-of-risk for the possible impact of Apophis in 2036. Although the chances it will hit are now only 1-in- 38,000, if it does strike, it will do so on or very near the red line in the figure. That path qualitatively differs from its 2029 path, placing much greater emphasis on tsunamis. This is useful information. It may be relevant for people we can't even imagine (e.g. developers of resorts in Costa Rica). There are myths about the downsides of putting all information out, used as rationalizations by astronomers and space agency officials for withholding information, but which are counter to the policies of expert social scientists. Professional opinion in the hazards community is that the potential for people reacting to information with fear and panic is a myth concocted by the news media and has no support from studies of social psychology. However, until it is studied, there may be aspects of the impact hazard (e.g. that the threat is usually decades rather than days in the future) that could suggest a different approach for NEOs than the one adopted for more common natural disasters.

NASA must develop risk communication policies and procedures so that future communications are done in accurate, professional, and consistent ways. These are not simple responsibilities and, so far, have been carried out by well-intentioned astronomers who are, however, mostly unfamiliar with the professional methodologies of the scholarly field of risk communication. If risk communication is done poorly, people may become unduly alarmed, they may lose faith in the veracity of official statements, they may misunderstand what's being communicated, they may ignore important warnings, and so on. Communicating with other disaster management agencies has its own challenges in the case of the NEO impact hazard. These agencies do not (yet) have NEO disaster response plans on-the-shelf, ready to implement. The points of contact have not even been specified, and – despite popular movies and TV documentaries about asteroids – there is essentially no technical competence in these agencies about NEO-specific issues. So NASA's risk communication activities must include major elements of education about this unusual kind of disaster.

<u>Strategic End-to-End Planning and Decision-Making.</u> A simplistic view is to say that the predicted impact of a NEO many decades from now is of no immediate consequence. Let's wait until we are 10 or 20 years from the predicted impact, and then see what we might do about it. Our analysis of the Apophis case (also Chesley 2006) has taught us that reality can differ sharply from our preconceptions. It turns out to be orders-of-magnitude easier to divert Apophis from impact in 2036 if the deflection is done in the mid-2020s than if it is attempted after 2029. This is because one only has to deflect the body from passing through a 600 m wide keyhole in the 2020s rather than deflecting it across the radius of planet Earth afterwards. Yet another factor affects Apophis. Because it is an Aten, it is virtually impossible to observe almost all of the time. Favorable opportunities for either optical or radar tracking occur only every 7 years or so. Therefore, its orbit cannot be continuously tracked. Prior to May 2006, the probability of impact was estimated at 1-in-6000. It was expected that if the radar observations attempted that month were successful, the impact probability would either go up, or – more likely – go to zero. Instead, the probability diminished, but remains very significant at 1-in-38,000. Although, with effort, optical tracking may be possible before 2012, Apophis is very unlikely to be retired from its TS=1 status until 2012/2013, at which time its impact probability could rise (this time it seems as though it must rise appreciably, or more likely vanish). But 2013 is getting rather close to the mid-2020s if one is to mount a spacecraft mission to deflect it. And we will need to know its position extremely accurately with

respect to a keyhole only 600 m wide. So, if a keyhole strike is still possible after 2013, a mission to deploy a transponder in the mid-to-late teens would seem required to justify (or rule out) the much more complex deflection mission. Considerations such as these already affected priorities for observing Apophis with the unique and over-subscribed Arecibo radar facility in May 2006, and imply a quick decision some 7 to 8 years from now to implement a transponder mission.

This cogently exemplifies how a far-distant impact possibility may merit decisions and actions in the very near-term. A similar analysis of 2004 VD17 reveals reasons why it might be best to deflect it fairly soon, despite the fact that its potential impact (another TS=1) is 96 years from now; it is much easier to divert it within the next few decades than to hope for advanced technology in the last decades of the 21st century. (Technology does not inevitably improve, even in our business: how long has it been since we have had the capabilities of the Saturn V rocket?) In other cases (a short-term warning of impact by a small NEO, or potential impact by a large comet where deflection is not technologically feasible), we may require very different responses, including storing up food supplies, stockpiling medical supplies, establishing environmentally secure hospitals, or planning for mass evacuations, where the process more nearly resembles traditional disaster management scenarios.

However it is decided that NEO responsibilities will be shared among different agencies in the future, it is clearly NASA's responsibility to study the scenario timelines, as exemplified above, because they are so intimately tied to the telescopic survey logistics as well as space mission development timelines that are a NASA specialty. An integrated plan must be developed by NASA to coordinate telescopic and radar observations, potential reconnaissance or transponder missions, and deflection missions, even if responsibility for some of these activities is ultimately given to another agency.

III. Broader Responsibilities for Threat Mitigation

An end-to-end mitigation strategy must necessarily extend to include response and recovery operations. Elements of response may or may not be assigned to NASA, but some would naturally fall within the purview of other agencies. Nevertheless NASA must cleanly interface with these other agencies and lend its expertise to them, especially regarding technical facts about NEOs and impacts which may be relevant in the response and recovery phases of an actual impact disaster. For example, NASA scientists have the expertise to explain – to the public, to officials, to other agencies – features of NEA impacts that differ from more common disasters (e.g. unlike earthquake aftershocks, there are no "after-impacts"; NEOs are not radioactive; etc.).

We briefly outline broader NEO threat mitigation measures that need to be undertaken by some combination of agencies (cf. Garshnek *et al.* 2000; Chapman, Durda & Gold 2001):

● Evaluation of the physical and environmental effects of impacts by NEOs of different sizes and types, impacting different kinds of locations (ocean, shallow-water, urban areas, rural regions) and studies of the expected consequences for society (including infrastructure, agriculture, economies, trauma and mortality, psychological after-effects, etc.). Chapman (2003) broadly treated these issues, but they need to be particularized to individual countries, cities, etc. and the underlying science about the consequences of impacts needs to be further developed. For instance, it has been recently concluded (Birks *et al*. 2004) that NEOs as small as 500 m diameter could seriously damage the Earth's ozone layer; is this result robust and what does it imply for people or for agriculture, say in the American mid-west?

● Evaluation of potential social and psychological responses to the more likely non-disasters by NEOs. It is much more likely that there will be very close near-misses, or strikes by large-but-not-very-dangerous NEOs (say several megatons), or other events much more serious than any past scares than that there will be a mega-disaster from a NEO strike. Recalling widespread public fears in the 1970s about the impending fall of Skylab, it is distinctly possible that government officials and mental health-care providers will have to deal with a significant NEO event that falls short of an actual disaster. They should be prepared.

● Enhancement of disaster mitigation measures to account for NEOs. As we said at the outset, many aspects of a NEO impact disaster will resemble common disasters for which the all-hazards planning will be relevant during response and recovery. But there are differences. NEOs can hit anywhere, including locations where analogous disasters are rare or impossible. We saw in 2004 that all the disaster planning and awareness of potential tsunamis around the Pacific Rim were irrelevant to the unusual major tsunami in the Indian Ocean. Tsunamis produced by NEOs not only may occur in oceans where tsunamis are rare, but the behavior of the waves will generally differ for a NEO tsunami than for a tsunami resulting from an earthquake or landslide. There should be available to disaster managers an on-the-shelf description of both similarities and differences between plausible NEO impact disaster scenarios and familiar disasters.

● Long-term preparations for a NEO disaster. The NEO hazard is unusual in that it is plausible that there will be years or decades of warning before an impact happens. That provides an unparalleled opportunity – which, however, must be taken advantage of – to spend years preparing to evacuate ground-zero; assemble and safely store food, medical supplies, and other vital human and material resources to deal with the disaster when it happens; and plan for the recovery. Policy issues need to be addressed well in advance: Who secures property/infrastructure in regions to be evacuated? Who is responsible for loss of property values in evacuated areas? Internationally, who is responsible if a mitigation attempt fails part-way through operation, and the NEO hits a country not previously threatened? While major preparations need not begin until an actual impact is forecast, it is desirable to begin to establish policies and to outline how these procedures should unfold, should they prove necessary.

IV. Conclusions

As the entity responsible for the Spaceguard early warning system, NASA should embark on a modest but serious effort to interface with the risk communication and disaster management communities, to evaluate the reliability of its impact probability estimates, to improve its effectiveness in communicating about these complex issues, and to develop broad-based interfaces with national and international disaster mitigation infrastructures. Beyond that, whether undertaken in part by NASA or wholly by other government agencies, we encourage the Panel to recommend that the NEO impact hazard be made more explicitly part of the nation's hazard reduction plans.

FEMA first adopted a National Mitigation Strategy more than a decade ago. Since then, there have been various attempts to develop a cohesive disaster reduction plan for the United States. For example, in 1996 the President's National Science and Technology Council's (NSTC) Subcommittee on Natural Disaster Reduction (since renamed Subcommittee on Disaster Reduction), recommended that the U.S. government increase pre-disaster anticipation and assessment of risks, focus on resilient mitigation planning comprehensively and from the beginning, and implement information and warning systems that can raise the awareness of citizens to a threatening disaster.

Last year the NSTC Subcommittee issued a new report, "Grand Challenges for Disaster Reduction," that suggested ways to address the six "grand challenges" that it identified. Although the report failed to include NEO impacts among the disasters it treated (except in one sidebar, which mentions "meteorites" among things that can cause tsunamis), most of these challenges are directly relevant to the NEO impact hazard: (a) providing hazard and disaster information, (b) understanding the natural processes that produce hazards, (c) developing hazard mitigation strategies and technologies, (d) reducing vulnerability of critical infrastructure, (e) developing resilient, comprehensive risk assessments (and learning from past events), and (f) raising public awareness about hazards and how to respond effectively. Because of the impact of major, recent disasters (especially 9/11 terrorist attacks and Hurricane Katrina), federal approaches to disaster management are under review. It is, therefore, an opportune time for the NEO impact hazard to be included in the "all-hazards" mix. Disaster management officials at all levels should have, developed and waiting for implementation, plans of how to respond if and when astronomers report (through whatever formal channels are established) that there is a serious threat of a NEO impact. Indeed, astronomers, NASA officials, and disaster management officials should plan for more effective handling of the NEO incidents (e.g. predictions of possible impacts) that have occurred already and will continue to occur at an increasing rate, once the next phase of the Spaceguard Survey is underway.

The cost of mitigating the impact hazard is difficult to measure, until there is an explicit public policy decision about the priority of addressing this hazard in the national agenda. Presently, the threat is addressed by the several-million-dollar-per-year Near Earth Object Observation program, most of which supports the Spaceguard Survey; nearly all of the remainder supports characterization of NEOs. There is close to zero support (from NASA or any other funding agency) for any other approaches to addressing the NEO threat. This includes mitigation, whether by deflection or the other approaches discussed in this White Paper. In this context, any funding at all of an integrated NEO threat management activity would be welcome.

There have been several past attempts (cf. Canavan 1994) to calculate, using cost-benefit analysis techniques, the value of mitigating the impact threat. Results range from tens- of-millions-of-dollars-per-year to over ten-billion-dollars-per-year. While it makes sense that a substantial fraction of such costs be spent on telescopic or space-based surveys that can "retire the hazard," it is reasonable also to spend money (perhaps a quarter of the total) on planning for mitigation – should a threatening NEO be discovered. And a balanced approach to mitigation should place significant resources (perhaps a quarter of the quarter) on the kinds of approaches to mitigation discussed in this White Paper, beyond just planning to deflect a NEO. That would amount to expenditures ranging from hundreds-of-thousands-of-dollars to $500 million per year, depending on which cost-benefit analysis is adopted. (Of course, at the present time, the nation's investment in the NEO hazard is only a tenth of the smallest estimate from the cost-benefit analyses.) Thus elements of a professional, integrated threat management strategy can be developed at various cost levels, commensurate with the overall priority given to the NEO impact hazard.

References

J.W. Birks, P. J. Crutzen & R.G. Roble 2006. Frequent ozone depletion resulting from impacts of asteroids and comets, In *Comet/Asteroid Impacts and Human Society* (P. Bobrowsky & H. Rickman, Eds., Springer Verlag), in press.

G.H. Canavan 1994. Cost and benefit of near-Earth object detection and interception. In *Hazards due to Comets and Asteroids* (T. Gehrels, ed., Univ. Ariz. Press, Tucson), 1157-1189.

C.R. Chapman 1999. Asteroid impact hazard: Role of uncertainties. Abstract for "Asteroids/Comets/Meteors" conference, Cornell Univ., 26-30 July 1999.

C.R. Chapman, D. Durda, and R.E. Gold 2001. "The Comet/Asteroid Impact Hazard: A Systems Approach." SwRI White Paper, 24 Feb.● 2001. http://www.internationalspace.com/pdf/NEOwp_Chapman-Durda-Gold.pdf.

C.R. Chapman 2003. How a Near-Earth Object Impact Might Affect Society, paper commissioned by the OECD for *Workshop on Near Earth Objects: Risks, Policies, Actions*, Jan. 2003, Frascati, Italy. http://www.boulder.swri.edu/clark/oecdjanf.doc.

S. Chesley 2006. Potential impact detection for Near-Earth asteroids: the case of 99942 Apophis. *Asteroids, Comets, Meteors* (Proc. IAU Symp. 229, Cambridge Univ. Press), 215-228.

V. Gashnek, V., D. Morrison & F. M. Burkle Jr. 2000. The mitigation, management, and survivability of asteroid/comet impact with Earth. *Space Policy* **16**, 213-222.

D. Sarewitz, R.A. Pielke, Jr., and R. Byerly, Jr. (eds.) 2000. *Prediction: Science, Decision Making, and the Future of Nature* (Island Press, Wash. D.C.), 405 pp.

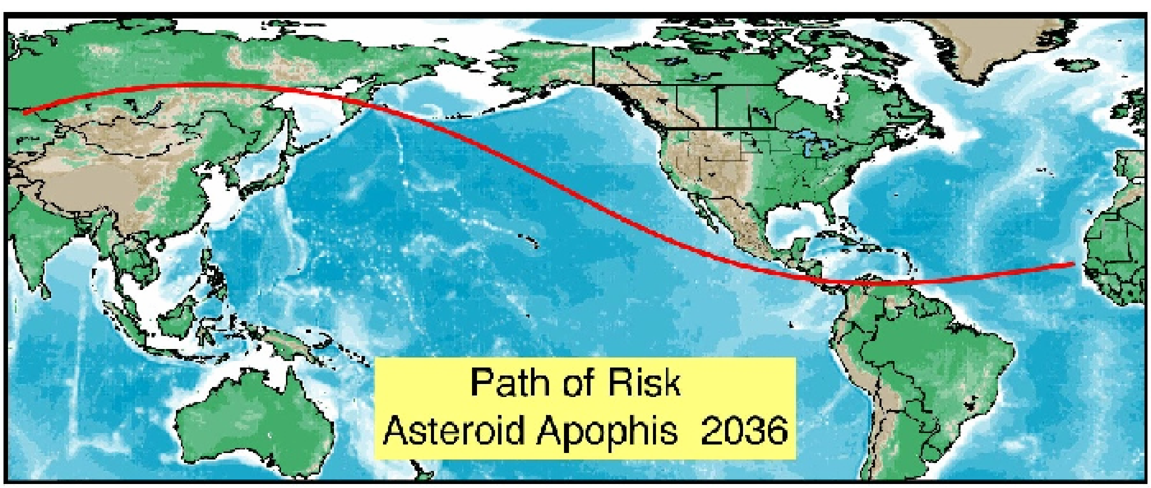

Figure 1. Apophis path of risk.