Acta Astronautica ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Impact decision support diagrams

Mark Boslough *

Sandia National Laboratories PO Box 5800, Albuquerque, NM 87185, USA

ARTICLE INFO

Article history:
Received 28 May 2013
Received in revised form
30 July 2013
Accepted 19 August 2013

Keywords:
Impact
NEO
Risk assessment
Decision support
Uncertainty quantification

ABSTRACT

One way to frame the job of planetary defense is to “find the optimal approach for finding the optimal approach” to NEO mitigation. This requires a framework for defining in advance what should be done under various circumstances. The two-dimensional action matrix from the recent NRC report “Defending Planet Earth” can be generalized to a notional “Impact Decision Support Diagram” by extending it into a third dimension. The NRC action matrix incorporated two important axes: size and time-to-impact, but probability of impact is also critical (it is part of the definitions of both the Torino and Palermo scales). Uncertainty has been neglected, but is also crucial. It can be incorporated by subsuming it into the NEO size axis by redefining size to be three standard deviations greater than the best estimate, thereby providing a built-in conservative margin. The independent variable is time-to-impact, which is known with high precision. The other two axes are both quantitative assessments of uncertainty and are both time dependent. Thus, the diagram is entirely an expression of uncertainty. The true impact probability is either one or zero, and the true size does not change. The domain contains information about the current uncertainty, which changes with time (as opposed to reality, which does not change).

1. Introduction

At any instant, there are probability, size, and size-uncertainty estimates for a given NEO. As these change, the NEO will follow a trajectory in the three-dimensional domain. NEOs with multiple potential impact dates will have multiple trajectories. The decision should depend only on the current position of the NEO in the decision domain, not on its phase-space trajectory. Thus there will be a volume within which a given action is recommended. Uncertainty is included in the size estimate, so the assessed NEO size will change with time (almost always getting smaller as uncertainty decreases) but at any given time we must assume the worst and act accordingly. Decision domains will be separated by surfaces. The diagram is for NEOs that do not pass through keyholes, but the concept is also applicable to keyhole passages.

The NRC action matrix [1] will map directly to the “probability equals one” plane where examples of possible decision domains can be used to generate a notional diagram. This hypothetical diagram could, for example, recommend that NEOs smaller than 100 m not be deflected, define a region where slow-push is optimal, a region where nuclear deflection is optimal, and a region that is beyond any realistic mitigation attempt. As time progresses, the prescribed strategy would change from slow-push to nuclear, so the need for a “back-up plan” is explicit. Virtually every NEO that has been discovered is moving on a trajectory that is within an epsilon of the $p=0$ surface. PHOs can rise above this surface into a region in which action is recommended. The first-level action could be “characterize and plan.” For a given size, there would be some probability threshold above which production of hardware (rockets and warheads) should commence. This would also depend on time-to-impact. The amount of time

* Tel.: +1 505 845 8851.
E-mail address: mbboslo@sandia.gov

0094-5765/$ - see front matter © 2013 Published by Elsevier Ltd. on behalf of IAA.
http://dx.doi.org/10.1016/j.actaastro.2013.08.013

needed depends on ΔV requirements, so a "scaled time" axis would be useful.

Every plane associated with a given NEO size would have a family of curves separating various action domains. They could be generated from a dense matrix based on expert consensus. The first step should define the action domains and how they should relate to one another, but not define their boundaries.

Finally, the decision support diagram only considers technical/science/engineering issues. Clearly there are political, economic, and diplomatic issues that would also be part of the actual decision making. Decision-makers will make a "go/no-go" decision that is ultimately based on information other than technical. The planetary defense community needs to make "go" an option for them, or else there would be no decision for them to make.

2. Decision support diagrams

The concept of impact decision support diagrams was presented as an e-poster at the 2011 Planetary Defense Conference. The following description is adapted from the poster narration and selected figures from the poster are reproduced.

Impact decision support diagrams are intended to provide a playbook for when an asteroid is discovered. The Torino scale (Fig. 1) communicates the seriousness of a potential impact, but not recommendations for action. It is not a decision support tool. However, it is a useful starting point for thinking about decision support. After an asteroid is discovered, its size and impact probability can be estimated. The best estimates can be plotted as a single point in a two-dimensional plane.

A one kilometer asteroid with an impact probability of one-in-a-million is level zero on the Torino Scale, defined as "no hazard." However, this scale does not consider size uncertainty. An unusually dark or odd-shaped asteroid can appear much smaller than it really is. To be conservative, we should add an error bar to capture this uncertainty.

A three-sigma margin of error assumes the worst-case. The upper bound is now in the category 1 domain–still not an unusual level of threat, but a slightly greater cause for concern.

Continued observations of an asteroid will move its position in this two-dimensional plane, as its size and orbit are refined. Often the apparent impact probability will go up as the error ellipse in its future position gets smaller, but still contains the earth. As the size uncertainty shrinks, the three-sigma value will usually decrease.

This can be plotted as an incremental trajectory in the two-dimensional Torino scale plane (black arrow in Fig. 1).

Continued observations will further refine the size and orbit, and these trajectories can be plotted (Fig. 2). In the vast majority of cases, the probability will reverse as the error limits shrink past the projected location of the Earth. In exceedingly rare cases, the probability of impact will increase to one. The Torino scale tells us that this will be a bad thing, but does not tell us what to do.

We can also watch this trajectory in the two-dimensional plane, like frames of a movie. By super-imposing these "movie frames" a three dimensional volume can be created, in which the third dimension is time (or time until impact, see Fig. 3). The actual trajectory follows a path in a three-dimensional volume, which can be used to build decision support diagrams. The stacked surfaces can be visualized as a volume of the same orientation (Fig. 4).

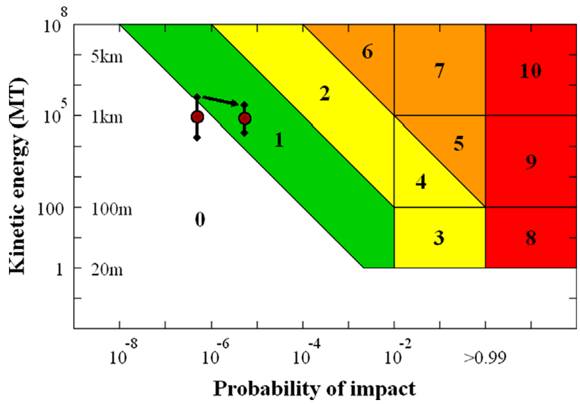

Fig. 1. The Torino scale and position of asteroid (red circle) with size uncertainty error bars at two different observation times. Black arrow indicates incremental trajectory of NEO in this two-dimensional plane. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

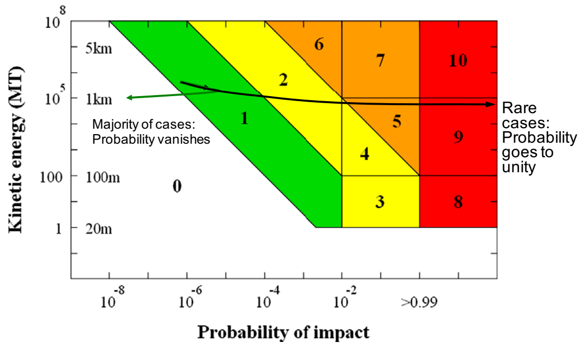

Fig. 2. Trajectories in two-dimensional Torino scale plane.

This volume can be transformed into a more useful format by reversing the probability axis and considering the two-dimensional plane for which probability equals one: the left-hand face. By rotating the box, we can consider the 100% probability surface (Fig. 5).

For purposes of illustration, domains are defined for various actions. According to this diagram, civil defense is the best decision for objects smaller than 100 m in diameter. The smallest objects that are harmless can be opportunities for research or even tourism. Regardless of how much time there is to prepare, this diagram suggests that it would be better to evacuate the area than to attempt to deflect a small hazardous asteroid. In reality, it would depend on the population density and other factors, and the threshold for active mitigation versus civil defense is by no means settled. One purpose of these diagrams would be to force their creators to think about these issues in advance and communicate their opinions clearly and comprehensively.

Please cite this article as: M. Boslough, Impact decision support diagrams, Acta Astronautica (2013), http://dx.doi.org/10.1016/j.actaastro.2013.08.013

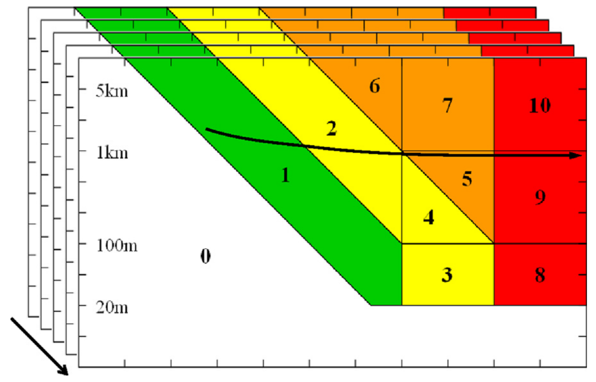

Fig. 3. Snapshots of the two-dimensional Torino scale plane can be stacked to create a three-dimensional volume.

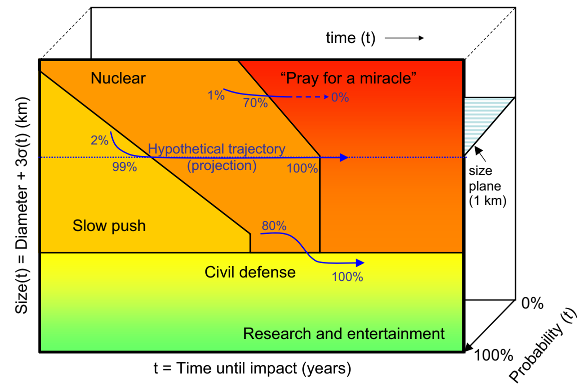

Fig. 5. Transformed and rotated volume of Torino scale surfaces, hypothetical NEO trajectories and decision domains.

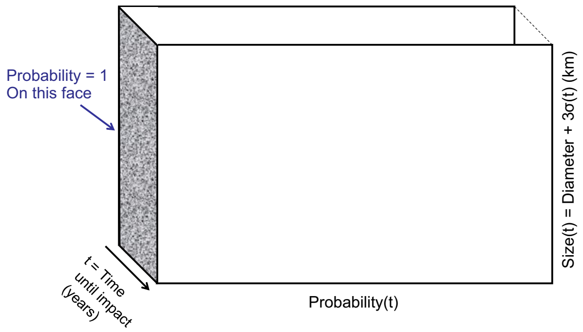

Fig. 4. Three-dimensional volume with time-until-impact as third axis.

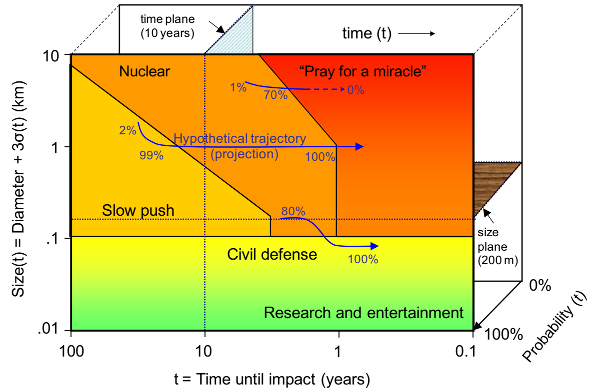

Fig. 6. Decisions support volume with 200-m asteroid size plane, and 10-year time plane.

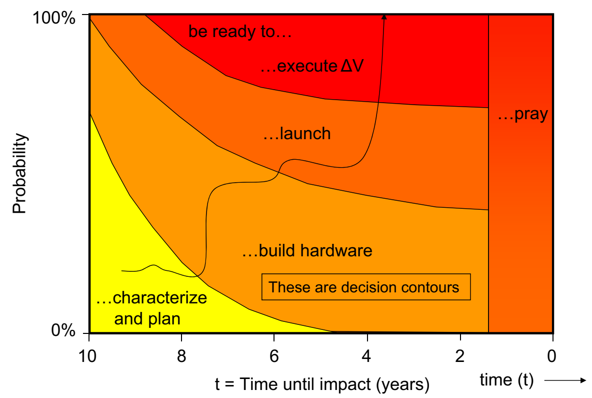

Fig. 7. Notional action domains for two-dimensional slice corresponding to a 200-meter NEO.

Notional action domains on this diagram indicate that large objects with plenty of time can be deflected by slow push methods, large objects with less time would require nuclear methods, and there is nothing that can be done about large objects with little warning time except "pray for a miracle".

Threat trajectories can also be plotted in this volume and projected onto the 100% probability plane. Sometimes the probability will grow to 100% and intersect this plane; however, in most cases it will go to zero and there will be no impact.

Trajectories can also be projected onto internal planes, for example a plane defined by a 1 km asteroid. Orthogonal planes can be defined for any asteroid at a specific time, such as 10 years before impact.

The size plane for a 200-meter asteroid is shown in Fig. 6. In Fig. 7, it is shown face-on to illustrate how actions can be defined as domains in this plane. These domains are actually slices of three-dimensional volumes that span the space defined by the box.

By plotting action domains on every such plane, we can provide a playbook for decision makers. Depending on the size and probability of impact, the recommendation is to characterize and plan, build hardware, launch the mission, or execute the deflection maneuver. The domain boundaries could be recommended by a committee of experts, long before a dangerous asteroid is discovered.

The two-dimensional surfaces can be used to build up a three dimensional volume of action surfaces, or impact decision support diagrams.

Finally, it is worth noting in this context that the evolution of impact probability–and therefore warning time–depends critically on NEO size. According to Chodas [2], warning time is a strong function of size. Smaller

Please cite this article as: M. Boslough, Impact decision support diagrams, Acta Astronautica (2013), http://dx.doi.org/10.1016/j.actaastro.2013.08.013

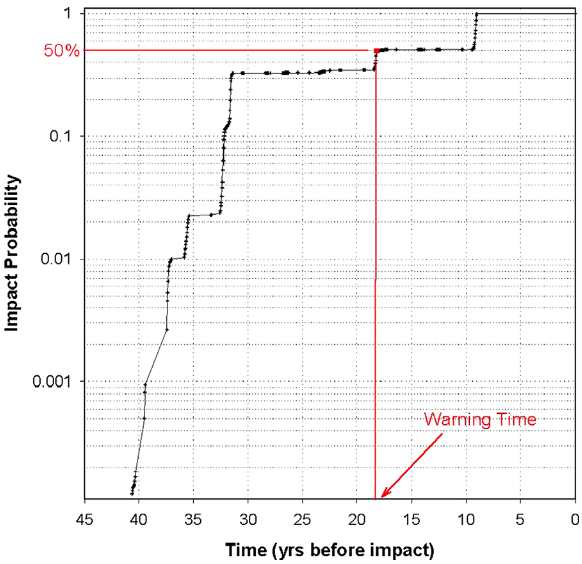

Fig. 8. Evolution of impact probability as a function of time for hypothetical threat, from Chodas [2].

objects have shorter warning times, and some (such as the Chelyabinsk event of Feb. 15, 2013) strike with no warning at all. Fig. 8 illustrates the evolution of impact probability with time. The time before impact at which the probability reaches 50% is defined as the warning time.

Acknowledgments

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

References

[1] Committee to Review Near-Earth Object Surveys and Hazard Mitigation Strategies, National Research Council, Defending Planet Earth, Near-Earth Object Surveys and Hazard Mitigation Strategies (2010) p. 152.

[2] Chodas, P., NEO Warning Times for NEAs and Comets, Planetary Defense Conference (2007).

Please cite this article as: M. Boslough, Impact decision support diagrams, Acta Astronautica (2013), http://dx.doi.org/10.1016/j.actaastro.2013.08.013