OVERVIEW OF COLLISIONAL-THREAT MITIGATION ACTIVITIES AT LAWRENCE LIVERMORE NATIONAL LABORATORY.

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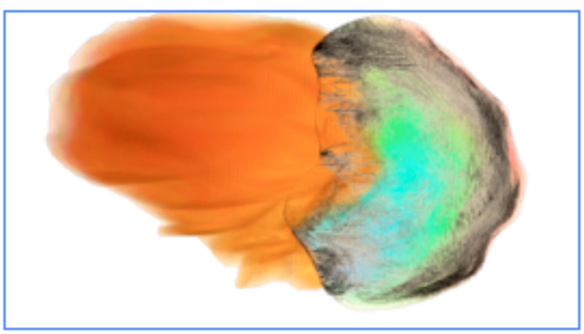
Introduction: Nuclear explosions provide a means to divert objects on a collision course with Earth. For scenarios in which there is little warning time before impact, or if the object is very large, nuclear explosives are often the only option for mitigation, so understanding their effect is critical. Our project at Lawrence Livermore National Laboratory (LLNL) is investigating issues important to the nuclear approach, including the development of scenarios of impact objects, modeling energy coupling to asteroids, response to the energy deposition, and orbital dispersion. We are evaluating a variety of strategies for a range of scenarios and assessing current U.S. capabilities. In pursuit of this, we are also conducting verification and validation work, error analysis, optimization studies, and algorithmic and simulation advances. A selection of results from throughout the project will be presented.

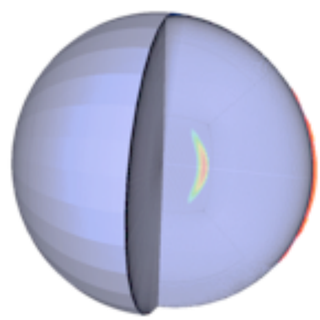
Simulation tools: We are utilizing a range of simulation capabilities, taking advantage of the strengths of different approaches. Codes include Adaptive Smoothed Particle Hydrodynamics (ASPH), ALE rad/hydro, Godunov-based Eulerian with AMR, and Lagrangian Finite Element–Discrete Element capabilities.

Deflection: We are simulating the deflection of objects, including tools to visualize the PHO distribution and the minimum required deflection velocities as a



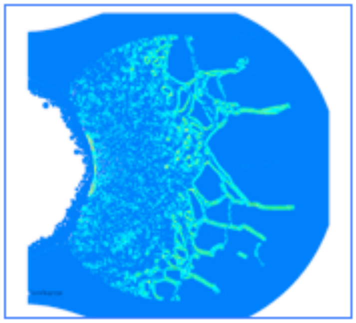
function of orbital parameters. Here, an example uses a scaled Geographos model with a realistic shape but with a 500-m-equivalent diameter, 750 kt nuclear explosion with 150 kt deposited energy. The graphic above combines volume rendering of three quantities: energy density in the ejecta (orange color scale), velocity (RGB color scale), and damage (grey scale).

Lower Limits on Deflection Velocities from Blow-off Momentum: A major source of uncertainty in predicting the response of a specific NEO to a nuclear detonation arises from the unknown, possibly complicated, internal structure of the body. For this reason, we consider non-disruptive deflection events and obtain lower bounds on deflection velocities for NEOs using the momentum of the ejected surface. We assume the surface properties of an NEO are known and model the response to a standoff nuclear detonation using ALE Rad/Hydro simulations. Lower bounds on the deflection velocities are determined as functions of deposited energy, monochromatic source type, and NEO mass. These results will inform the choice of device and standoff distance for generic NEO deflection scenarios. The graphic below shows the response of a 500 meter diameter SiO_2 NEO (no porosity, no strength) to a 165 meter standoff 27 kt neutron-source at time t = 0.05 sec. The RGB color scale shows the pressure wave in the asteroid. The red cap shows the change in density as material is ejected from the surface.

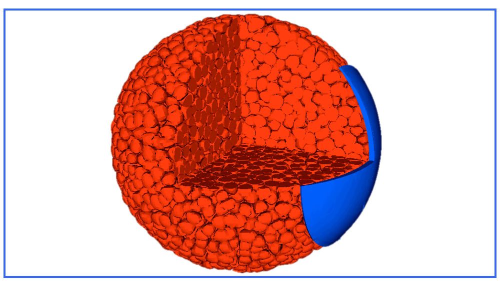


Porosity: Object porosity has a strong influence on the propagation of shock waves and subsequent damage and fracture behavior resulting from a strong impulsive energy deposition. We will report on a study of the impact of porosity.

Strength, damage, and fracture modeling: We model objects with strength, and simulate damage and fracture from impulsive deflection events. Below is an example of damage to an object with a strengthless layer of “regolith” on the outside.

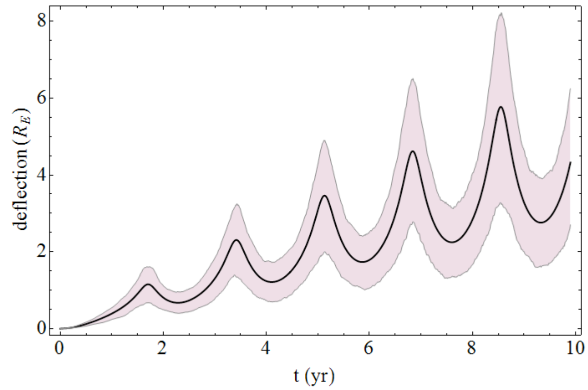


Rubble piles: Evidence suggests that some asteroids may be conglomerations of loosely bound fragments, boulders, rocks, and finer particles or regolith. We are modeling "rubble pile" objects as collections of individual boulders, and are examining the response of the object to the impulse imparted by a nearby nuclear explosion. Below is an example of an initial setup, with the energy deposition region shown as a blue cap.



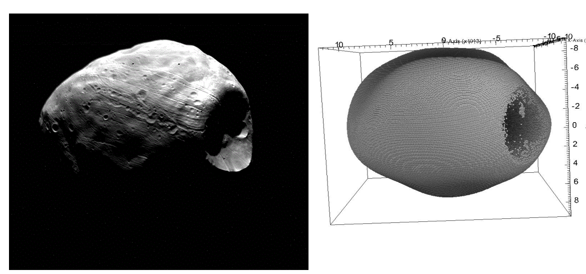
Dispersal: In the event of "rubble pile" types of objects necessitating a large deflection, as well as for other disruption scenarios, the potential for breakup and dispersal is significant. We have developed methods to assess the spread of fragments from an object through subsequent orbits. From this, mass deposition amounts and rates on the Earth may be estimated and plotted. Examples will be presented.

Uncertainty Quantification in Impulsive Deflection Scenarios: For the majority of NEO impact scenarios, optimal deflection strategies use a massive impactor or a nuclear explosive, either of which produce an impulsive change to the orbit of the object. However, uncertainties regarding the object composition and its interaction with the deflection event will lead to a non-negligible uncertainty in both the deflection velocity and direction. Propagating this error through the resulting orbit will create a positional error ellipse for the original time of impact. We calculate an analytic evolution of an impulsively deflected NEO and perform a full propagation of errors that is nonlinear in the deflection velocity vector. This provides a complete understanding of both the optimal deflection velocities needed for a given time-to-impact scenario, as well as the resulting positional error and corresponding residual impact probability. This result will also guide our computational efforts of deflection scenarios by providing a computational accuracy needed to obtain the desired deflection.



The deflection distance with errors is shown above (in Earth radii versus time from deflection in years) for the deflection of a nominal NEO with orbital characteristics of 2011 AG5, with an initial deflection velocity of 2 cm/s and 20% uncertainty. The shaded region depicts the 95% confidence interval for the deflection distance.

Validation: As part of our validation work, we have simulated impacts upon Mars' moon Phobos, and the resultant formation of the large Stickney crater. The energy released in the impact event is estimated at approximately 100 Megatons. The crater has a diameter of about 9 km.



References:

[1] Burns, J.A. (1976). *Elementary derivation of the perturbation equations of celestial mechanics*, Am. J. Phys. 44, 944-949.

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