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Asteroid-Characterization Priorities for Planetary Defense

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Extended Abstract—

We discuss a prioritized list of asteroid characteristics from a threat-mitigation perspective, discussing why each characteristic is important and providing examples of how each plays a role in mitigation. The list is prioritized by the authors in order to foster and focus discussion of the relative importance of each characteristic to mitigation approaches, to assist in identifying gaps and needs, and to inform tradeoffs in situations with limited time to plan and act. An underlying question is: What needs to be measured, and how well?

#1 Orbit

The highest-priority characteristic on our list is the orbit of a threatening object. The orbit determines if an impact will occur, along with when and how. It defines warning time and Δv requirements; sets the best time, location, and direction for deflection; and defines the impact location, angle, and velocity of impact. In addition, uncertainty of the orbit drives impact probability, influencing the decision to take action.

For most discovery scenarios of objects that are headed to impact Earth, astrometric measurement uncertainties initially will yield small probabilities of impact. The impact probabilities grow only with successive refinements of the orbit by means of additional measurements, until a point at which impact is certain (for an impacting scenario). Further refinements are necessary to localize the impact point. There is little chance that action will be taken to prepare expensive missions and/or emergency response actions until the impact probability reaches a sufficiently large value. The exact "trigger" value is unknown, but the time lost in the interim between discovery and the decision to take action may be very valuable. Shortening the time to decision, either ruling out an impact or confirming one, is of key importance.

In the event of an impact, the prevalence of oceans covering Earth suggests a water impact is likely. An example is shown in Figure 1 of 3-D hydro modeling of an impact by a 50-meter asteroid off the coast of California, with the subsequent wave generation and propagation.
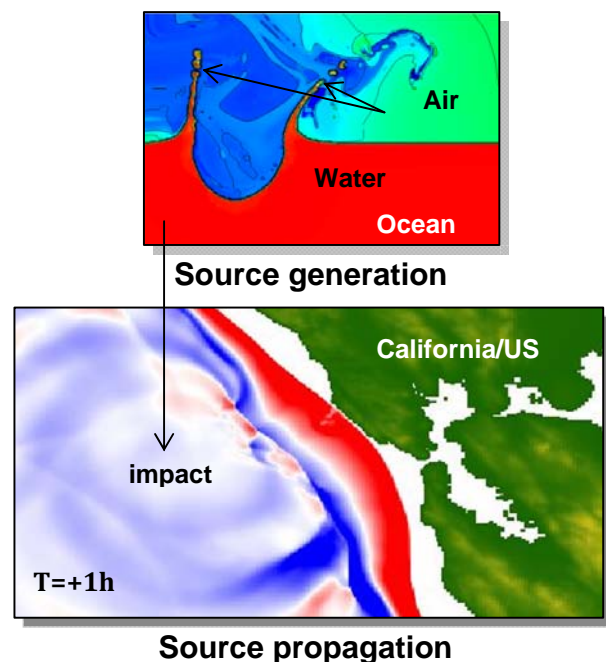

Source generation

Source propagation

Figure 1 — Simulation of asteroid impact in the Pacific Ocean near San Francisco, California. (credit: Souheil Ezzedine, LLNL)

#2 Mass

The second characteristic on our list is the mass of the asteroid. The mass, combined with warning time, sets deflection difficulty, as well as the consequences if an impact occurs. The determination of mass is often intertwined with other physical characteristics of the asteroid, including volume, surface area, and diameter; composition; bulk density; and porosity. There are a

number of ways to determine or estimate mass either directly or indirectly, and for cases requiring assumptions or informed guesses, the uncertainty of the result may span an order of magnitude. For example, if the only available information about an asteroid is its brightness, an estimate of albedo and density must be made to approximate the mass. With wide variation in both albedo and density, the resulting uncertainty range in mass may span an order of magnitude. The most accurate mass determinations are from radar observations of a natural moon or from tracking an orbital spacecraft, but neither option is likely for a real impact scenario.

#3 Composition

The next most important asteroid characteristic is composition — the elemental, chemical, and mineralogical makeup of the asteroid. Composition sets the (full) material density at the micro scale and plays a central role in determining the material strength. It influences how an asteroid reacts to either a kinetic impactor or a nuclear deflection. The composition determines the behavior of the material under impact, via the equation-of-state, including the melting and vaporization points. The material response drives the ejection of material in a kinetic impact, and is key in determining imparted-Δv estimates.

Composition is also critical in the deposition of nuclear-generated x-ray energy. In particular, the presence of high-Z (metals) or low-Z (volatiles) elements plays a big role. Table 1 lists four canonical materials for comparison of x-ray deposition depths. The greater the deposition depth, the more mass is involved in resulting blow off. More deflection is obtained by heating larger amounts of material to lower (but still melted or

Table 1 — Table of densities and x-ray penetration depths for four material compositions. (credit: Kirsten Howley and Rob Managan, LLNL)

Material	Density (g/cm³)	1 keV depth (µm)	10 keV depth (µm)
Ice	1.0	2.4	1900
Quartz	2.65	1.2	200
Forsterite	3.25	1.1	190
Fe-Ni	7.5	0.14	8

vaporized) temperatures than heating less material to higher temperatures. For two values of x-ray energy, 1 keV and 10keV, the penetration depth varies by factors of 20 and 200, respectively, between the cases of water ice and Fe-Ni metal, with intermediate materials

somewhat in the center of the ranges. Uncertainties in composition generate significant uncertainties in deflection effectiveness.

#4 Porosity

There are a range of porosities, from microscopic to macroscopic, and bulk (or average) porosity is really neither. This complicates discussions of porosity.

Porosity influences effectiveness of kinetic impactors, as well as the potential for disruption. It strongly affects the momentum-enhancement (β) factor for kinetic impactors. Porosity generally has the effect of dampening shocks and reducing the reactive response of the object to an impact or energy deposition. Except for very small asteroids, asteroid surfaces are typically covered with a layer of regolith, with its corresponding inter-granular porosity. That layer is the first material that interacts with an impactor. Figure 2 illustrates the effect of varying regolith porosity in an impactor scenario. The right half of the image corresponds to higher porosity, and the tendency to damping of the compaction response is seen.
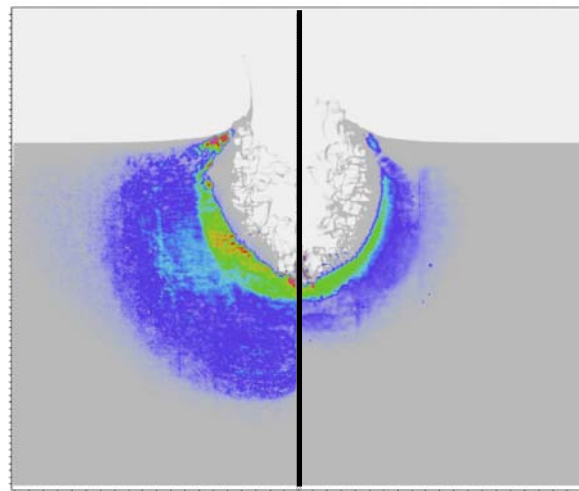

Figure 2 — Simulation of a kinetic impactor with a layer of regolith. Left side: porosity 10%. Right side: porosity 40%. (credit: Eric Herbold, LLNL)

Porosity at depth in the asteroid also affects the shock and material response, tending to reduce the damage and the tendency to break up or disrupt the object. Disruption is a major concern for smaller objects and/or short warning times that require large deflection Δv values.

#5 Shape

Shape influences the effectiveness of both kinetic and nuclear deflections. The slopes of an asteroid surface affect the direction and magnitude of Δv from kinetic impact. Figure 3 shows a snapshot from a simulation of an impactor approaching a non-spherical asteroid

(based on the shape of Golevka) from the direction of the red arrow. The momentum vector of the ejected material (colored polyhedrons) is not in the line of approach, illustrating the effect. The effect of slope generally diminishes deflection effectiveness.
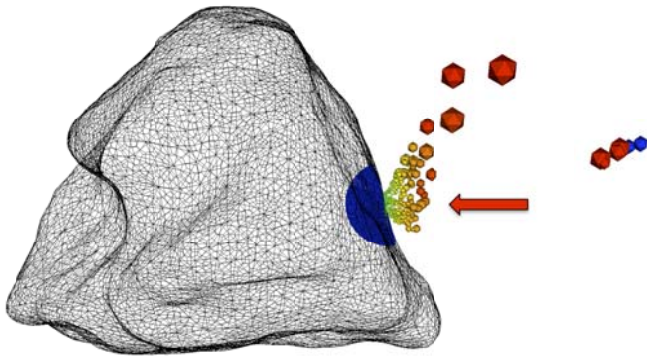

Figure 3 — Simulation of a kinetic impactor with an asteroid of the shape of Golevka. (credit: Megan Bruck Syal, LLNL)

Shape also diminishes or enhances the effect from nuclear-generated x-ray deposition compared to a spherical shape. For example, prolate ellipsoidal shapes driven from near their narrow tip show a diminishment from angled surfaces of energy deposition, while flatter regions of oblate ellipsoids provide an enhancement. These effects can diminish or enhance nominal deflection (spherical shapes) by factors of two or more.

Rotation (spin) further complicates shape effects, as discussed below in #7.

#6 Structure

The structure of an asteroid is an important characteristic and is intertwined with shape, porosity, strength, and cohesion. Structure is multiscale and heterogeneous, inherently difficult to characterize. Internal structure is particularly hard to determine. The interior structure influences the potential for disruption by a deflection. Many of the smaller asteroids are believed to consist of loosely aggregated collections of material, or "rubble piles." Such objects, particularly those of small size and very weak gravity, are susceptible to breaking up and dispersing if subject to strong accelerations or shocks. While intentional, robust disruption is a potential strategy for some impact-threat scenarios, unintentional disruption that occurs during a deflection could be very undesirable.

Figure 4 shows an example of the initial response of two asteroids, 500 meters in diameter, to the impulse delivered by nuclear-generated x-ray deposition. The one on the left is an aggregate of loosely bound material and the one on the right is a fractured, but otherwise monolithic, body (with microporosity). The color scale depicts velocity magnitude from 0 to 1 m/s.

Figure 4 illustrates that the internal structure has a direct influence on the response of the asteroid. The surface structure also plays a role. For deflection using nuclear explosives, surface features affect x-ray energy deposition by influencing re-radiation of the deposited energy (see poster by Joe Wasem et al., this conference). In addition, surface structure plays a role in the momentum-enhancement factor (β) for kinetic impactors.
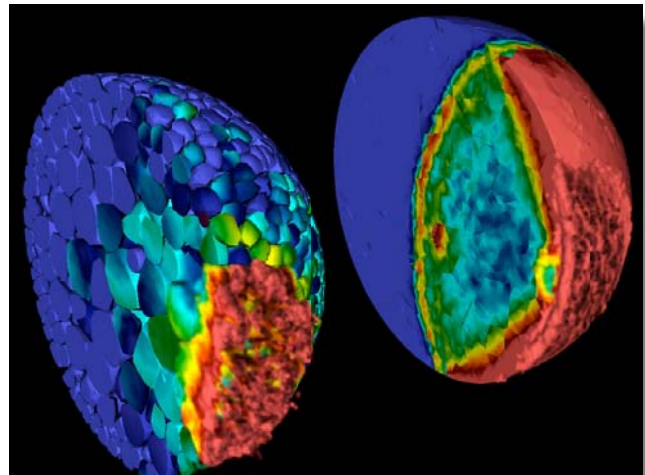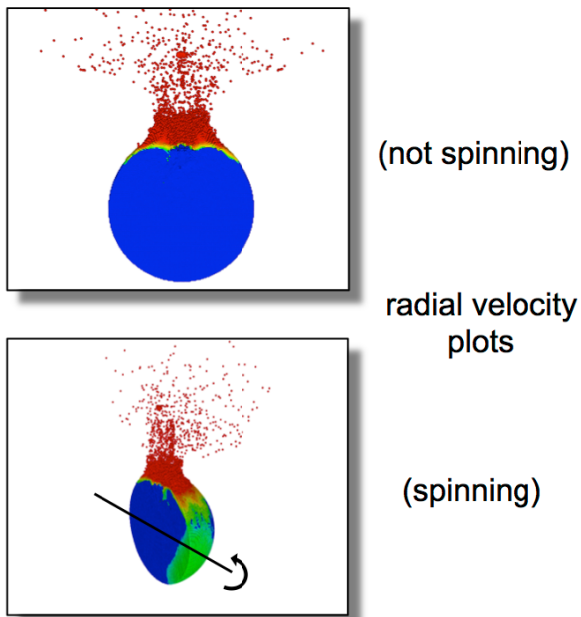

Figure 4 — Simulation of initial asteroid response to x-ray energy deposition; an aggregate boulder pile is shown on the left and a fractured monolith on the right. (credit: Eric Herbold, LLNL)

Another aspect of structure is that some asteroids have binary (or even tertiary) companions, and are not single objects. Knowledge of such a situation is important in advance of a deflection as it poses additional complications.

#7 Spin

Spin further complicates the response of an object and introduces timing issues for interceptors. As evidenced by the well-known "spin limit" plot, an asteroid with limited cohesive forces may barely hold together. A deflection acceleration may exceed cohesive limits and result in breakup and dispersal of some or all of the body. Such a response must be factored into deflection strategies. An example is shown in Figure 5 of a kinetic impact on an asteroid that is not spinning (top) and one that is (bottom). Additional material is imparted with velocity greater than the escape velocity (non-blue colors) of the body.

(not spinning)

radial velocity plots

(spinning)

Figure 5 — Simulation of a kinetic impactor on a stationary (top) and spinning (bottom) asteroid. (credit: Megan Bruck Syal, LLNL)

In addition, for both kinetic impactors and nuclear deflection, in light of the shape effects discussed earlier, spin adds a timing complication. For non-spherical asteroids, there will likely be optimal and non-optimal locations for impact or detonation to achieve maximal deflection velocity. Knowledge of the rotation period and phase would be needed to plan for the appropriate timing.

Summary

We have described a prioritized list of seven asteroid characteristics important to planetary defense. They are: orbit, mass, composition, porosity, shape, structure, and spin. With those in mind, the next topic for consideration is what methods and platforms are available to obtain data on these characteristics, both in general and for specific objects, when and if needed.

Measurement methods may be astrometric, visual, radar, spectral, gravimetric, or sample return, among others. Platforms may be Earth-based, space-based, flybys, rendezvous, or sample return. Each measurement technique and platform has its advantages and disadvantages. Differences between flyby, rendezvous, and sample missions warrant careful consideration. Flybys, while faster and relatively inexpensive compared to rendezvous, yield limited data on small targets. In particular, mass determination

normally requires rendezvous and is difficult even then for asteroids smaller than 100-m diameter. As planning and discussions continue, modeling and simulation efforts can quantify and further prioritize data needs. It is important to put the influence of asteroid-characteristic uncertainties into a quantitative perspective when considering alternative investments.