4^{th} IAA Planetary Defense Conference – PDC 2015
13-17 April 2015, Frascati, Roma, Italy

IAA-PDC-15-04-13

METRICS FOR EVALUATING EFFECTIVE DISRUPTION OF HAZARDOUS NEAR-EARTH OBJECTS

Brian D. Kaplinger(1)
(1)*Florida Institute of Technology, 150 W. University Blvd., Melbourne FL, USA,*
+1 (321) 674-7043

Keywords: *simulation, disruption, computing, deflection, mitigation*

Extended Abstract—

This paper presents the results of simulations and analysis investigating the relationships between mass distribution, velocity distribution, and risk of impact for a disrupted near-Earth object (NEO). A preliminary set of metrics for the comparison of such simulations is developed, and a discussion is begun considering what it means to have an effective mitigation strategy.

Introduction

In moving the science of NEO threat mitigation to effective engineering, many questions transfer from the laboratory to simulations of these ideas applied in a low gravity environment. As our understanding of NEO characteristics becomes better, many research groups have developing simulation packages to investigate strategies to best deflect, disrupt, or otherwise mitigate a threatening mass on an impacting (or near-impacting) trajectory. If all uncertainties regarding the behavior of a particular body under a mitigation strategy could be eliminated, bounded, or modeled, then computer simulations would represent a near-perfect truth case. Even in this unrealistic scenario, there would still be operational uncertainties related to the actual mitigation mission. This is especially the case when disruption of a target is the intended outcome [1], or for higher energy deflection methods where unintentional disruption is a very real (even likely) possibility [2]. Disruption has been proposed as the method of highest readiness for mitigating the most likely near-term threat of small NEOs, which contribute to dangerous high-altitude airburst events [1,3].

Given the outcome of a particular disruption simulation, the question arises: “Does this represent an effective strategy for mitigation of the target?” Answering this question is deceptively complicated. Early attempts focused on a particular sample case, such as the asteroid Apophis or a fictional impactor. In analyzing these cases for a fixed lead time ahead of impact, it is clear that there is a dominant deflection and/or disruption direction, and that the metric of “total mass remaining on impacting trajectories” is highly dependent on this choice of direction with two degrees of freedom. This is unfortunate because in many cases that metric is the number a policy maker wishes to know before endorsing a strategy. To makes matters worse, some deflection directions (possibly including the optimum direction) are unachievable at any given lead time, and this metric of impacting mass is also dependent on lead time. For this scenario, we focus on investigating some common moments of the mass and velocity distributions represented by post-disruption debris to begin the development of an effective set of computational metrics.

In addition to the limitations investigated in the previous scenario, using the metric of impacting mass is necessarily orbit-dependent. We attempt to characterize this dependence using a large cross section of known NEO orbits parameterized in an (a, e, i) space, which represents much of the variance in observed hazardous objects. This analysis is used to limit the set of measures that are feasible for evaluating the effectiveness of a disruption attempt.

Finally, the author’s thoughts on what parameters are needed to report and recreate an effective mitigation strategy are presented in order to stimulate a dialogue to better understand quantitative figures of “effectiveness” such as those given by NRC and NASA reports.

Debris Source Model and Limitations

Four debris source models were used for the present study. Two are the result of simulations, while two are distributions that are sampled to determine an initial debris field. The coordinate system is the same for all models as reported in this paper. The X axis is considered a dominant disruption direction, considered to be the vector in the direction of mean momentum after disruption relative to an initially stationary target. The Y and Z axes are arbitrary and considered to be in the plane perpendicular to the dominant direction, which is commonly the direction of the approach of the mitigation spacecraft. This choice is made to be inclusive of 2D models, which are commonly used to represent axisymmetric problems (even in the case where the simulation equations of motion assume cylindrical symmetry, which would introduce errors). In the case of a standoff deflection attempt resulting in disruption, the dominant momentum direction is typically along the path from the energy source to the target. For the purposes of clarity, the dominant direction is considered to be the mean change in momentum after the end of the simulation.

Model 1 utilizes a fragmentation model of a 270 m diameter asteroid originally reported in Reference 4. The source simulation was conducted by David Dearborn using the CALE code at Lawrence Livermore National Laboratory (LLNL). Features of this debris source model include a clear dominant debris momentum direction, and axisymmetric distribution of radial velocity. As the result of a 2D ALE code, the fragment model is generated from control volumes by placing equally sized masses at random azimuths from the mean direction. Higher fragment count models were created by interpolating the state information within each control volume. An example distribution generated using this data is shown in Figure 1.

Model 2 utilizes a debris source processed from a simulation conducted at Iowa State University [5]. The target was a contact binary with largest dimension of approximately 80 m. As an SPH model, fragments for this simulation were created by a selection of neighbors of undamaged material. Features of this debris source model includes a dominant direction, with a greater dispersion of radial velocity off of the dominant axis than is seen in Model 1. Total fragment velocities for this distribution average over 100 m/s, though lower velocities are observed for intact core material. The result of the 3D simulation is almost axisymmetric in momentum, though some azimuth directions differ substantially in terms of fragment momentum due to the evolution of the simulation dynamics. The resulting fragment distribution is not uniform in terms of fragment mass. The initial target model and resulting distribution are shown in Figures 2 and 3. Success of this simulation as a mitigation was previously reported as being dependent both on lead time and the direction of the dominant momentum compared to the orbit of the target.

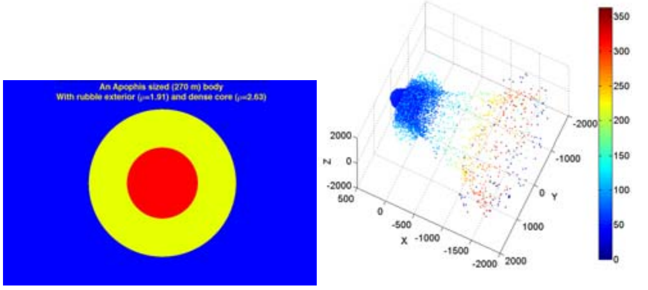

Figure 1. Initial 270 m Target and Resulting Debris Velocity (m/s), Model 1.

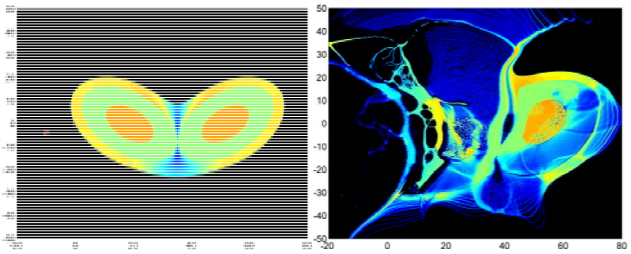

Figure 2. Initial and Final Density Distribution for Irregular 80 m Target, Model 2.

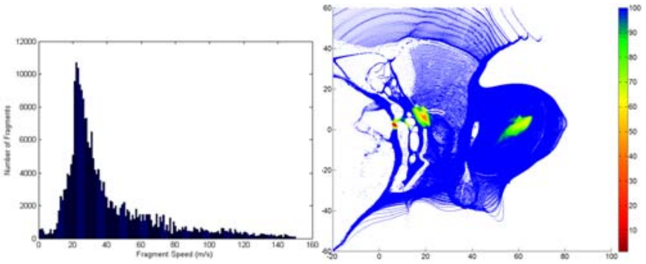

Figure 3. Fragment Velocity Histogram and Distribution, Model 2.

Models 3 and 4 are the result of sampling distributions for a presumably axisymmetric debris source. A bias momentum is applied along the dominant axis, and the radial velocity in the plane perpendicular to the dominant axis is also selected for each fragment. Distribution of fragments in the azimuth direction around the X axis is assumed to be uniform. These two models differ in how the mass of fragments is assigned. Model 3 is assumed to be a uniform distribution of mass, while Model 4 assigns mass based on a power law [6]. The nominal fragment position and velocity cumulative distributions for Models 3 and 4 can be observed in Figure 5. The selected fragment velocities and positions are scaled to best match the desired starting conditions in terms of the moments of the initial distribution.

Orbit Selection and Mission Feasibility

The unmitigated threatening asteroid orbit is presumed to impact the Earth at 0 hrs UT on January 1, 2015. The location of impact is randomly selected using two degrees of freedom, an angular displacement parallel to Earth's equatorial plane, and an angular displacement normal to the equatorial plane. A radial coordinate is chosen so that the nominal orbit path at the impact time is uniformly distributed throughout the assumed ellipsoidal volume of the Earth.

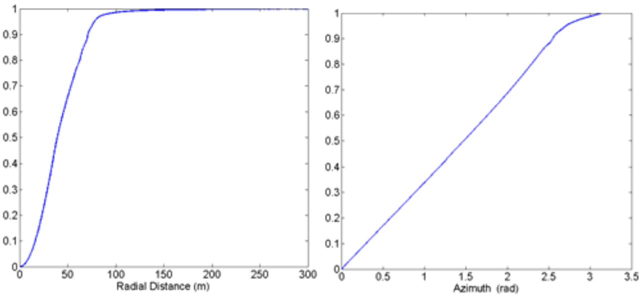

Figure 4. Radial Location Cumulative Distribution Functions for Models 3 and 4. Velocity is weighted to maintain dominant momentum direction.

For a given location of impact, the semimajor axis, *a*, eccentricity, *e*, and inclination, *i*, are chosen for the impacting orbit. The selection of these parameters is done so that the statistics of the selected orbit have the same probabilities as the observed population of Potentially Hazardous Objects (PHOs). The selection of NEAs meeting this criteria had over 1500 orbits [7] as of the time of writing. The parameterization of this (*a*, *e*, *i*) orbit space is shown by the histograms in Figure 5. The only restriction on the selection of these parameters was that the orbit had to be Earth-crossing. With 3 orbital parameters and a state vector at the impact time, the remaining classical orbit parameters were computed, generating an impacting orbit for the potential debris cloud hazard.

For a selected lead time, a selection of over 1000 orbits was obtained for a debris cloud. The point mass representation of each fragment was placed on the selected orbit ahead of impact, with a perturbation to the velocity added. Each fragment state was integrated through 1 day following the nominal impact time, and collision with the Earth was predicted for the entire debris cloud, in order to generate an orbit-independent impacting mass estimate.

Results

For an independent case of orbital dispersion including a fixed lead time and debris cloud conditions, Model 1 shows an optimal ratio of impacting mass between 0.5% and 13% dependent on the target orbit. An example of the distribution of closest approach, and the dependence on the approach vector is shown in Figure 6. Not all of the optimal approach directions are achievable for an intercept system limited to 5 km/s ΔV. More expensive systems, and equivalently longer program lead times, or a higher acceptable impact threshold would be necessary for the example case of 15 days lead time on some approach orbits. This would indicate that the example simulation might not be an effective mitigation strategy at 15 days lead time when considered as an orbit-independent case, unless an impacting mass of up to 32% is acceptable. Each 1% of the initial impacting mass for Model 1 corresponds to approximate 200 impact events of bodies in the 10-40 m diameter band. More information is needed to identify whether damage due to local clouds of impactors are dependent on each other, and if not what the acceptable threshold for impacting mass may be considering the risk of atmospheric fireballs and the uncertainty in the initial orbit.

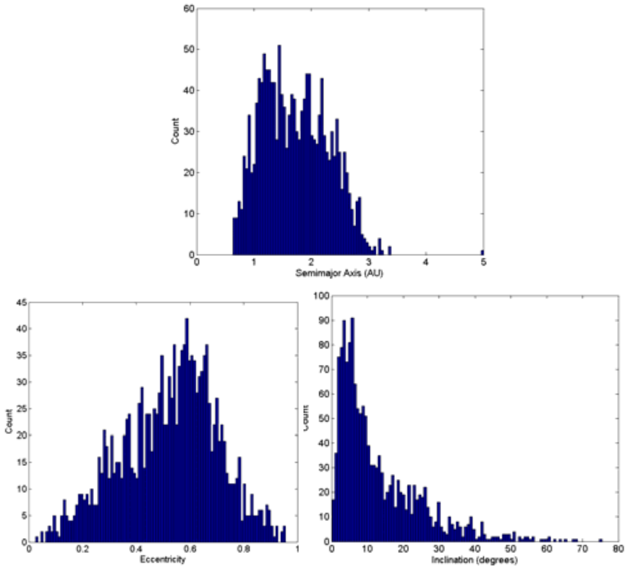

Figure 5. Initial Distributions of Sampled Orbits Using Orbit Parameters of Known PHOs.

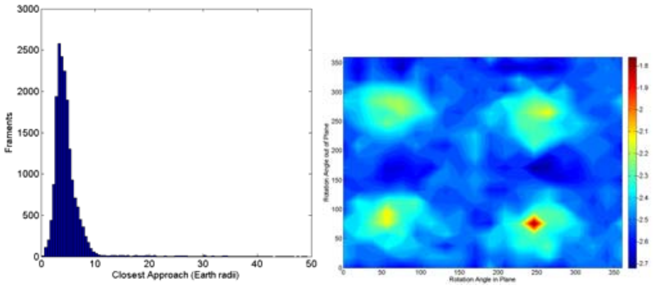

Figure 6. Example Simulation Closest Approach and Dependence on Approach Vector, Model 1.

The general dependence of a specific scenario on lead time is in general near-exponential for a fixed velocity distribution. For lead times below 10 days, almost no pairings of initial distribution velocity with orbit results in an impacting mass less than 80% of the original mass. A typical relationship between these two parameters includes an inflection point in the derivative, for an given impacting mass threshold, similar to that observed in Reference 8, which is reproduced in Figure 7. With enough lead time, drastically less velocity is needed, though it is not clear how this interacts with achievable mission success in an orbit-independent way. For the purposes of determining metrics independent of the lead

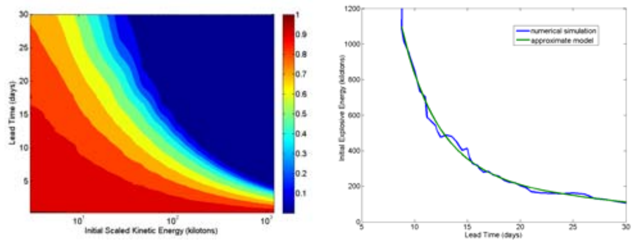

Figure 7. Example Case Relationship Between Lead Time and Required Total Initial Kinetic Energy.

time, an inflection point of 15 days lead time is assumed for the reporting of all further figures.

As expected the mean radial velocity is an important figure of merit for effectiveness of a strategy. A mean radial velocity for the initial fragment distribution in excess of 40 m/s results in an impacting mass threshold on most representative orbits below 10%. For a majority of these orbits, the impacting mass is less than half of that amount, though a few extreme cases of initial impact orbit have higher mass remaining on a trajectory for eventual impact.

The first and second moments of velocity are important as well, with the momentum representative of the mass distribution. A threshold for the mean momentum divided by the total mass, or equivalently a mass-averaged velocity, is approximately 50 m/s for the 10% impacting mass threshold. This metric may not be effective for instances in which high likelihood of a single large impactor remains. There may need to be an additional established criterion to handle this case. A proposed limit is that no mass in excess of 10% of the initial target mass have a resultant velocity of less than 10 m/s. It is not clear how this would be implemented as a stochastic case for simulation, other than establishing a probability distribution for a single largest fragment and evaluating its velocity.

Finally, further work regarding the reporting of data for simulation cases must be conducted. While a finite set of model moments can be reproduced with a known mass distribution, the resulting set of possible debris clouds meeting the constraints is infinite. A model from fuel injector design is proposed to reduce the set to a known, least entropy condition. This would minimize the reporting criterion for reproducible data sets.

References

[1] Committee to Review Near-Earth Object Surveys and Hazard Mitigation Strategies. *Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies*. National Research Council, 2010.

[2] J. Sanchez, M. Vasile, and G. Radice. On the Consequences of a Fragmentation Due to a NEO Mitigation Strategy. In *59th International Astronautical Congress*, number IAC-08-C1.3.10, September 2008.

[3] M. Boslough. Airburst Warning and Response. In *2nd IAA Planetary Defense Conference*, number IAA-PDC-2166721, May 2011.

[4] Kaplinger, B.D., Wie, B., and D. Dearborn, "Efficient Parallelization of Nonlinear Perturbation Algorithms for Orbit Prediction with Applications to Asteroid Deflection," AAS-10-225, *20th AAS/AIAA Space Flight Mechanics Meeting*, San Diego, CA, February 14-17, 2010.

[5] Kaplinger, B., Premaratne, P., Setzer, C., and B. Wie, "GPU Accelerated 3-D Modeling and Simulation of a Blended Kinetic Impact and Nuclear Subsurface Explosion," *IAA Planetary Defense Conference*, Flagstaff, AZ, April 15-19, 2013.

[6] O'Brien, D., and R. Greenberg, "Steady-State Size Distributions for Collisional Populations: Analytical Solution with Size-Dependent Strength," *Icarus*, v. 164 i. 2, 2003.

[7] http://neo.jpl.nasa.gov/cgi-bin/neo_elem, Accessed March 2015.