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# The Use of Nuclear Explosives To Disrupt or Divert Asteroids

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# **The Use of Nuclear Explosives To Disrupt or Divert Asteroids.**

by

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## **Abstract:**

**Nuclear explosives are a mature technology with well-characterized effects. Proposed utilizations include a near asteroid burst to ablate surface material and nudge the body to a safer orbit, or a direct sub-surface burst to fragment the body. For this latter method, previous estimates suggest that for times as short as 1000 days, over 99.999% of the material is diverted, and no longer impacts the Earth, a huge mitigation factor. To better understand these possibilities, we have used a multidimensional radiation/hydrodynamics code to simulate sub-surface and above surface bursts on an inhomogeneous, 1 km diameter body with an average density of 2 g/cc. The body, or fragments (up to 750,000) are then tracked along 4 representative orbits to determine the level of mitigation achieved.**

**While our code has been well tested in simulations on terrestrial structures, the greatest uncertainty in these results lies in the input. These results, particularly the effort to nudge a body into a different orbit, are dependant on NEO material properties, like the dissipation of unconsolidated material in a low gravity environment, as well as the details on an individual body's structure. This problem exists in simulating the effect of any mitigation technology. In addition to providing an greater understanding of the results of applying nuclear explosives to NEO-like bodies, these simulations suggest what must be learned about these bodies to improve the predictive capabilities. Finally, we will comment on some of the popular misinformation abounding about the utility of nuclear explosives.**

## Introduction

Based in the strong force, nuclear energy is likely to remain the most mass efficient way of transporting energy for the foreseeable future, an important consideration in space flight. The question is the best means of using that energy to deflect an approaching asteroid, or near earth objects (NEO). The two common approaches include a direct burst to create a debris field so large that only a tiny fraction of the parent body remains on an impacting trajectory. Previous work suggests that this method provides substantial mitigation for intercept times of only a few years (though earlier interdiction remains better). Alternatively, a nuclear device detonated some distance from the surface can ablate material from a hemisphere and nudge the (non-disrupted) body into a sufficiently different orbit to avoid an impact. With a decade or more of lead-time, the object can be diverted with an impulse sufficient to change the speed of the object by a few cm/s, with reasonable expectation of maintaining the body substantially intact.

Nuclear explosives are a mature technology, with operational space experience, and abundant data on effects. Measurements exist for radiative efficiency as well as shock generation for surface and subterranean bursts, with simulations to match experiment (Fig 1). The greatest uncertainty in understanding their effect here is the present knowledge of the range of asteroid structures and compositions. That uncertainty limits the ability to simulate most deflection technologies, as the use of a nuclear explosive to divert a body by impact/explosion, or by an ablative process, is not qualitatively different from many non-nuclear proposals. The nuclear option simply pack more punch per unit mass enabling currently available payloads to divert larger bodies than can be done by non-nuclear means.



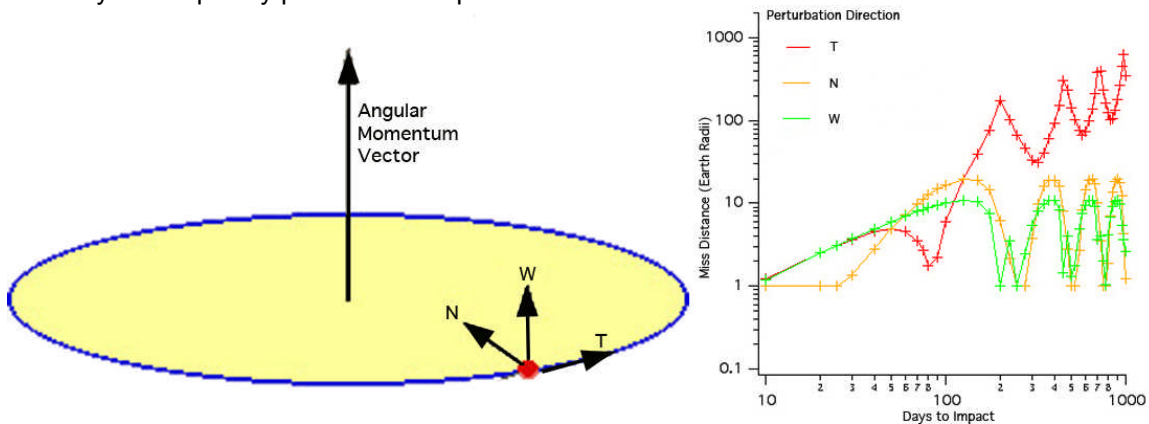
**Figure 1: LLNL is active in simulating weapons effects like nuclear cratering, and high velocity impacts.**

The simplest method for using a nuclear explosive is to impact the object, and detonate it some meters below the surface. This requires modest maneuvering to impact the body at a speed that permits penetration. This penetration can reach significant depths in terrestrial soil or tuff, and will be greatly facilitated if asteroid mantles are composed of the loose aggregates as often suggested. With this initial condition, we have used CALE, a radiation/hydrodynamics code developed at LLNL, to simulate a near surface explosions of 900 kt and 9 Mt on standard 1 km,  $10^{15}$  gm structures. These calculations are made with and without mechanical strength in portions of the body, and we track the impulse as it propagates through the bodies, converting them into expanding debris fields.

A more elegant method of using nuclear explosives is to detonate one above a body, using the output (x-rays or neutrons) to heat a thin hemispheric surface layer. The blow-off of this layer provides a well-distributed impulse. This can be done once or in a series of impulses such that the bulk velocity distribution remains below escape velocity (except for the thin layer of ejecta). Here again, the use of nuclear explosives is not qualitatively different than a number of suggested ablative technologies. It simply provides more impulse per unit of mass delivered to the body,

and our previous analytic work suggests speed changes of centimeters per second will be achievable.

Before the impulse, the material is at rest in the body's reference frame, and all of it is on a collision course with the earth. The direction of the velocity perturbation is of some consequence. The preferred perturbation is aligned with or against the direction of motion (**T** direction in fig 2). A speed change along this axis changes the period of the body resulting in a phase change in the body's orbital position that grows with each orbit. If large enough, speed changes in the other orthogonal directions (**N** or **W**) can result in a miss that is sensitive to the orbital phase at the time of perturbation. Miss distances that result from perturbations in these directions change only if the body subsequently passes near a planet.



**Figure 2: Defining the T, N, and W directions and the miss that results from applying a speed change in these directions at progressively earlier times.**

The solar system is not a force-free environment, and the impulse required to create a comfortable miss depends on the orbit. Following the hydrodynamics calculation, a separate code follows the orbital dynamics of the perturbed body, or the debris field as it expands and evolves. The remains are tracked along 4 orbits representative of those observed in the NEO population (Fig 5). While not exhaustive, these orbits have a broad range of periods and eccentricities, and one orbit was selected to be particularly challenging. For the nudge (heated hemisphere) model, the miss distance versus impulse time (days before impact) will be reported, and a speed change of centimeters per second usually results in a comfortable miss if applied only a decade before impact.

If the discovery is late (less than a decade), or other mitigation approaches fail, the surface burst option may become necessary to avoid catastrophe. The surface burst simulations create debris field that grows with time. The speed change in the bulk material will be measured in meters per second, and the mitigation efficiency will be reported in the fraction of the original mass that remains on an impacting trajectory.

On short timescales, it may not be possible to arrange for the burst to occur at perihelion passage, and for very eccentric orbits (like 1 and 2) this is significant loss. For orbit 1, the period change caused by an impulse at perihelion is 8 times larger than the same speed change created at aphelion, and the difference is a factor of 3 for orbit 2. Because of the short timescale posited here, we have arbitrarily applied burst times of 1000 and 100 days prior to impact. For most orbits, a megaton class explosive provides mitigation factors of  $10^4$  to  $10^5$ . The masses of such payloads are well within the limits that have been flown.

As a preview to our conclusions, the outstanding problem with in simulating asteroid deflection by nuclear explosives or other means is a lack of detailed composition and structure information. When a threatening object is discovered, learning about its detailed internal composition and

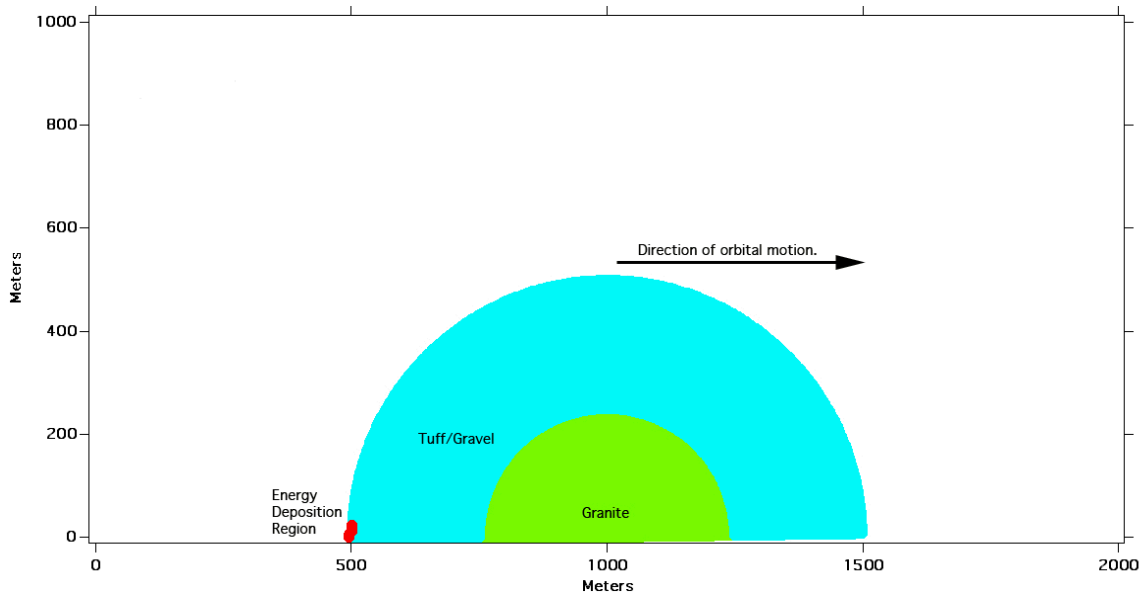
structure is critical. There should be a threshold to prioritize such a mission even before impact is a certainty.

An additional result will be that while nuclear explosives are a known technology that can greatly reduce the NEO threat, they too must be applied years to decades before the impact. Moreover, as stockpiles are reduced, the time to prepare or make the appropriate nuclear explosive must be added to the required lead-time.

In the following sections we will describe our standard NEO structures, the orbits considered, and the results of applying the energy of nuclear explosives to two different structures.

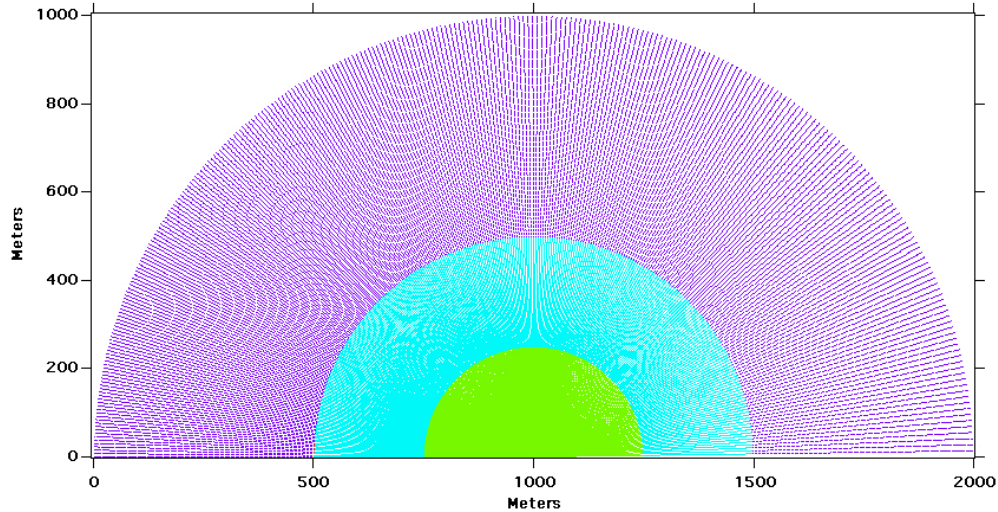
### The Structure and Energy Deposition:

NEO structure is one of the outstanding uncertainties in mitigation studies. The discovery of asteroids with rotation periods below 2 hours demonstrates that material strength is significant in some of these objects, but the limited number with such short periods suggests that most such bodies are aggregates, dependant on gravity to hold them together.



**Figure 3: Granite zones are marked in green, and tuff in light blue. The red area is where the energy source is applied.**

In the absence of detailed information we consider a general structure, with a diameter of 1 km. It has a 250-meter radius inner core with an equation of state (EOS) consistent with granite (density 2.63 g/cc). This is surrounded by a 250-meter thick mantle with an EOS of tuff, a soft, porous rock that formed by the compaction of volcanic ash (density 1.91g/cc). The total mass is  $1.05 \times 10^{15}$ g or just over a billion tons (Fig 3), and the average density is near 2. The rotation period of the well-studied asteroid DA1950 (Giorgini et al, 2002) requires it to have density near this value. This structure will be used to construct a model that has no material strength, to simulate an object that is unconsolidated, as well as a model that includes material strength in the core. The yield strength in the core is set to 14.6 MPa, with a shear modulus of 35 MPa. This is somewhat weaker than measured for most granites, and is near the low-end for limestone.



**Figure 4: Each zone is marked as a dot. Granite zones are marked in green, tuff in light blue, and low-density gas zones in purple.**

We have codes capable of three-dimensional (3D) radiation/hydrodynamics calculations in a massively parallel environment, but before attempting to study the added complexity (and assumptions) of geometry, we chose to start with spheres. With this shape, better resolution is achievable by using the two-dimensional (2D) code, CALE. Zoning was spherical and included about 87000 zones in the model asteroid (for an average cell size 3 meters on a side). For computational ease, a low-density ( $10^{-6}$  g/cc) region surrounded the body, with another 30000 zones (Fig 4). Zoning was not equal, and resolution was on the meter scale in the region of the energy deposition. The code includes energy transportation by radiation, and diffusion, handling them with a diffusion approximation. For this study the energy was sourced into a region, and energy transportation was not included.

We considered two general types of energy deposition. The first mimics a near surface nuclear burst. Energies in the Megaton range (9 Mt and 0.9 Mt) are deposited into a volume about 8 meters below the surface. The energy deposition is done over a time scale appropriate to forming the volume into which the energy is deposited. Initially the intense radiation field burns outward at a speed greater than the shock speed, ionizing all surrounding material and resulting in a strong shock as the high-pressure plasma bubble expands. This expanding bubble ejects the overburden at a very high speed, and carries away the bulk of the energy as a hot plasma expanding at kilometers per second. When the heated region breaks the surface, it is no longer hot enough to radiate away significant energy.

The second type of simulation modeled the effect of using the flux from a nuclear burst to heat a hemisphere of the asteroid. Blow-off from the heated hemisphere provides an impulse that propagates through the body, leaving it with a changed velocity. As the only binding of which we can be confident is gravitational, the goal of this calculation is not just to determine what the velocity perturbation is, but what fraction of the material is lost to form a debris field and what fraction remains bound. In the body studied here, the escape velocity from the surface is about 0.5 m/s,

The maximum heating is experienced at the point nearest the detonation (ground zero). As one moves away from the ground-zero point, the flux received from the device is reduced by distance, and asteroid curvature. The height of burst,  $d$ , is parameterized in terms of the asteroid radius:

$$x = d/R$$

The flux distribution across the irradiated region is:

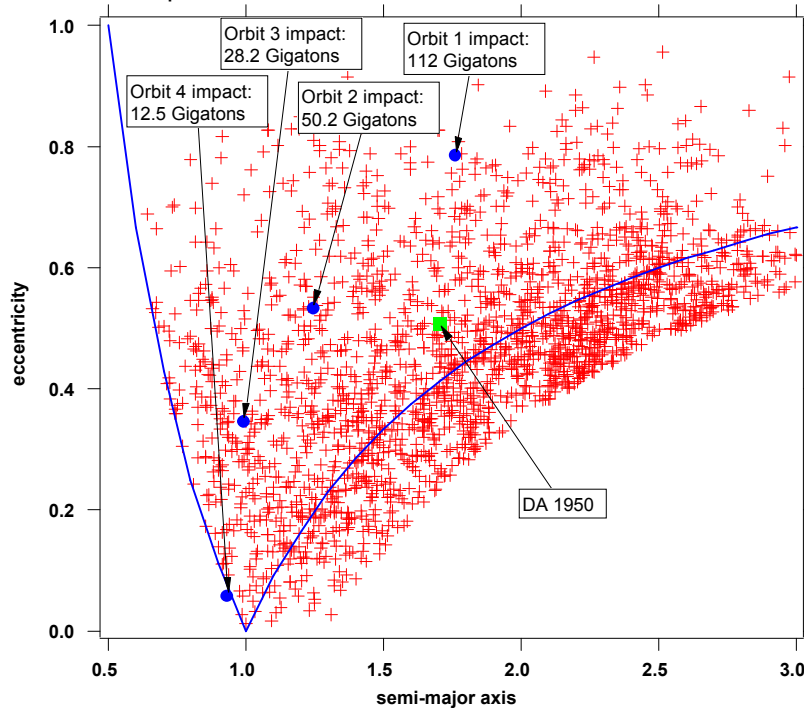


$$F(\theta) = \frac{Yield}{4\pi R^2} \frac{(1 + X)\cos(\theta) - 1}{(1 + (1 + x)^2 - (2 + 2x)\cos(\theta))^{3/2}} \text{ cal/cm}^2$$

where  $\theta$  is measured from the center of the asteroid, and is zero at ground zero. The fraction of the energy impinging on the asteroid depends on the solid angle it subtends. As the burst altitude increases the fraction of the energy available for deposition is reduced. Detonation at a lower altitude will use more of the energy, but will expose less material to the energy, resulting in a smaller impulse and stronger gradients. As a result, there is an optimum height of burst that we previously found to be near 0.6 of the radius (Dearborn 2004).

### The Orbits:

When a 2D simulation was completed, it was rotated through 360 degrees to produce a 3D position and velocity distribution. This distribution was placed on each of the 4 standard orbits, 100 and 1000 days prior to impact. The position of each fragment was then followed until it either impacted the earth or flew past.



**Figure 5: The red markers indicate the observed eccentricities and semi-major axes of about 1200 NEO's tabulated by JPL. Bodies that lie between the blue lines are on earth crossing orbits.**

The 4 Earth-crossing orbits have a range of elements consistent with those seen in the NEO's tabulated by JPL (Fig 5). All orbits are prograde, with progressively shorter periods. They also become more circular (lower eccentricity), and the impact speeds diminish (Table 1). For a 1 km diameter body with a mass near a billion tons ( $1.05 \times 10^{15}$  g), the impact speeds correspond to energies in the range of 12 to 112 Gigatons (1 Gt = 1000 Mt).

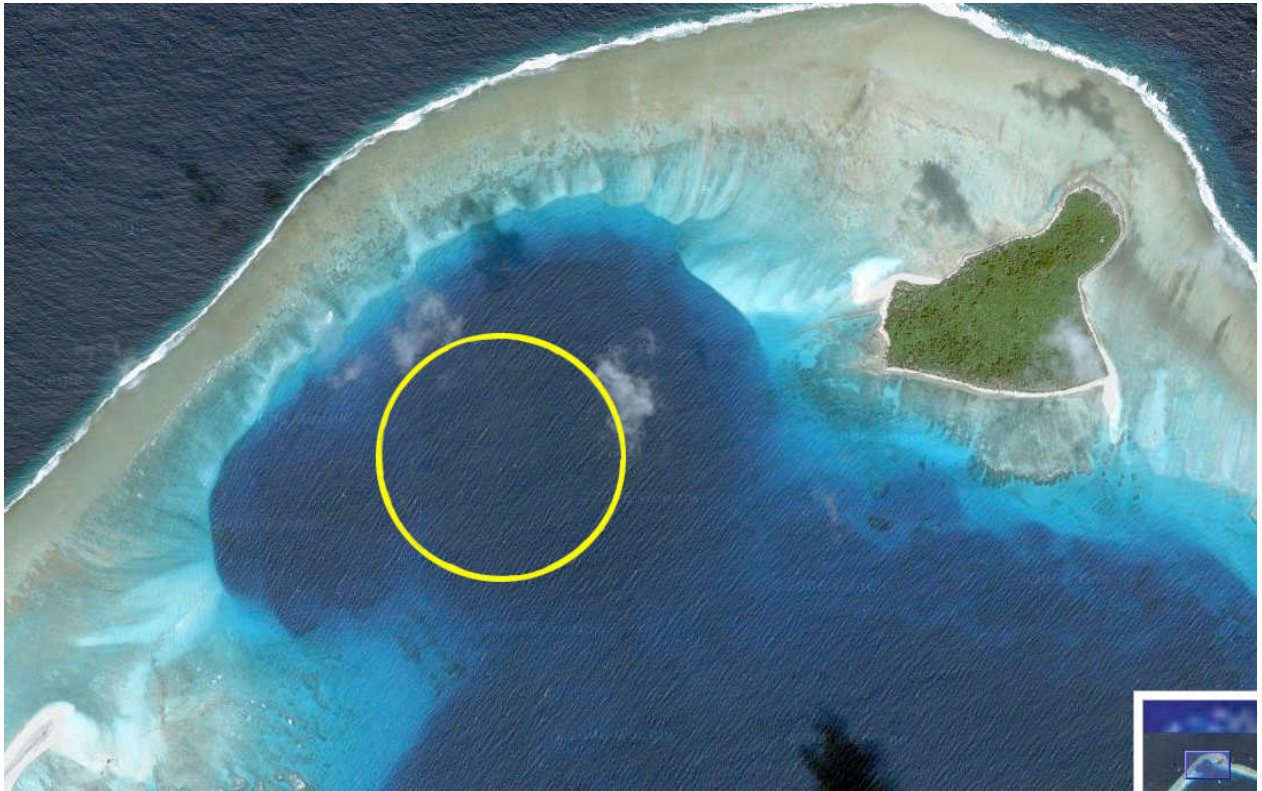
**Table 1: Orbital Elements**

	P	a	e	i	Node	Aperi	$V_{\text{impact}}$ (km/s)
1	2.3358	1.7605	0.7844	22.891	339.7	66.2	30
2	1.3914	1.2464	0.5318	1.149	340.3	280.5	20
3	0.9912	0.9941	0.3455	6.140	339.7	70.3	15



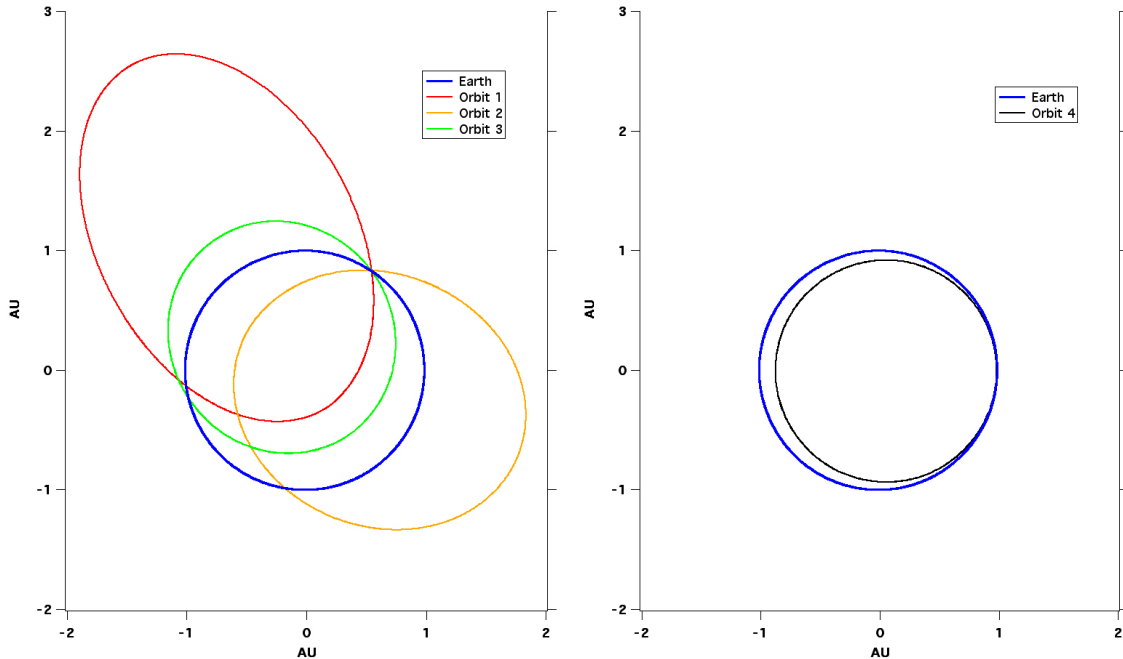
4    0.9011    0.9329    0.0524    0.113    286.5    347.0    10

The first three of these orbits are earth crossing with angles that drop from  $50^\circ$  to  $27^\circ$ . They are targeted on the Bikini Atoll ( $11^\circ 35' N$ ;  $165^\circ 23' E$ ), with an impact on the day of the 53<sup>rd</sup> anniversary of the Castle Bravo test, 2/28/2007. In that test, a 15 Mt device was placed about 2 meters above the surface of a causeway, 970 meters from the southwest tip of the island, Namu. The crater that was produced in the reef is visible today (fig 6).



**Figure 6: For scale, a 1 Km diameter circle is drawn in the crater of the Castle Bravo event of 2/28/1954 at 18.75 UT. (image from Google Map)**

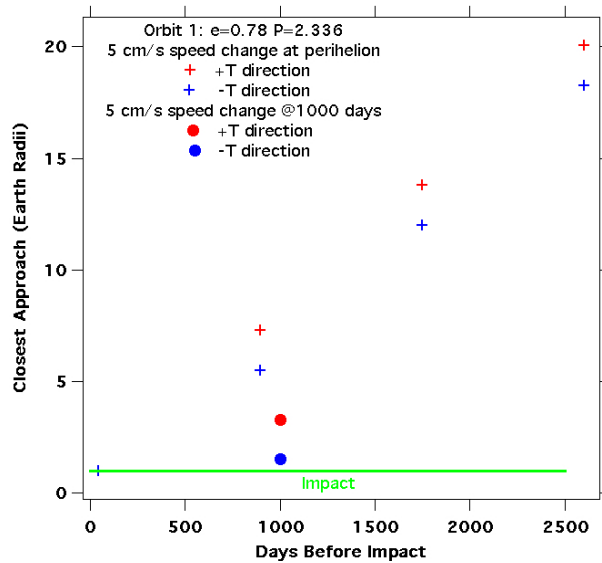
The fourth orbit is characteristic of an impact by an NEO that lies near one of the blue lines in figure 5. It actually starts in a non-earth-crossing orbit, but close passages with the earth change the trajectory to one that gently caresses the Earth's at its aphelion point. It is aimed to impact in the Darfur region of Africa on (the organizer) David Lynch's birthday in 2006, with an impact speed of 10 km/s (12 Gigatons see figure 7).



**Figure 7: The Earth's orbit is shown in blue, along with orbits 1, 2, and 3 (left side). Orbit 4 (black) is shown against the Earth's orbit on the right.**

**Orbit 1:**

A burst date (**2 June 2004**) of 1000 days before impact (28 Feb 2007) provides an impulse at a point in the orbit that is midway between aphelion and perihelion. Over the next 40 to 50 days, the body passes behind the earth at a distance of 0.22 AU. This is the closest that the two bodies pass, until the impact date itself.

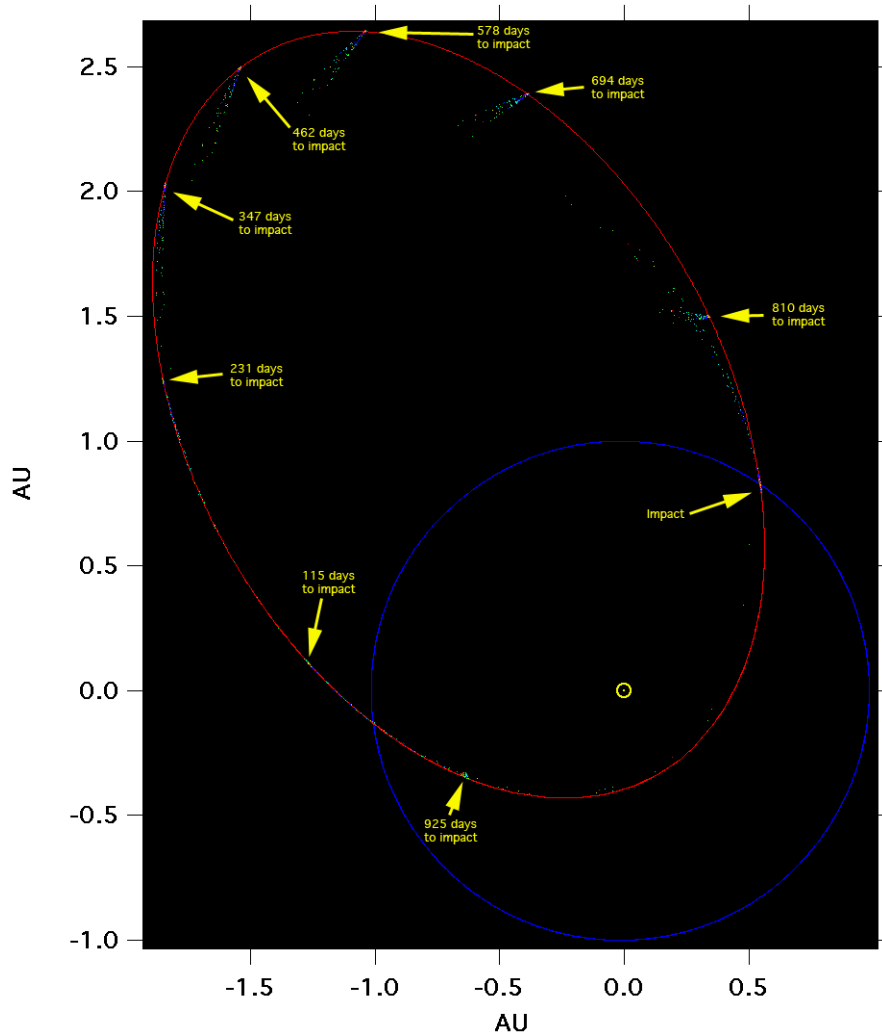


**Figure 8: Crosses show the miss induced by changing the speed by 5 cm/s near perihelion passage. The red and blue indicate a speed change aligned with the direction of motion or opposed to the direction of motion. The green line is at 1 earth-radius to show where a collision occurs.**

For such an eccentric orbit, this is far from the optimal (perihelion) perturbation point, but also far from the worst (aphelion). The magnitude of this effect is shown in figure 8. A 5 cm/s speed

change applied near perihelion passage 895 days before impact results in a closest approach to the earth of 7.3 (+T) or 5.5 (-T direction) Earth-radii instead of an impact. Application of this same impulse, 105 days earlier (not at perihelion) results in Earth passage distances reduced by more than a factor of 2 (3.3 and 1.5 Earth-radii).

Given sufficient time, a small speed change will convert the impact to a close passage, and with time, the likelihood of achieving a perihelion encounter is improved. In these circumstances a perturbation that provides a nudge of some centimeters per second is the preferred option. On shorter timescales, like the 895-day case shown here, the nudge option may work, but is very risky. The ability to predict the speed change associated with any impulsive perturbation will have uncertainties associated with the impactor's composition and structure. When there is not sufficient time for a second attempt/perturbation, this option becomes an all or nothing. Small differences in the magnitude of the nudge can be disastrous. In this case, the buried burst option can provide considerable mitigation (reducing the material impacting the earth by factors of  $10^4$  or  $10^5$ ) on shorter notice.

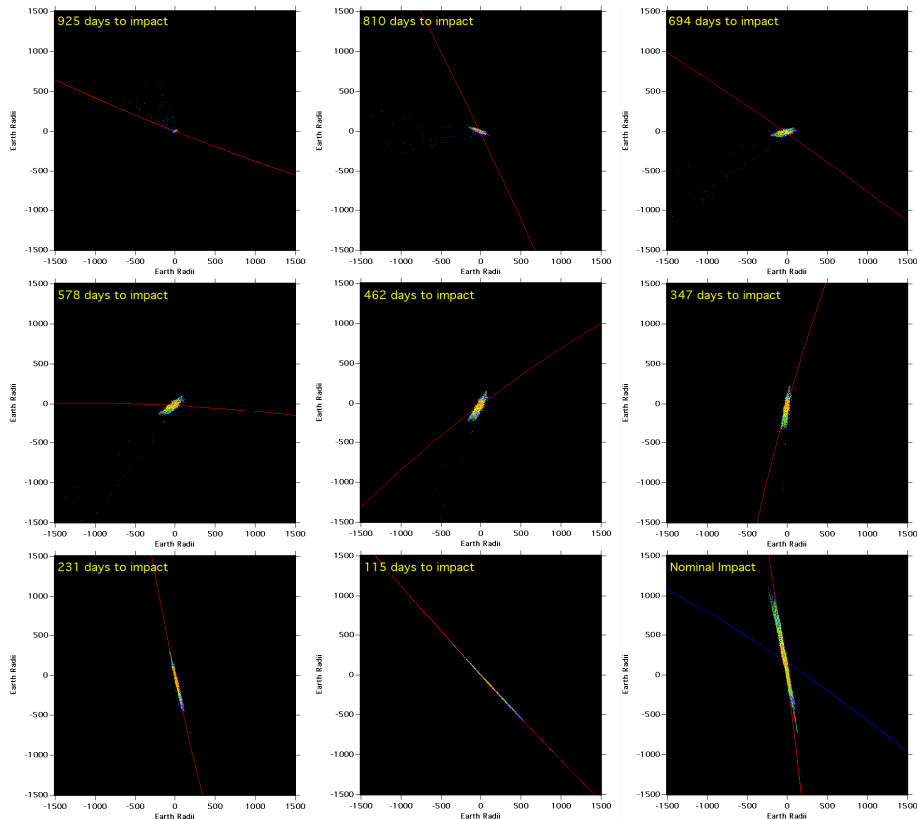


**Figure 9: Orbit 1 is shown in red, and the earths orbit in blue. The position of the debris field is shown at 9 times from 925 days before impact to nominal impact.**

As discussed in the introduction, the debris field that results from a nuclear explosion expands. It will elongate substantially along the orbital path. This is shown in figures 9 and 10 for the 900 kt near surface burst, with no material strength. Seventy-five days after the burst the bulk of the material (> 93%) has expanded to a volume with diameter about 20 Earth-radii (fig 10). At this

early time, the higher speed ejecta reaches >500 Earth-radii (fig 9). After 190 days, the debris ellipsoid is over 150 earth radii long and 50 in diameter. The debris ellipsoid has begun to rotate from alignment with the orbit as the material that changed speed along the direction of motion shows its new semi-major axis and period. This rotation is another factor in the mitigation as the path that the earth takes through the evolving ellipsoid.

The ellipsoid expansion continues to grow with time. By the nominal impact date, the debris ellipsoid is over 1500 earth radii long, and 80 across at the place where the earth penetrates it. The high-speed material, including all of the material directly exposed to the nuclear device, is dispersed along more than 1 AU of the orbit. As a result, the material that was concentrated to impact at one location, with 112 Gt of impact energy has dispersed over nearly 10 million times the volume of the Earth. In passing through the debris field, the earth should intercept only about  $10^{-5}$  of the original material. This mitigation factor is achieved with burst only 3 years before impact. Earlier discovery and action can considerably enhance the protection.



**Figure 10: The growth of the core debris field containing 93% of the mass is shown at 9 times.**

While the impulse occurs a sub-optimal point, the large crossing angle of this orbit ( $50^\circ$ ) is favorable (Fig 11). The higher the angle between the earth's and the NEO's orbit, the shorter the path length through the debris field, and the less likely an unpleasant encounter.

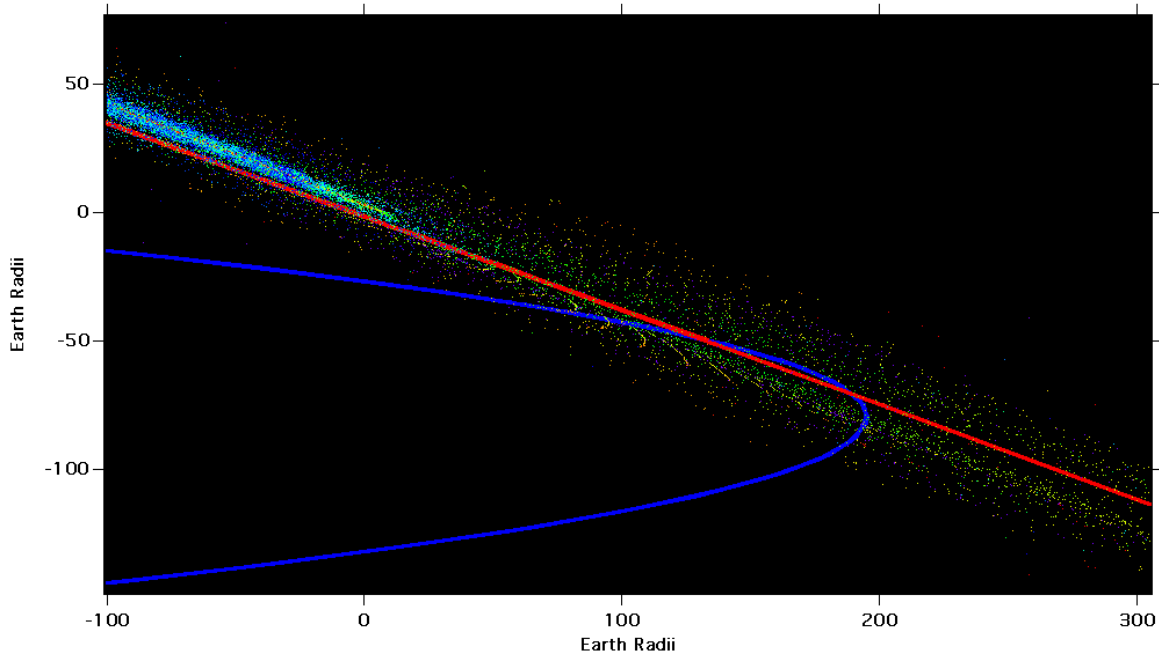


Figure 11: Path of the earths passage through the debris field is shown.

**Orbit 2:**

For this orbit, the NEO crosses inside of the Earth's about 10 days before the (1000 day) burst, and about 90 days after the Earth passed that intersection point. Eighty days after the burst, the NEO passes about 0.29 AU in front of the earth as it climbs out towards aphelion. After this, the two bodies remain far apart until impact. The angle between orbits ( $35^\circ$ ) is less than orbit 1 forcing the Earth to take a path through the debris that is about 33% longer.

Orbit 2 has a smaller eccentricity than orbit 1, but still considerable. For this orbit, figure 12 shows the miss distance for a 5 cm/s speed perturbation applied near perihelion passages, and ones applied 1000 days before impact. Here a change of only 40 days in an orbit of 509 days makes a significant difference.

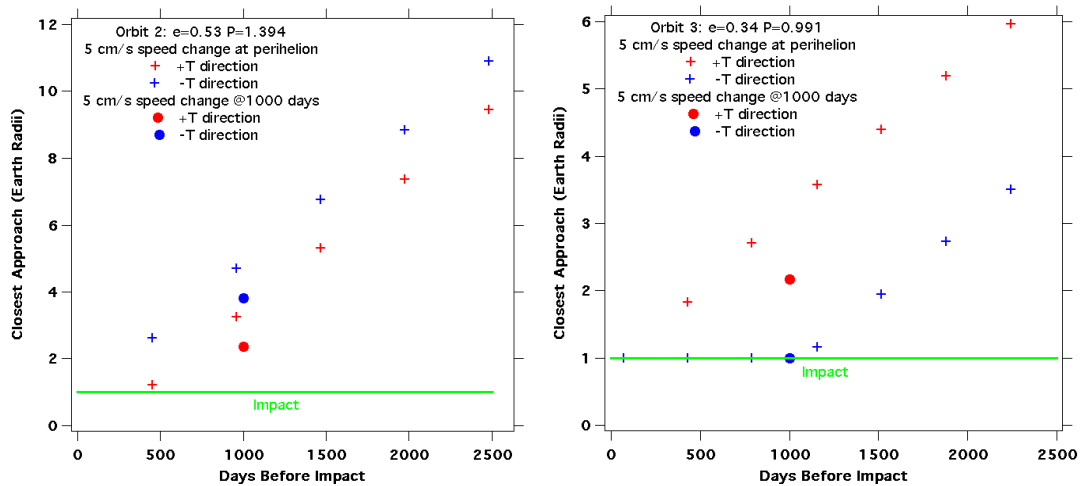


Figure 12: For orbits 2 and 3, crosses show the miss induced by a 5 cm/s speed change near perihelion passage.

**Orbit 3:**

One thousand days before impact, the NEO is approaching aphelion, but the detrimental effect is diminished by the lower eccentricity (Fig 12). Because of the period is very near that of the Earth, this orbit has 2 relatively close approaches to the Earth, prior to impact. Two years before impact it passes within 2600 earth-radii, and the year before impact it is only 1200 earth-radii. On the third passage, the earth passes through the debris field at an angle of 27 degrees, resulting in a longer path through the debris, but in this case (lower eccentricity) the penalty for not acting at perihelion is much less, and compensates for the path length difference.

**Orbit 4, the get thee behind me orbit:**

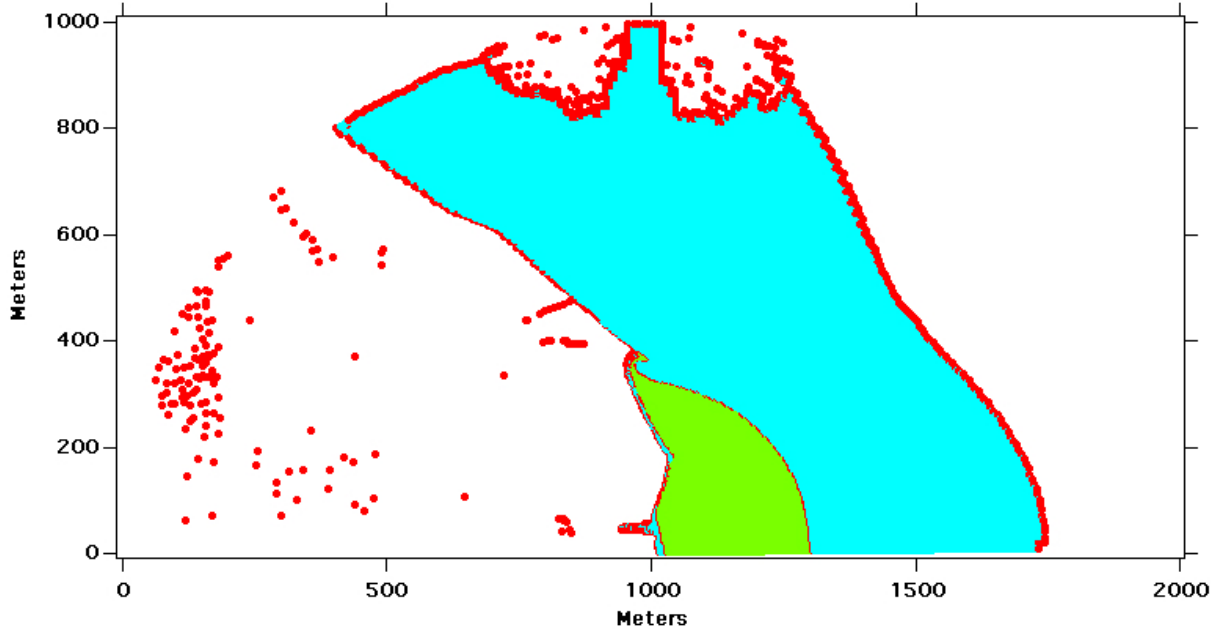
This orbit is an accident waiting to happen. While the impact speed/energy of this orbit was the lowest considered, it was the most difficult object to avoid. It has the lowest inclination ( $0.1^\circ$ ) and at the point of impact is nearly parallel to the earth's orbit ( $<1^\circ$ ). The collision occurs as the earth overtakes the asteroid (or debris field) sweeping it up.

Where the other orbits, require only a small speed perturbation (5 cm/s) applied near perihelion, a few years in advance to (barely) avoid an impact, the long parallel path of this orbit raises the requirements. The low eccentricity ( $e=0.05$ ) removes most of the sensitivity to the orbital phase at which the speed perturbation is applied. The speed change (in the direction of motion) required to avoid a collision is near 3 m/s if applied 1000 days in advance, and 1.5 m/s at 2000 days. Given the phase of the impact, and that the earth is sweeping up the body, this orbit has a substantial improvement when the speed perturbation is applied opposite the direction of motion (the  $-T$  direction). In this case, the requirement to avoid a collision drops to 0.5 m/s if applied 1000 days in advance, and 0.25 m/s at 2000 days. The ability to apply such a large velocity change without fragmenting the body is remote. On orbit 4, small speed changes can work if applied early enough. A 5 cm/s change (in any direction) applied 25 years before the impact is insufficient. However, applied in the direction opposite the motion, 30 years before the impact results in a comfortable, 100 Earth-radii, miss.

**Burst Model A (900 kt, no material strength):**

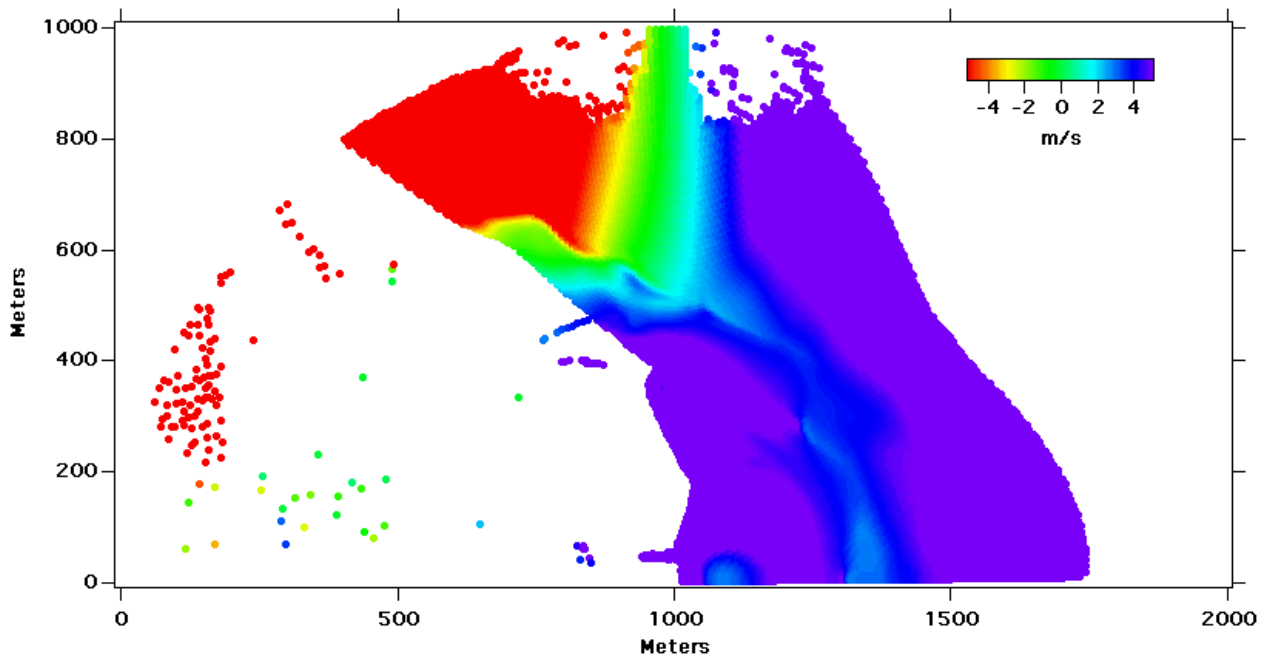
This calculation begins with the standard structure, a diameter of 1000 meters, and a mass of  $1.05 \times 10^{15}$  g. It is intended to simulate a rubble pile, and so the material is given no material strength, and behaves like a viscous fluid. An energy totaling 900 kt is injected into a small volume centered about 10 meters below the surface. After 18 sec, 7.6% of the mass ( $7.96 \times 10^{13}$  g) has left the problem boundaries, with an average speed of  $>100$  m/s, and 92.3% ( $9.67 \times 10^{14}$  g) of the mass remains. The default burst position is taken to be at the aft pole of the body, so the nominal push is in the T direction. However, we will consider pushing in the  $-T$  direction for Orbit 4.

Though it is deformed, essentially all of the core material is still in the problem (Fig 13). The center of mass has shifted by 77 meters, and the core by 114 meters. At this time, the core region has developed a speed of nearly 7 m/s in the T direction. In addition to this translational speed, the core has an RMS velocity dispersion over 3 m/s, nearly 6 times the escape velocity from the core surface. Viewed in the context of the Virial theorem, the kinetic energy exceeds the potential energy by more than a factor of 300, so there is little chance of re-coalescence.



**Figure 13** The tuff exterior is shown in blue, and the denser granite core material shown in green. The zones with mixed compositions total under 5% of the mass, and are shown in red.

In the exterior (tuff) region, the ratio of kinetic to potential energy exceeds 1200. This region has gained a mass averaged speed orthogonal to the push direction of 9.4 m/s. Along the direction of push, the mass averaged speed is only 2.6 m/s, but the dispersion is quite high as a substantial amount of material is moving opposite the direction of push (Fig 14). In the whole body, over 17% of the mass is moving in the  $-T$  direction at over 5 m/s, and 40% has a speed over 5 m/s in the  $T$  direction.

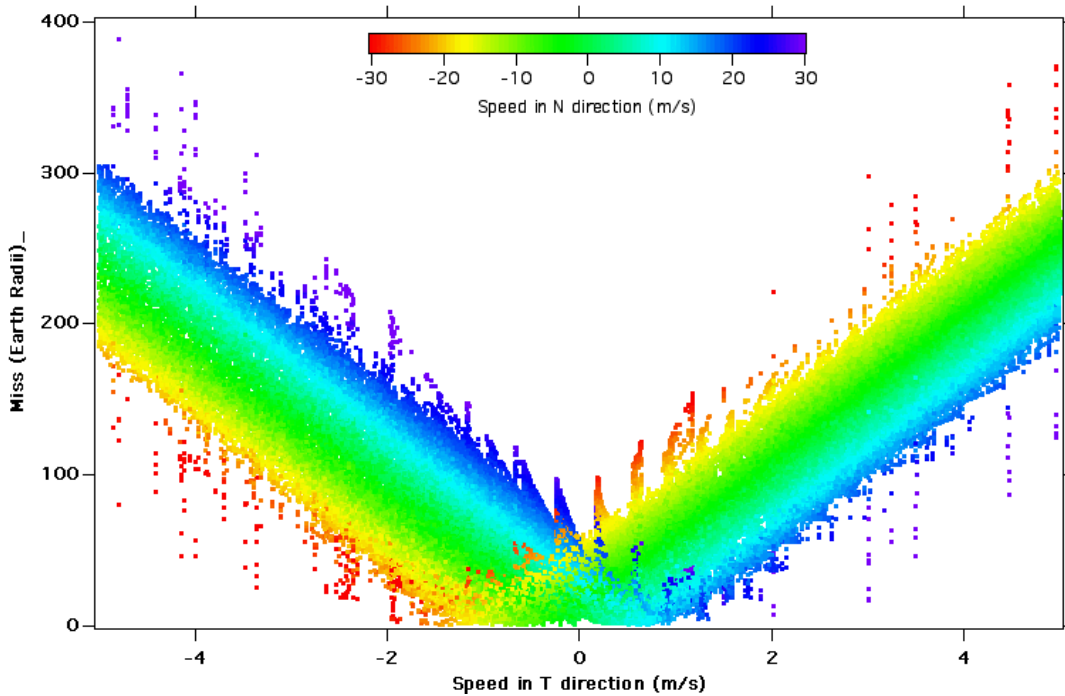


**Figure 14:** Color codes the speed of the material in the  $T$  direction. Purple regions are moving faster than the original body by 5 m/s, and the red regions are slower.



In the reference frame of an asteroid traveling on an earth-impacting trajectory, the material that remains at zero velocity will hit the earth as scheduled. Material that is expanding laterally to the direction of motion, but in the plane (the N direction) may also impact the earth, a bit before and a bit after the nominal impact time.

The speed limits of the material that remains a threat to the earth is shown in figure 15, for a burst occurring 1000 days before impact on Orbit 1 (P=2.3 years, e=0.78). The only fragments to pass within 10 Earth-radii of the earth started with a speed in the direction of motion (T direction) between -2 and 2 m/s. Beginning about 3 hours before the nominal impact time, those fragments that were accelerated to 30 m/s in the negative N direction and slowed by 2 m/s in the T direction begin making their closest approaches to the Earth. Those fragments with no acceleration in the N or T directions make their passage near the nominal impact time, and fragments that were accelerated to 30 m/s in the positive N direction and sped up by 2 m/s in the T direction begin to their passages. The threatening material is shown in green to light blue in figure 14, and amounts to about 8% of the original mass. While some of the material in this speed range pass within 10 earth radii, the bulk of the material misses by much more (up to about 150 Earth radii).



**Figure 15: The speed imparted by the burst in the direction of motion (T) is plotted against miss distance for each fragment. Additionally, the fragment is color coded for its speed in the N direction.**

To estimate what fraction of the body remains on an impacting trajectory, the 2D simulation was rotated to produce a 3D position and velocity distribution. The body was then divided into as many as 750,000 fragments (sufficient to obtain a credible statistical fraction that still impacts the Earth). This distribution placed on each of the 4 standard orbits at the body's position 1000 days before impact (columns O1 to O4). Column O4a provides results for placing the explosive on the fore pole of the asteroid, and pushing in the  $-T$  direction. The position of each fragment was then followed forward in time until it either impacted the earth or flew past. The results are given in the following Table 2a. Table 2b provides similar information for a burst only 100 days in advance.

**Table 2a: Burst 1000 days before impact.**

O1                      O2                      O3                      O4                      O4a

Fragments	511808	767600	511696	31988	31988
Mass Fraction	$2 \times 10^{-5}$	$1 \times 10^{-4}$	$5 \times 10^{-5}$	$2 \times 10^{-2}$	$3 \times 10^{-3}$
Hit Fraction	$3 \times 10^{-5}$	$1 \times 10^{-4}$	$1.5 \times 10^{-4}$	$2 \times 10^{-2}$	$4 \times 10^{-3}$
Avg. Diameter	10	10	10	30	30
Tot Diameter	25	45	40	265	150
Z Speed (m/s)	+/- 2	+/- 0.25	+/-1.5	-2 to 7	-2 to 7

**Table 2b: Burst 100 days before impact.**

	O1	O2	O3
Fragments	255904	255904	255904
Mass Fraction	$1-2 \times 10^{-3}$	$5-8 \times 10^{-3}$	$2-5 \times 10^{-3}$
Hit Fraction	$2 \times 10^{-3}$	$4 \times 10^{-3}$	$3 \times 10^{-3}$
Avg. Diameter	15	15	15
Tot. Diameter	125	185	150

For a wide range of orbits, a 900 kt burst just below the surface of a 1 km diameter body reduces the amount of mass that impacts by a huge factor in a relatively short period. With 1000 days of growth, the debris cloud reaches such a size that only  $3 \times 10^{-5}$  to  $1.5 \times 10^{-4}$  of the fragments remained on an impacting trajectory for orbits 1 through 3. The fragment number was increased until a significant number of impacts occurred. When the probability of impact was low, this required dividing the body into more small fragments. In this case, the average size of an impacting fragment was only about 10 meters, and the impacts occurred over periods of 5 to 8 hours. Instead of 112,900 Mt of energy impacting the Earth's surface, the expectation from orbit 1 is about 2.4 Mt of energy deposition divided among 12 to 18 impact sites. For the average size fragment, the energy deposition occurs rather high in the atmosphere, and should have little impact on the ground (see Hills and Goda, 1993; Ivanov and Ryzhanski, 1997 and 2000), and the average thermal loading from this is negligible.

In orbits 1 through 3, nothing with a speed in the +/-T direction of more than 2 m/s remains a threat to the earth. Because the earth sweeps up material dispersed along Orbit 4, a greater fraction of the fragments with speeds of -2 to 7 meters per second are potentially threatening. The speeds necessary to avoid an impact for this orbit present a greater problem for any mitigation mechanism. While reducing the amount of material impacting the Earth to less than 1/100<sup>th</sup> is an improvement, it is far from adequate. There is a modest improvement from pushing in the -T direction. An earlier burst will certainly improve this result, or as discussed in the next section a bigger hammer approach has merit.

Finally, the discovery and affirmation of an NEO threat is likely to occur some decades in advance. With this option, there is time to consider the technologies du jour, before committing to a nuclear solution, but even the nuclear solution requires time to prepare and deliver.

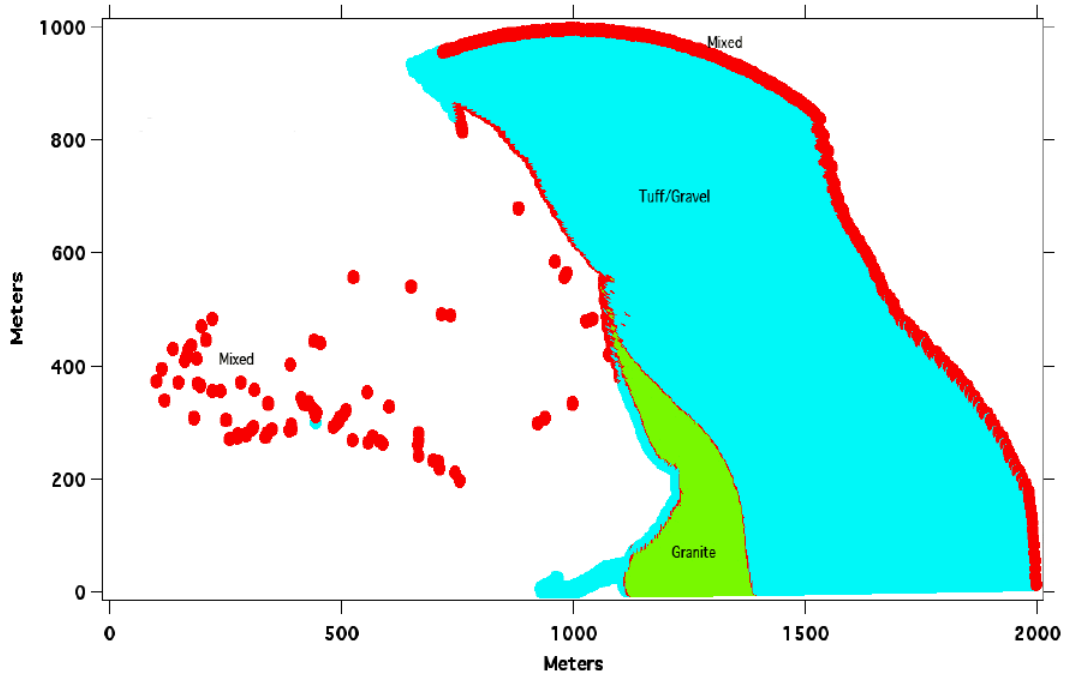
### **Burst Model B (9 Mt, no material strength):**

Model B has the same physical characteristics of model A, and the impulse energy was sourced into the same location. The energy however was increased to 9 Mt (no more diddly-squat bombs). Ten meters depth of burial was less than optimal for coupling 900 Kkt into the body, and it is far less than optimal for converting energy to momentum with a 9 Mt device. As before, the immediate response to the energy deposition is a crater with high-speed ejecta, and a strong shock passing through the core. Over 11.3 seconds, 25% of the mass (from the tuff portion of the body) leaves the problem at high speed. While some of the early ejecta leaves the problem at >1 km/s, the center of mass velocity of the lost material is  $\approx -50$  m/s (-T direction). The overall mass averaged speed of this lost material is near 75 m/s. As with model A, the ejecta speed takes this material far from an impacting trajectory.

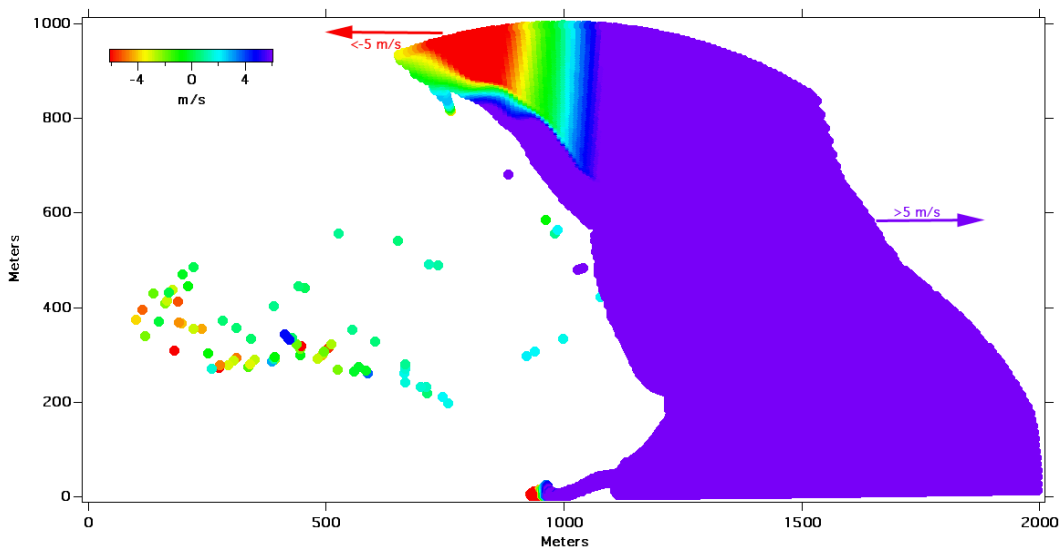
In the 75% of original mass that is present in the problem, only 0.51 Mt (5.6%) of energy remains at the end of the calculation. Most of this energy is in the form of a higher temperature (about 2

degrees C if averaged over the whole body but it isn't). About 0.7% of the original energy remains in kinetic energy.

Again essentially all of the core material is still in the problem (Fig 16), and its center of mass has been pushed nearly 200 meters. The center of mass of the remaining material has shifted nearly 240 meters. The core region, like all of the material near the axis, has developed a speed of near 20 m/s in the T direction. Only 5% of the body has a speed below 5 m/s (green in Fig 17) in the T direction, and for Orbits 1, 2, and 3 only a tiny fraction of this material passes within 20 earth radii of the planet. The core is expanding at about 8 m/s, and the kinetic energy exceeds the potential energy by more than a factor of near 30,000, so there can be little chance of re-coalescence.



**Figure 16: Again granite is green, and tuff is blue. The red zones are mixed layers (partially low density gas and partially tuff).**



**Figure 17: Speed along the direction of motion. Material that is red or purple has been accelerated or decelerated by 5 m/s.**

As expected with the additional energy input, speeds are higher and even less material on orbits 1 through 3 (O1, O2, and O3) remain in an impacting trajectory. The fraction of mass that still impacts the earth (Table 3a and b) is less than  $10^{-5}$ , and the total impact energy (spread over hours) is less than 1 megaton. Even Orbit 4 shows improvement, with 2 to 5  $\times 10^{-4}$  of the mass impacting. The impact energy is down to 56 Mt from 112,000 Mt and spread over many days. Again, much of the material is not expected to reach the ground, and when compared to results of no action, the improvement is considerable.

**Table 3a: Burst 1000 days before impact.**

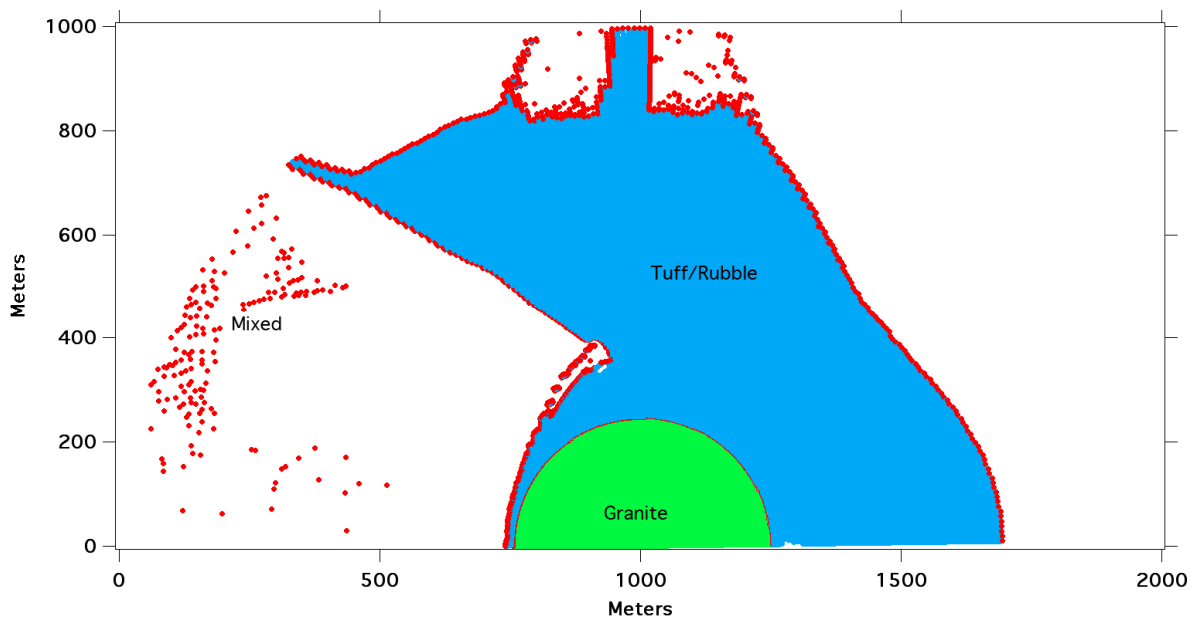
	O1	O2	O3	O4	O4a
Fragments	690744	690744	690744	230248	230248
Mass Fraction	$8 \times 10^{-6}$	$6 \times 10^{-6}$	$2 \times 10^{-6}$	$5 \times 10^{-4}$	$2 \times 10^{-4}$
Hit Fraction	$5 \times 10^{-6}$	$1 \times 10^{-5}$	$1 \times 10^{-5}$	$1 \times 10^{-3}$	$8 \times 10^{-4}$
Avg. Diameter	13	9	7	12	11
Single Diameter	19	19	13	80	65
Z Speed (m/s)	-3.5 to 2.5	-0.2 to 0.15	+/-2.5	-3 to 8	-3 to 8

**Table 3b: Burst 100 days before impact.**

	O1	O2	O3
Fragments	460496	460496	460496
Mass Fraction	$1.5 \times 10^{-4}$	$4 \times 10^{-4}$	$3.5 \times 10^{-4}$
Hit Fraction	$2 \times 10^{-4}$	$8 \times 10^{-4}$	$5 \times 10^{-4}$
Avg. Diameter	10	10	10
Single Diameter	50	75	65

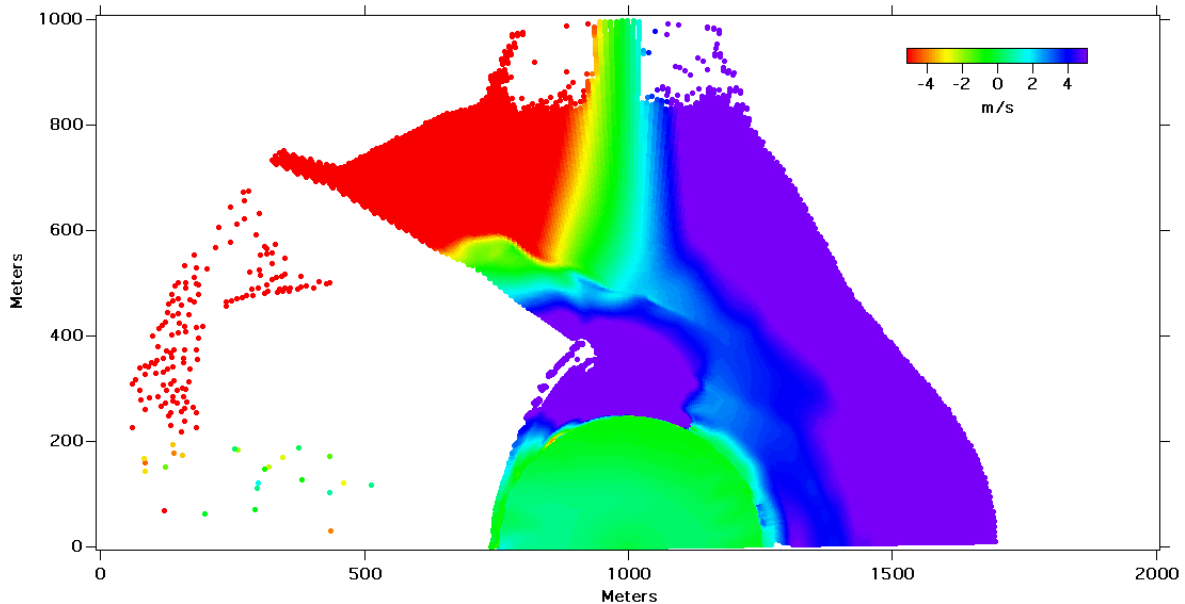
**Burst Model C (900 kt, A big rocky core):**

As discussed in the introduction, NEO structure is one of the major uncertainties in calculating nuclear or other effects. This sensitivity is illuminated by model C in which a solid core (one with material strength) is surrounded by a lower density mantle with no strength.



**Figure 18: Again granite is green, and tuff is blue. The red zones are mixed layers (partially low density gas and partially tuff).**

Again, a 900 kt device is detonated 10 meters below the rubble surface, and the impulse followed for 14 seconds. At this point 4% of the mass has left the problem at high speed, and the remaining 96% of the mass has a kinetic energy of 0.08 Mt (nearly 9% of the deposition energy). The rubble exterior has a mass averaged radial expansion speed of 10 m/s. Its mass averaged speed in the T direction is only 2 m/s, but again material is moving in both the +/- T direction, and the RMS velocity of this component is over 5 m/s. The ratio of kinetic to potential energy in this material is about 1500, comparable to that seen in the mantle of model A. The rubble exterior (75% of the mass) will form an extended debris field very similar to that seen in Model A, and only a fraction of the material that has a speed change < 2 m/s (green in fig 19) remains a threat to the earth. The big difference is, of course, the core.



**Figure 19: Speed along the direction of motion. Only a fraction of the material in green remains a threat.**

In Model A, the core was substantially deformed by the shock transit. Here the core has transmitted the shock but maintained its shape. The center of mass of the entire body has shifted by only 32 meters. There are still shocks moving in the core, and at this point, the kinetic energy in the core is nearly twice the potential energy, but the velocity field is not generally expanding. The mass averaged radial velocity (velocity of expansion) is only 4 cm/s (1/8<sup>th</sup> the escape velocity of the bare core) corresponding to a kinetic energy much smaller than the potential. The core is likely fractured, as the shocks continue to thermalize, but it is probably gravitationally bound. The net speed change of the core along the direction of motion is only 8 mm/s. Surprisingly it is in the -T direction. The behavior here is analogous to that in a Newton's cradle where the centerpieces remain at rest when an impulse is transmitted through them. Here the material on the far side of the core is spalled off, and the core is recoiling slightly.

This model emphasizes the importance of knowing the structure. Here, the impact from the explosive dispersed the outer layer of rubble, cleaning off (and probably fracturing the rocky core). The speed of such a core will depend on how well centered it is in the mantle, and if well centered the speed change can be very low. As shown in Table 4, such a remnant is likely to impact if left alone, and an intercept of 1000 days leaves little time for a second try on the core itself. If the core remains whole, the impact energy is near 30 Gt.

**Table 4: results of an 8mm/s speed change from 1000 days.**

orbit	+T	-T
1	miss	hit

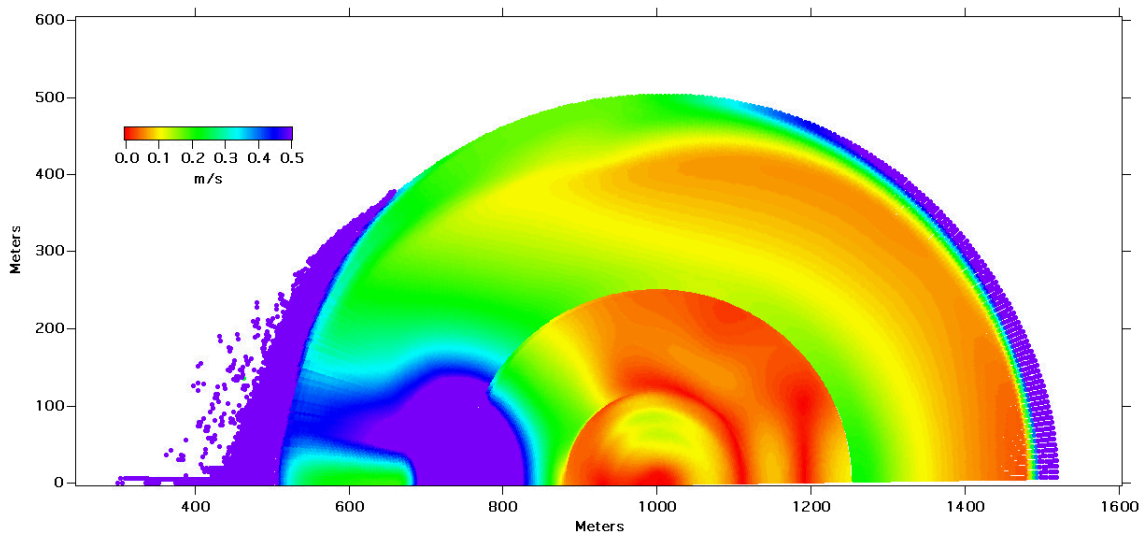
2	hit	miss
3	hit	hit
4	hit	hit

### The Nudge Model:

In this model we return to the no material strength structure used in model A, but instead of placing the energy in a small volume 10 meters below the surface, 11.5 kt of energy is sourced into thin and tapering set of surface zones (approx 10 cm), across 39° of a hemisphere (half-angle). This energy input is consistent with the energy incident from a 100 kt source about 300 meters above the surface.

Approximately 20 seconds after the hemisphere is irradiated, only about 0.02 kt of kinetic energy remains in the problem. At this point, only 0.003% of the ablated mass (about 30,000 tons) has left the simulation. Another 1% of the mass has a speed in excess of the escape velocity (50 cm/s). Most of this (purple in fig 20) can be seen expanding from the irradiated region where a crater will form, and a lesser amount is spalled in the forward direction.

The remaining 99% of the mass has a kinetic energy near 1/4<sup>th</sup> the potential energy and should be expected to re-coalesce to a single body. The momentum of the portion not escaping is currently 5 mm/s, though as the crater forms it should increase. Differencing the momentum of the escaping spall region and the escaping ablation region, the net momentum in the coalesced region is expected to settle at about 6.5 mm/s.



**Figure 20: the material speed is shown 20 seconds after the hemisphere**

If the burst is done near perihelion, 30 years before impact, a net core speed of only 5 mm/s is sufficient to cause a miss on orbits 1, 2, and 3 when perturbed in the T direction, as well as orbit 4 when perturbed in the -T direction. All motion will subside on a timescale of many 10's of seconds, following which the process can be repeated.

### Conclusions

Nuclear explosives are a mature technology, and for most of the NEO orbital parameter space, provide considerable mitigation when used only a few years prior to impact. The payload mass necessary to deliver sufficient energy is well within current space capabilities and many popular objections to their use are based in ignorance and a lack of understanding of their true effects.

The preferred approach to their use is a stand-off detonation at an optimal height. Neutron output has certain advantages (Dearborn (2004), as the energy coupling is relatively insensitive to the

surface composition and density, but x-rays can be used. In this approach, a thin layer of material is ablated from one hemisphere providing an impulse that changes the body's speed. The model considered here shows speed changes of order 1 cm/s are plausible with gravitational binding maintaining the vast bulk of the material in a single body. In the case studied here, about 1% of the body mass is lost from the impulse. For most orbits, speed changes of the magnitude seen here are sufficient if applied a few decades in advance. The ejecta in minimal and evolves to such a low density that it becomes negligible factor to the Earth.

If the regolith viscosity is more dissipative than modeled here, the results are improved as the forward spall is reduced. In this case, the body's forward momentum is considerably higher. This uncertainty can be considerably reduced with low frequency seismic measurements during an NEO impact like those proposed for the cancelled Clementine II mission.

While Monte Carlo simulations (Dearborn 2004) and the more deterministic approach used here shows that fracturing and dispersing an NEO can effectively eliminate an impact problem, with a detonation only a few years before impact. The statistical nature of the improvement makes this a less satisfying solution, but the short lead-time required makes this a strong option when discovery is late or other approaches have failed.

This approach has been popularly dismissed/demonized for a number of ill-founded reasons. It has been suggested that the explosive must be placed deeply to have any effect. While energy deposition near the surface is not efficient, the abundance of energy is shown to provide credible improvements to allowing the impact. The net deposition of a small fraction of a megaton is sufficient to scatter the debris with speeds that spread fragments over a volume millions of times larger than the earth leaving very little on an intercepting trajectory. It is true that depth of burial improves coupling, but it is a myth that explosive must be placed deeply to have effect. As also shown when more effect is needed (orbit 4), simply increasing the device yield works with minimal mass penalty. The 10-meter depth of burial assumed here is based on demonstrated penetrator technology on terrestrial soils. If the NEO regolith is low density and loose, this technology will simply penetrate deeper, improving the overburden.

While the direct blast results are less-dependant on material properties (than the nudge approach), we have shown that it is potentially sensitive to structure. The model that included a well-centered core with material strength showed the impulse to eject the regolith, but to leave the core intact. Acting like the central weights on a Newton's cradle, the core transmits the impulse to the regolith on the far side, and rebounds with only a small speed change, inadequate for a miss on short timescales. This behavior would have been quite different if the large solid block had been off center, but then knowing where to best place the explosive becomes an issue. The conclusion from this is that learning the actual structure of the threatening body is critical. Density and strength inhomogeneities are a significant issue for any impulsive approach, and we suggest developing a threat level that mandates a mission to study the threatening body.

Another myth that is obvious quantitative nonsense, but frequently made in popular sources, is that the debris through which the earth passes is (dangerously) radioactive. First, consider that using standard solar system abundances (Anders and Ebihara 1982), the body that is diverted contains nearly a ton of uranium that is no longer being distributed around the Earth if the body is diverted. More to the point, in these simulations, the material that was part of the explosive, as well as the material that was directly exposed to it (possibly activated), is spread over astronomical units. Over years (after much of it has decayed), the Earth will sweep up tiny fraction of the bomb debris that spreads through the inner solar system. For the spreading seen in the 900 kt simulation after 3 years, it amounts to 10 billionths of the material. Distributed over the Earth, the dose from this is un-measurable, not the case for our native sources that we are exposed to in our daily lives, much less the results from the atmospheric test days when hundreds of megatons of fission debris was spread across the Earth.



Finally, in spite of the NEO structure uncertainties that impair rigorous prediction of the use of any mitigation technology, detailed simulations show that nuclear explosives will provide considerable protection. While their use to nudge a body some decades out remains the more desirable option, fragmenting the body remains a viable back-up option with only a few years of lead-time. Even for the challenging orbit 4, a difficult problem for any technology, the consequences were markedly improved by fragmentation. However, it is not a safe assumption that an appropriate nuclear explosive will always be available on short notice. The NEO threat is not a problem for tomorrow, but one with a timescale of decades, centuries, or more. Shrinking stockpiles, and the changing security environment make it a real possibility no nuclear explosives will be available when the threat actually materializes. In that case, the time to respond will be extended by the time to manufacture new devices. Before experience in this field is relegated to historical documents, more should be done to understand the NEO mitigation potential of nuclear explosives. The calculations done here should be considered just a start in that direction, and one that should be coupled with missions to learn more about NEO structure.

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