# Scenarios for Dealing with Apophis

Donald B. Gennery
*Consultant, 1881 Alpha Road #17, Glendale, CA 91208*
*dgennery@earthlink.net*

**In the unlikely event that future observations indicate that the asteroid Apophis is going to hit Earth in 2036, it is possible to deflect it in order to prevent the collision. Because of the very close pass by Earth in 2029, such deflection is easy to do before 2029, and either the kinetic-impact method or a gravitational tractor can be used. Sample scenarios are presented in which missions using these methods are launched at various times during the years 2020-2023. Each of these scenarios requires only one launch vehicle of currently available types, although some of the scenarios also use a precursor mission to place a radar transponder on Apophis. After 2029, producing sufficient deflection is much more difficult, but it can be done by means of nuclear explosions, either buried or in standoff mode. The problem of dispersing fragments of the asteroid, which exists with both the kinetic method and the nuclear method, is discussed, and it is shown that the associated danger can be made very small, especially in the kinetic case.**

## Nomenclature

$b$ = coordinate in plane at Earth perpendicular to approach velocity to Earth without Earth's gravity
$c_r$ = effective exhaust velocity of rocket engines used by gravitational tractor
$c_t$ = overall resultant effective exhaust velocity while towing ($c_r \cos\theta$)
$f$ = dimensionless coefficient relating deflection to result
$G$ = Newton's gravitational constant ($6.674\times10^{-11}$ m$^3$ kg$^{-1}$ s$^{-2}$)
$m_A$ = mass of Apophis
$m_d$ = mass that must be delivered to vicinity of Apophis (before rendezvous, for gravitational tractor)
$m_e$ = mass that produces the desired effect by impact or gravitational attraction
$m_h$ = minimum mass of hardware that must be delivered to Apophis
$m_{tp}$ = mass of propellant used by gravitational tractor while towing
$R_A$ = radius of Apophis
$r$ = distance of tractor from center of Apophis while towing
tTNT = unit of energy representing a nominal ton of TNT ($4.184\times10^9$ J)
$v_a$ = relative approach velocity of spacecraft to Apophis
$v_\infty$ = hyperbolic excess velocity of spacecraft escaping from Earth
$v_{||}$ = component of $v_a$ parallel to the orbital velocity of Apophis
$\Delta b$ = maximum deflection needed in $b$ plane to ensure missing Earth
$\Delta t$ = duration of towing by gravitational tractor
$\Delta v$ = magnitude of the change in Apophis's orbital velocity needed to produce $\Delta b$
$\theta$ = angle by which engines of gravitational tractor are diverged while towing
$\sigma_b$ = assumed standard deviation of orbital uncertainty in $b$ plane
$\tau$ = time interval from deflection ($\Delta v$) to result ($\Delta b$) at Earth encounter

## I. Introduction

AS of Feb. 8, 2007, the asteroid (99942) Apophis (originally 2004 MN4) has the probability $2.2\times10^{-5}$ of hitting Earth on April 13, 2036.[1] Its estimated diameter is 0.25 km, and the estimated energy of a potential impact is roughly 400 MtTNT, so an atmospheric entry over land would cause destruction over an area about 100 km in diameter, whether or not the asteroid makes it to the surface intact. If it hits the ocean intact, it could cause a tsunami affecting coasts thousands of kilometers away.

Since the probability of impact might not change much before the favorable observing opportunities around 2013, it is advisable to think now about the actions that could be taken in the unlikely event that deflection of Apophis turns out to be needed. Even if the danger is ruled out earlier, Apophis still would be an interesting case, and devising appropriate methods for dealing with it could turn out to be useful if a similar case with less warning time is discovered.

One reason that Apophis is so interesting is that it will make a very close pass by Earth (about 38,000 km from the center) on April 13, 2029, at which time there is a “keyhole” only 0.61 km wide[2] (in the *b* plane) through which Apophis would need to pass in order to hit Earth in 2036. Because of the deflection by Earth’s gravity, any changes in the orbit of Apophis before this close pass are magnified by a factor of about 40,000 in terms of their result in 2036. Therefore, any action to protect Earth by deflecting Apophis is much easier if it is done before 2029 rather than afterwards, but the uncertainty in the orbit is larger than the width of the keyhole, so the amount of deflection must include the uncertainty (from both measurement errors and the Yarkovsky effect[3]) in order to ensure that the trajectory misses the keyhole.

In a previous report that David Morrison included in his NEO News e-mail newsletter on August 8, 2005, I presented some preliminary analysis of how a kinetic impact could be used to deflect Apophis before 2029. This paper revises that analysis by using improved estimates provided by Steve Chesley[2] of the accuracy of Apophis’s orbit that is likely to be available at various times in the future, it extends that analysis to consider the use of a gravitational tractor, and it considers possibilities for the difficult task of deflection after 2029.

It has been estimated that cost of the damage that would be caused if Apophis hits Earth would be around 400 billion dollars.[4] Since the cost of a mission to deflect Apophis before 2029 might be around 400 million dollars, on the basis of mathematical expectation it would make sense to start work on a deflection mission if the probability of impact becomes greater than about 0.001 (which could happen around 2013), unless there is time to wait to see if the probability greatly decreases (which then might not happen until around 2021).

A recent estimate[1] of the mass of Apophis is $2.1\times10^{10}$ kg. However, there is a considerable uncertainty in this value. Therefore, a safety factor of 2 will be applied, so that its mass is assumed to be $4.2\times10^{10}$ kg here for the purpose of computing how much impulse must be given to Apophis in order to achieve a given change in its velocity.

## II. Deflection before 2029

The amount of deflection that might be needed before 2029 is so small that it is practical to deflect Apophis by kinetic impact or by the use of a gravitational tractor.

In the kinetic method, a spacecraft simply hits the asteroid. Not only is the momentum of the spacecraft imparted to the asteroid, but also in some cases the kinetic energy of impact can blast material from the asteroid, causing a recoil that can impart several times as much momentum. However, the amount of this additional momentum is uncertain, and it may be very small in the case of a low impact velocity or a rubble-pile asteroid, as Holsapple has pointed out.[5] Therefore, to be conservative, it is ignored here, and only the momentum of the spacecraft itself is considered.

The gravitational-tractor method was recently proposed by Edward Lu and Stanley Love.[6] In that method, gravitational attraction between a rocket-propelled vehicle and an asteroid tows the asteroid along as the rocket operates.

It is assumed below that, for rendezvous, the gravitational tractor uses either chemical rockets with an effective exhaust velocity of $c_r$ = 3.1 km/s (specific impulse 316 s, equal to what the orbital maneuvering engines on the Space Shuttle produce) or solar-electric rockets with $c_r$ = 31 km/s (specific impulse 3160 s, approximately what Deep Space 1 used). However, for towing, the rocket engines must be angled out (by angle $\theta$) so that their exhaust misses the asteroid, and it is assumed that the overall resulting effective exhaust velocity then is only $c_t = c_r \cos\theta$ = 1.8 km/s with chemical rockets or 18 km/s for solar-electric propulsion. These values correspond to $\theta = 54.5°$.

It is also assumed that the spacecraft operates at a distance of $r$ = 250 m from the center of Apophis while it is towing. Since this is twice the nominal radius of Apophis, this corresponds to an angular radius of 30° for a spherical asteroid as seen from the tractor. Therefore, with $\theta = 54.5°$, an exhaust divergence semi-angle of 24.5° would be allowed. Using a more reasonable value for the latter of 12° would provide clearance with a diameter of 338 m instead of the nominal 250 m. This allows for some tolerance in the size estimate and in nonsphericity of Apophis.

The uncertainty in the orbit (and hence the amount of deflection needed) can be greatly reduced by means of a precursor mission that would place a radar transponder on Apophis or in orbit around it, as Schweickart has advocated.[4] However, kinetic impact can provide enough deflection so this may not be needed, although it would be helpful. A gravitational tractor provides its own transponder that would operate before, during, and after the deflection, so there is no need for a separate mission with it. However, after the tractor arrives at Apophis, it would take a while to accumulate the transponder measurements needed to achieve the accuracy assumed here. It is assumed here that one revolution of Apophis around the Sun (324 days) would be used for these measurements before the tractor starts operating, during which time the spacecraft would orbit Apophis. (If a separate transponder mission is used with the kinetic method, it would arrive a year or more before the kinetic mission.)

Three main scenarios are presented here for deflection before 2029, numbered 1, 2, and 3. Where appropriate, the letter K or G after the number denotes deflection by kinetic impact or a gravitational tractor. In the kinetic case, an additional letter T after the K denotes that there is a precursor transponder mission (assumed to arrive around the beginning of 2019), and a plus sign or a minus sign can be appended to denote the direction of deflection (adding to or subtracting from Apophis's orbital energy), since these require different trajectories in order to produce the correct direction of approach. (The direction of approach does not matter with a gravitational tractor.) In the case of a gravitational tractor, an additional letter C or E after the G denotes that chemical propulsion or electric propulsion, respectively, is used.

In Scenario 1, a vehicle whose design is based on the knowledge of Apophis's orbit available before 2020 is launched in late 2020 or early 2021 and arrives at Apophis a few months later. In Scenario 2, the launch occurs in 2023. Because the relative positions of Earth and Apophis are less favorable at this later time, the trip takes about four years. However, because of the more accurate knowledge of Apophis's orbit likely after 2021, less deflection is needed than with the earlier arrival (without a transponder). In Scenario 3, the launch is in 2020 or 2022, and the trip takes about three years on a trajectory designed to minimize the relative approach velocity to Apophis. The reason for desiring this low approach speed is to reduce the chance of dispersing Apophis in Scenario 3KT or to make the rendezvous easy in Scenario 3G. (With the kinetic method, usually a high approach speed along the orbital velocity vector of the asteroid is desired in order to maximize the deflection, as in Scenario 1K here. However, much less deflection is needed in the scenarios other than 1K.)

The results of approximate calculations for the above scenarios are summarized in Table 1. In the table, the standard deviation $\sigma_b$ likely in the 2029 $b$ plane at various times in the future is derived from Chesley's[2] Fig. 7, by using the curves that assume the availability of radar data. The deflection $\Delta b$ needed in the 2029 $b$ plane is assumed

TABLE 1
Summary of Pre-2029 Scenarios

| Scenario | Method | Launch | Arrival | $\sigma_b$ km | $\Delta b$ km | $v_\infty$ km/s | $v_a$ km/s | $v_{\|\|}$ km/s | $\Delta v$ μm/s | $m_e$ kg | $m_d$ kg | $\Delta t$ days |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1K+ | Kinetic | Sept. 1, 2020 | Jan. 1, 2021 | 30 | 150 | 4.73 | 3.53 | +3.02 | 242 | 3370 | 3370 | |
| 1K– | Kinetic | Mar. 15, 2021 | May 20, 2021 | 30 | 150 | 5.40 | 3.51 | –3.05 | 220 | 3030 | 3030 | |
| 1KT+ | Kinetic and transponder | Sept. 1, 2020 | Jan. 1, 2021 | 0.13 | 0.96 | 4.73 | 3.53 | +3.02 | 1.55 | 22 | 700 | |
| 1KT– | Kinetic and transponder | Mar. 15, 2021 | May 20, 2021 | 0.13 | 0.96 | 5.40 | 3.51 | –3.05 | 1.41 | 19 | 700 | |
| 1GC | Grav. tractor (chemical) | Mar. 15, 2021 | July 5, 2021 | 0.13 | 0.96 | 3.67 | 3.11 | –1.43 | 1.35 | 716 | 2000 | 20 |
| 1GE | Grav. tractor (1 N elect.) | Mar. 15, 2021 | July 22, 2021 | 0.13 | 0.96 | 3.67 | 3.11 | –1.43 | 1.35 | 902 | 1000 | 16 |
| 2K+ | Kinetic | Apr. 13, 2023 | July 10, 2027 | 1.1 | 5.8 | 5.16 | 4.78 | +4.07 | 41.4 | 427 | 700 | |
| 2K– | Kinetic | Apr. 13, 2023 | July 10, 2027 | 1.1 | 5.8 | 5.33 | 3.31 | –2.96 | 41.4 | 587 | 700 | |
| 2GC | Grav. tractor (chemical) | Apr. 13, 2023 | July 10, 2027 | 0.13 | 0.96 | 4.05 | 1.94 | –0.593 | 18 | 910 | 2100 | 210 |
| 2GE | Grav. tractor (1 N elect.) | Apr. 13, 2023 | July 21, 2027 | 0.13 | 0.96 | 4.05 | 1.94 | –0.593 | 18 | 921 | 1000 | 210 |
| 3KT+ | Kinetic and transponder | Apr. 14, 2020 | Jan. 15, 2023 | 0.13 | 0.96 | 5.62 | 0.595 | +0.583 | 2.04 | 147 | 700 | |
| 3KT– | Kinetic and transponder | Apr. 13, 2022 | Dec. 15, 2024 | 0.13 | 0.96 | 5.46 | 0.352 | –0.343 | 2.47 | 302 | 700 | |
| 3GC | Grav. tractor (chemical) | Apr. 13, 2022 | Dec. 15, 2024 | 0.13 | 0.96 | 5.46 | 0.352 | –0.343 | 2.81 | 733 | 858 | 42 |
| 3GE | Grav. tractor (0.1 N elect.) | Apr. 13, 2022 | Dec. 29, 2024 | 0.13 | 0.96 | 5.46 | 0.352 | –0.343 | 2.81 | 703 | 715 | 43 |

to be $5\sigma_b$ plus the semiwidth of keyhole. (This is a worst-case scenario, in which the probability distribution is centered exactly around the keyhole. By the time a deflection is needed, if ever, the distribution could be considerably off-center, as it is now, so that less deflection would be needed if it is done in the short direction.) The speed $v_\infty$ of the spacecraft relative to Earth after escaping and the relative approach speed $v_\mathrm{a}$ to Apophis are derived by assuming Keplerian orbits with no perturbations. ($v_\infty^2$ often is called $C_3$, "escape energy," or "launch energy," but actually it is twice the energy.) The quantity $v_{||}$ is the component of $v_\mathrm{a}$ parallel to the orbital velocity of Apophis, and it is approximately the useful component for kinetic deflection when it is done well in advance.

The velocity change $\Delta v$ needed to Apophis when the deflection occurs (on the arrival date for a kinetic impact or somewhat later for a gravitational tractor) is that which produces $\Delta b$ in 2029, under an approximation that takes into account the shape of Apophis's orbit (without perturbations) and the point at which the deflection is done but assumes that the lead time $\tau$ is long compared to Apophis's orbital period. It can be stated in simple form as follows:

$$\Delta b = f\tau\Delta v \tag{1}$$

where $f$ is a dimensionless constant that depends on the particular orbit and for any particular orbit is proportional to the orbital velocity at the point where the deflection is done. (See Ref. 7, for example, for more details.) Specifically, for the orbit of Apophis before 2029 and the result on April 13, 2029, $f \approx 3.307$ if deflection is done at the perihelion, $f \approx 2.496$ if it is done at the node where Earth's orbit is crossed, and $f \approx 2.245$ if it is done at the aphelion, for example. (When done well in advance, deflection is more effective at the perihelion for typical orbits, but it is not always convenient to get there, depending on the direction of approach that is desired. The node is the easiest point to get to, if there is plenty of time.)

It is assumed that the mass of the hardware needed for propulsion, guidance, and other instrumentation in the kinetic case is $m_\mathrm{h} = 700$ kg, which puts a lower bound on the mass $m_\mathrm{d}$ that must be delivered to Apophis. In the kinetic case, $m_\mathrm{e}$ in the table is the amount of mass needed to produce the needed impulse:

$$m_\mathrm{e} = m_\mathrm{A}\Delta v/v_{||} \qquad \text{(kinetic)} \tag{2}$$

since $m_\mathrm{e}$ is negligible compared to $m_\mathrm{A}$ (the mass of Apophis), and since we are ignoring recoil from blasted-out fragments. Thus,

$$m_\mathrm{d} = \max(m_\mathrm{h}, m_\mathrm{e}) \qquad \text{(kinetic)} \tag{3}$$

The value of 700 kg chosen for $m_\mathrm{h}$ seems to be reasonable based on experience from the Deep Impact project,[8] which performed a similar task with a 650-kg flyby spacecraft that carried a separate impactor. (The Don Quijote project[9] plans to use an impactor spacecraft of only 532 kg, but it will have a separate orbiter spacecraft of 395 kg to make observations. Here we might want a flyby spacecraft to monitor the impact and an impactor that are launched together and separate shortly before impact, as with Deep Impact.)

Perhaps $m_\mathrm{h}$ could be less for a gravitational tractor if chemical propulsion is used, since rapid maneuvering and a separable vehicle are not needed. However, the mass must be great enough to produce sufficient gravitational attraction, and in the cases here 700 kg seems to be a reasonable compromise, although an accurate optimization was not done. Therefore, $m_\mathrm{h} = 700$ kg is used also for gravitational tractors with chemical propulsion and in Scenario 3GE, where a thrust of only 0.1 N is assumed. However, Scenarios 1GE and 2GE use a higher thrust of 1 N, which would require more mass for the solar arrays and thrusters, so $m_\mathrm{h} = 900$ kg is assumed in these cases.

In the case of a gravitational tractor,

$$m_\mathrm{e} = m_\mathrm{h} + m_\mathrm{tp}/2 \qquad \text{(gravitational)} \tag{4}$$

where $m_\mathrm{tp}$ is the amount of propellant used while towing, so that $m_\mathrm{e}$ is approximately the average mass that attracts Apophis during the towing duration. From conservation of momentum, since $m_\mathrm{d}$ is negligible compared to $m_\mathrm{A}$,

$$m_\mathrm{tp} = m_\mathrm{A}\Delta v/c_\mathrm{t} \tag{5}$$

Since $m_\mathrm{d}$ includes the hardware and all of the propellant needed for deflection and rendezvous,

$$m_{\mathrm{d}} \;=\; (m_{\mathrm{h}} + m_{\mathrm{tp}})\exp(v_{\mathrm{a}}/c_{\mathrm{r}}) \qquad \text{(gravitational)} \tag{6}$$

The towing duration $\Delta t$ is computed as follows:

$$\Delta t \;=\; \Delta v\, r^2/(G m_{\mathrm{e}}) \tag{7}$$

where the distance $r$ is assumed to be 250 m, as stated above. The towing is assumed to start one Apophis revolution after arriving (plus a little more in Scenarios 1G and 3G, in order to get closer to the perihelion). The lead time $\tau$ from the midpoint of the towing duration to April 13, 2029, was used to compute $\Delta v$ from $\Delta b$ as described above in connection with Eq. (1). In Scenario 2G, $\Delta t$ starts immediately one revolution after rendezvous and is long, so its value affects the time of the midpoint and thus $\tau$ and $\Delta v$, which is used to compute $\Delta t$ by means of Eqs. (5), (4), and (7). Therefore, an iterative process was used in this case. Also in Scenario 2G, the deflection is so close to 2029 that the approximation in computing $\Delta v$ is not very good (the towing ends less than four months before the close encounter with Earth), and $\Delta t$ is so long that using its midpoint might not be very accurate. Therefore, there is a poorer approximation in this case, so the table uses fewer significant digits. For example, only two significant digits are shown for $\Delta v$ and $m_{\mathrm{d}}$ in Scenarios 2GC and 2GE, whereas three significant digits are shown for these quantities in the other scenarios. (Of course, all of these values depend on the assumptions that were made, for example about $m_{\mathrm{h}}$. Therefore, many of the values in the table actually are accurate only to about one significant digit in terms of what an actual mission might involve, but they are mutually consistent to a greater precision than that.)

Using solar-electric or nuclear-electric propulsion instead of chemical propulsion can lower the amount of propellant needed by a gravitational tractor by a factor of 10 or more, although some additional mass would be needed for the power supply and electric thrusters, depending on how much thrust is needed, since these are low-thrust systems. It is assumed here that a thrust of 0.1 N is used for rendezvous in Scenario 3GE. This allows the rendezvous velocity of 352 m/s to be eliminated in only 29 days (assuming an average mass of 710 kg). This amount of time is easily accommodated, since there are almost three years of travel time and more than four years before the close encounter with Earth. For towing, the thrusters need to be angled out, so only 0.058 N of thrust is available, but the gravitational attraction of the assumed $4.2\times10^{10}$-kg mass of Apophis and the maximum vehicle mass of 706 kg (at a distance of 250 m) is only 0.032 N, so the available thrust is more than adequate. The hardware mass needed to produce 0.1 N of thrust at an effective exhaust velocity of 31 km/s probably can be accommodated easily within the total hardware allowance of 700 kg.

A thrust of 0.058 N also is more than enough for the towing in Scenarios 1GE and 2GE. However, the rendezvous is more difficult for two reasons. First, the rendezvous velocity is greater (3110 m/s and 1940 m/s) than in Scenario 3GE. Second, there is less time available for long acceleration. (In Scenario 1G there are less than four months from launch to intercept, and in Scenario 2G there is not much time to spare after intercept.) Possibly alternate scenarios could be devised (in addition to Scenario 3GE) that reduce the problem. However, here it is assumed that a total thrust of 1 N is available in these two scenarios, and an additional mass of 200 kg is included in $m_{\mathrm{h}}$ for this purpose. The time needed for acceleration during rendezvous then is 34 days in Scenario 1GE and 22 days in Scenario 2GE.

The table assumes that approximately the same trajectory is used from Earth to Apophis approach in the gravitational-tractor scenarios with electric propulsion as with chemical propulsion. However, the gradual rendezvous because of the low thrust would delay the actual arrival at Apophis by about half of the duration of acceleration, so the arrival times shown for the electric cases take that delay into account.

In constructing the table, it is assumed that the trajectory of the vehicle to Apophis, after escaping from Earth, is a single orbit with no midcourse maneuvers other than small course corrections (excluding the rendezvous operation with a gravitational tractor). (A mass allowance of 10% should be more than adequate for such course corrections when chemical propulsion is used, or 2% if electric propulsion on a gravitational tractor is used for this purpose.) For these trajectories, launch dates and intercept dates that are fairly efficient are used, but thorough searches to find absolutely optimum dates were not done. (Izzo et al.[7] have computed optimized trajectories for the kinetic method that include planet flybys, in order to maximize the deflection. However, some of these produce high impact velocities that might increase the danger of dispersing the asteroid, and they are not needed for Apophis unless a very late launch is desired.)

The spacecraft for every case in Table 1 can be launched by a single existing launch vehicle. (A precursor transponder would need a separate launch, of course.) The most difficult case is Scenario 1K, which would need to launch about either 3700 kg with $v_\infty = 4.73$ km/s or 3300 kg with $v_\infty = 5.40$ km/s (including propellant for course corrections). These are within the capability of the Atlas V 541. If a safety factor of 3 instead of 2 is used for the mass of Apophis (so that $6.3\times10^{10}$ kg would be assumed for its mass), Scenario 1K would require the launch of 5600 kg at 4.73 km/s or 5000 kg at 5.40 km/s. These are within the capability of the Delta IV Heavy, which is the largest launch vehicle currently available. The other cases are much easier. Based on the values in the table, Scenarios 1KT, 2K, 3KT, 1GE, 2GE, and 3GE each could be handled by one launch of a Delta II 7925H; Scenarios 1GC and 2GC would require a larger vehicle such as the Atlas V 511 or Zenit 3SL, for example; and Scenario 3GC could use an Atlas V 501, Delta IV Medium, or Zenit 3SL. If $m_h$ could be reduced to 570 kg instead of 700 kg, Scenarios 1KT, 2K, and 3KT could use a Delta II 7925. A similar reduction in mass for Scenarios 1GE, 2GE, and 3GE could allow this launch vehicle to be used for them also.

The capabilities of the launch vehicles mentioned above are described in Refs. 10 and 11. The cost of a launch using one of these vehicles ranges from about $60,000,000 for a Delta II 7925 to roughly $200,000,000 for a Delta IV Heavy. No doubt, launch vehicles in 2020 will differ from these, estimates of the mass of Apophis may improve, and predictions about its orbital accuracy will change, but considering what vehicles and information are available now helps to illustrate the feasibility of the task.

If the Arecibo radar becomes unavailable, Chesley's Fig. 7 indicates that $\sigma_b$ for Scenario 1K would increase by less than 20%, so that Scenario 1K would be only slightly harder than indicated above. However, without radar data in 2021 (and with no transponder), the improvement in $\sigma_b$ at that time would be much smaller, so that $\sigma_b$ after 2021 could be about an order of magnitude greater than the value in the table, and Scenario 2K would become considerably harder, but still doable with two launches instead of one.

The hardest part about the kinetic-impact method is the aiming of the spacecraft to cause it to hit as it rapidly approaches the asteroid or comet. The degree of difficulty depends primarily on the transverse acceleration that would have to be produced to correct for a given angular offset. For a given resolution of the camera used for aiming, the maximum acceleration needed is proportional to the square of the relative approach velocity and is inversely proportional to the diameter of the object. Deep Impact[8] hit the nucleus of comet Tempel 1, whose diameter is about 6 km, at a speed of 10.3 km/s. Compared to that project, the scenarios here range from 2K+, which is about 5.2 times as hard, to 3KT–, which is 36 times easier than Deep Impact. When likely improvements in technology are considered, even Scenario 2K+ should be reasonable. For example, the proposed Don Quijote project[9] plans to hit an asteroid of about 500-m diameter at a speed of about 10 km/s. Scenario 2K+ is 2.2 times easier than that.

The fact that an off-center hit causes some change in the rotation of the asteroid is irrelevant. Some additional energy is imparted to the asteroid to increase its rotation (or subtracted from it to decrease its rotation), but it does not subtract from (or add to) the energy given to it for translation, because of conservation of momentum. (It changes the energy going into heat and kinetic energy of blasted-out fragments, which is where most of the energy goes anyway.) The main danger (other than missing completely) is that the hit is so far off center that it merely knocks off a chunk of material, leaving the main part of the object practically undisturbed. With reasonable aiming accuracy, the latter problem can be avoided. (Any additional impulse due to the momentum of blasted-out fragments would be reduced by the cosine of their angle, but this additional impulse is not even being considered here.)

## III. Deflection after 2029

If nothing is done before 2029, observations of Apophis as it passes by Earth on April 13 should be able to determine its future course very accurately. If it then turns out that it will hit Earth in 2036, deflection becomes more difficult than before by a few orders of magnitude, and both the kinetic method and gravitational tractors are out of the question, unless there is a considerable improvement in technology by 2029. Also, with only seven years available for preparing and executing a mission, there might not be enough time to use one of the other methods of gradual deflection. These facts could leave the use of one or more nuclear bombs as the only option after 2029.

If Apophis were heading exactly for the center of Earth, the deflection needed in the 2036 *b* plane could be estimated by taking the average radius of Earth (about 6370 km), adding 50 km for the atmosphere, and multiplying by 2.145 because of the focusing effect of Earth's gravity on an object approaching at 5.87 km/s, to obtain 13,770 km, and then adding a few hundred kilometers to allow for the uncertainty in Apophis' orbit after 2029. (This uncertainty is only a small part of the total, so its exact value is not critical, unlike the situation before 2029). However, Apophis is not be headed for Earth's center. From the current knowledge of the orbit of Apophis, it is known that, if an impact point on Earth exists for 2036, it has to be somewhere along a narrow path that stretches from Kazakhstan, across Siberia, the Sea of Okhotsk, the Kamchatka Peninsula, the Pacific Ocean, Nicaragua, the southern Caribbean Sea, extreme northern Colombia and Venezuela, and the Atlantic Ocean, almost to Africa. As measured in the *b* plane, the most central of the possible impact points is displaced 53% from Earth's center towards the point where it would miss Earth completely.

Therefore, the maximum deflection after 2029 can be computed as follows. If it is done well in advance, the deflection most easily would move the impact point along the path described above, so that the maximum deflection that might be needed in the *b* plane is (13,770 km)$\sqrt{1 - 0.53^2}$ = 11,680 km. Adding an allowance for uncertainty in the orbit would bring the total to about 12,000 km. (This is the worst case. After 2029, the actual impact point will be known within a few hundred kilometers, so it might turn out that much less deflection would be needed.) If deflection is done on the final approach to Earth, it would most easily be done in the shortest direction, so that the maximum needed in the *b* plane would be 0.47(13,770 km) = 6440 km. With an allowance for uncertainty, which would be small at this late date, the total would be about 6600 km.

The $\Delta v$ needed to produce the above amounts of deflection would be roughly 0.025 m/s in 2031 or 0.13 m/s in 2035, depending on where in its orbit Apophis is intercepted, or 2.5 m/s one month before impact. (The first two values were obtained by using the generic approximation $f \approx 3$ in Eq. (1). The third value was obtained from $f \approx 1$, which is valid on the final approach to Earth, where the optimum direction of deflection is approximately perpendicular to the relative approach velocity, instead of parallel to the orbital velocity.)

First, consider buried bombs. From the information in Ref 12, it appears that, for the above three cases of preventing a 2036 impact by deflecting in 2031, 2035, or 2036, a buried bomb with the energy of about 2 ktTNT, 10 ktTNT, or 150 ktTNT, respectively, would be sufficient, even if there is considerable porosity to absorb the energy from a buried explosion. There are still plenty of bombs with these sorts of energy available, and there very well still could be 30 years from now. However, there is not much time for the preparation and execution of a mission that would land on Apophis and bury the bomb.

Computations assuming Keplerian orbits and based on the orbit that Apophis will have after 2029 if it actually is going to hit Earth in 2036 indicate that a launch on April 13, 2034, and a rendezvous on March 1, 2035, would have $v_\infty$ = 4.51 km/s and $v_a$ = 3.42 km/s. The mass of any of the above bombs to be buried would be small (about 200 kg or less), but the mass of the guidance devices, propulsion thrusters, robotic devices for burying the bomb, and sufficient propellant to eliminate the 3.42 km/s rendezvous velocity (and perhaps 0.2 km/s for course corrections) would bring to total to several thousand kilograms. If the total can be kept below 6400 kg, a Delta IV Heavy could be used to launch it. Otherwise, an earlier launch date could be found that would make the velocities smaller, but that could leave much less than five years for designing and manufacturing the robotic burial devices. Therefore, it seems that this approach depends on either having the burial equipment already available around 2029 or having it be not very massive.

Using a standoff nuclear explosion is easier and faster, but a much larger bomb is required. Consider the above assumed value $4.2\times10^{10}$ kg (twice the current estimate) for the mass of Apophis and the current estimate of 250 m for its diameter. (This is a pessimistic combination, since a larger mass probably would imply a larger diameter.) Then, by using Fig. 2 from Ref. 13, it can be estimated that the first case mentioned above ($\Delta v$ = 0.025 m/s, approximately what would be needed for deflection in 2031 to prevent an impact in 2036) would require a bomb with the energy of about 3.3 MtTNT if it is detonated 20 m from the surface of Apophis, 5.2 MtTNT at 30 m, or 8.3 MtTNT at 50 m, for example, if the bomb delivers 1% of its energy as neutrons (a fraction which is typical for existing bombs), even if we do not utilize any of the energy delivered by X rays. (If an actual bomb is used, it probably would be necessary to remove its outer container that allows it to be delivered as a weapon, in order to minimize the absorption of neutrons.) The B53 bomb has an energy of 9 MtTNT and a mass of 4000 kg, so it should be adequate even at 50 m. However, this bomb is no longer in service, apparently no information is publicly available about whether any still exist, and, even if they do, it is unlikely that they still will exist in 2029.

The largest U.S. bomb currently in service is the B83, which has an energy of 1.2 MtTNT and a mass of 1100 kg. It would take six of these, if they are detonated 20 m from the surface at separate times, to do the above job (with $\Delta v$ = 0.025 m/s), based on the above pessimistic assumptions, or three of them based on the nominal values of mass and diameter for Apophis. (If the bombs could be detonated simultaneously, three would be sufficient even in the pessimistic case, but doing that probably is not feasible.) This seems impractical on only two years notice, even if these bombs will still exist in 2029, since the two years includes the time for preparation, possible separate launches for up to six spacecraft, and travel time to Apophis.

Therefore, it might turn out that, in order to do the job with a standoff nuclear explosion, a bomb would have to be built to order. If one is, it could be just a recreation of the B53, or it could be a custom bomb designed to produce a larger neutron yield than existing bombs have, in order to deliver energy more efficiently to the asteroid. Since the design process in the latter case would take more time, which would result in a later launch, which could require a longer trip in order to have a reasonably efficient trajectory, assume that the deflection would occur in 2035 with $\Delta v$ = 0.13 m/s. From the assumptions in Ref. 13, which include a neutron yield of 10% (5% of the energy that a bomb not optimized for neutrons might produce), and the above pessimistic assumptions about Apophis, it appears that either one of the following combinations (or various combinations in between) would do: a 1.7-MtTNT bomb (with mass 1300 kg) detonated 20 m from the surface, or an 11-MtTNT bomb (with mass 6400 kg) detonated at 160 m. Although the first one of these requires less mass to be delivered to Apophis, the greater distance from the surface for the second one reduces the likelihood of dispersing the asteroid, and it gives greater control over the direction of deflection for a given approach direction, since the bomb can be detonated at various points as desired.

Approximate computations as above indicate that a launch on April 13, 2033, and an intercept on May 7, 2035, would have $v_\infty$ = 1.64 km/s, $v_\mathrm{a}$ = 5.63 km/s, and $v_{||}$ = –2.76 km/s. Since arccos(2.76/5.63) = 61°, the direction of approach differs greatly from the desired deflection direction, and is only 29° from being orthogonal to it. Unlike the case with deflection by kinetic impact, this situation is desirable here, because it allows deflection to occur in either direction, depending on which side of the asteroid the vehicle is steered for a flyby, and detonating at a distance of 160 m from the surface of a 250-m object gives us plenty of leeway for this choice. (However, since the desired direction of deflection would be known well in advance here, a trajectory probably could be found in each case that headed for an impact in the desired direction instead of a flyby. Then the most stringent accuracy requirement would be on the time of detonation instead of the aiming. Since the former can be done by proximity sensing using radar, it might be easier.)

Adding an allowance for equipment and propellant for course corrections to the 6400 kg for the above custom 11-MtTNT bomb would bring the total to a mass around 8000 kg. The Delta IV Heavy can launch 8900 kg with $v_\infty$ = 1.64 km/s, so there is no problem there. However, there are only four years (from 2029 to 2033) to design and manufacture the bomb. This probably is sufficient time, but if facilities for this sort of thing no longer exist in 2029, they would have to be created also. Also, keep in mind that the bomb used in this example (unlike the B53 or B83 bomb) is hypothetical, and apparently no bomb this large with such a high neutron yield has ever been built.

We have seen above that there are several possible methods of using nuclear bombs to deflect Apophis after 2029. Every one of the methods has problems, but very likely at least one of them could be made to work. The cost could run into billions of dollars, but that is a small amount considering the damage worth hundreds of billions of dollars that could result from an impact.

However, there are several problems of a partly political nature. One of these is the possible dispersal of Apophis, which will be discussed further in the next section. In the case of an object that is threatening to produce world-wide effects, the much smaller danger from a few fragments that might hit Earth would be tolerated. However, in the case of Apophis, which threatens only regional effects, controversy might ensue, since the fragments might hit anywhere.

Another such problem is similar to what Schweickart[14] called “The Real Deflection Dilemma,” although he was considering an impact point that was gradually moved across Earth, and here we are doing it in one jump or perhaps several jumps. If Apophis is going to hit Earth, after 2029 it will be known fairly accurately where it will hit. For example, suppose that the predicted impact point is in the Pacific Ocean southwest of Mexico or California. In order to avoid a devastating tsunami, we would want to deflect Apophis. The easiest way to deflect it to cause it to miss Earth (if done more than one revolution in advance) would be to move the impact point along the path of possible impact points mentioned above (since the effect of the deflection then accumulates over a few revolutions). The shortest way from the stated point would be to the east, across Nicaragua, Columbia, and Venezuela, but the people in those countries might object, because a partial failure that produced less deflection than planned could move the impact point to them. If we deflect in the slightly longer way, to the west, people along the way there might object. (If the deflection is done on the final approach to Earth, the shortest way to deflect it in this case would be to the north, over the U.S. and Canada, so actually it might be deflected the long way, to the south, where mostly ocean exists. If this much deflection capability is available for an earlier deflection, this direction could be used then, also, but it probably would require the use of a buried nuclear bomb.)

Another concern that is almost entirely political is that of radioactivity. The portion of the asteroid’s material that is irradiated by neutrons will become radioactive. However, the most heavily irradiated material will evaporate and dissipate in space, and most of the asteroid is shielded from neutrons by other portions of the asteroid. (Neutrons generally penetrate less than a meter.) If any small fragments of the asteroid break off and reach Earth, evaporation in the atmosphere will disperse whatever little radioactivity that they contain, and, of course, the most highly radioactive isotopes will decay before they can get to Earth.

Because of the objections that might be raised about a deflection attempt using nuclear explosives (and the question about who would pay for it if the predicted impact point is in a country with no such capability), the decision might be made to evacuate the affected area (which would be known seven years in advance) and to accept the property damage. Depending on where the impact point is, this would not be a very rational decision. (If the impact is in Nicaragua, it might destroy 5% of the country.) These difficulties would be avoided if any needed deflection is done before 2029.

## IV. The Danger of Dispersal and What to Do about It

A concern when a method of sudden deflection is used, whether by kinetic impact or nuclear explosion, is the possibility of dispersing the object. In some cases, especially with a large object, many fragments could be produced that would do more damage than the original object, if most of them hit Earth. Two of the important parameters in this regard are the gravitational binding energy and escape velocity of the object. Based on its estimated mass of $2.1\times10^{10}$ kg, its estimated radius of 125 m, and an assumption that it is spherical, the gravitational binding energy ($3Gm_\mathrm{A}^2/(5R_\mathrm{A})$) of Apophis is $1.4\times10^8$ J, and its escape velocity ($\sqrt{2Gm_\mathrm{A}/R_\mathrm{A}}$) is 0.15 m/s.

Based on the values in Table 1 for Scenario 3K, the mass $m_\mathrm{d}$ at speed $v_\mathrm{a}$ would have a kinetic energy of $1.24\times10^8$ J or $4.34\times10^7$ J when it hits Apophis. Since these values are less than the gravitational binding energy, a complete dispersal of Apophis would be impossible in this case, although Scenario 3K+ is marginal because of the uncertainty about the mass, size, and shape of Apophis. The kinetic energy in the other cases is larger than the binding energy, ranging up to $2.10\times10^{10}$ J for Scenario 1K+, which is about 150 times the binding energy. Therefore, dispersal is possible in principle in these other cases.

However, the largest $\Delta v$ given to Apophis in any of the kinetic scenarios is 242 μm/s, and Apophis's escape velocity is about 600 times this value. There are two consequence of this large ratio.

First, because of the large value of this ratio, if the asteroid disperses, the fragments would scatter by a large amount around their center of mass, which is deflected by the same amount whether or not dispersal occurs. (Such considerations have been discussed in detail for the general problem.[13]) Therefore, only a very small fraction of the fragments would hit Earth in the target year (2036). In fact, it is unlikely that Earth would be hit then by even one fragment large enough to overcome the protection provided by the atmosphere and thus to do any damage at all. However, as the fragments pass by Earth in 2029, a much larger (but still small) fraction could hit then, so it is important that dispersal does not occur in these cases.

Second, the large ratio of escape velocity to deflection velocity makes it very unlikely that dispersion would occur in the first place. This can be verified with the help of some information[15,16] that indicates that in this case there is not enough energy in the impacts to break up a monolith, and a rubble pile would absorb the energy so well that it could not be distributed to cause a large-scale dispersal. Of course, some pieces could be ejected locally at the impact site, but they probably would have sufficient velocity to miss Earth, and they probably would be so small that the atmosphere would protect us anyway.

In case there is any worry about the possibility of dispersal, however slight, there are some measures that could be taken to reduce the danger even further. In Scenario 1KT, the mass $m_\mathrm{e}$ could be ejected so that it would hit Apophis, with the rest of the vehicle missing (as was done with Deep Impact). In this case the kinetic energy of impact would be $1.2\times10^8$ J or less. Alternatively, as mentioned above, Scenario 3KT could be used, which was designed to have a low impact velocity.

In any of the kinetic scenarios, the impact on Apophis could be made more gentle by spreading it out in space and time by exploding the vehicle just before it hits. The debris would hit the asteroid, but the fact that it is spread out over a considerable portion of the surface instead of being concentrated at one point makes dispersal less likely. Also, since it hits over an appreciable interval of time, it applies a more gentle push to the asteroid instead of creating a shock wave in its material. For example, spreading the debris over about 150 m would still enable almost all of it to hit within the 250-m diameter of Apophis if the guidance is sufficiently accurate. At the highest approach velocity in Scenarios 1 and 2 of 4.78 km/s, the impact of a 150-m cloud of debris would be spread out over 0.031 s. If the speed of sound in the material is 2000 m/s, a disturbance would travel 62 m in this time, which is 25% of the diameter of Apophis. By shaping the vehicle and the explosive charge appropriately, it might be possible to spread out the cloud considerably more in the direction of approach than transversely, so as to increase this time even more and to make the push even more gentle.

If deflection by a nuclear bomb is done after 2029 (but about a year or more before Apophis would hit Earth), $\Delta v$ would be in the range approximately from 0.022 m/s to 0.15 m/s, depending on exactly when the deflection is done. The first is only somewhat smaller than the escape velocity, so there is some chance of dispersal, and the second is approximately the same as the escape velocity, so dispersal is fairly likely, but most of the fragments would miss Earth, especially in the first case. If the deflection is divided into several smaller impulses from separate launches (using six B83 bombs, for example), the chance of dispersal would be reduced.

If a buried bomb deflects Apophis one month before it reaches Earth, the $\Delta v$ of 5.3 m/s is 35 times the escape velocity, so dispersal is almost certain. If this last-chance attempt is made, it would be advisable to use a much larger explosion than the 300 ktTNT mentioned above, so as to disperse Apophis very widely. Depending on the results of better estimates of the likelihood of dispersal in the two cases of earlier deflection in the previous paragraph, this approach might be advisable with them also, where it could be even more effective, especially if a buried bomb is used. The idea is either to prevent dispersal or to cause very complete and wide dispersal so that very few, if any, large fragments hit Earth.

Thus the danger from fragments of Apophis hitting Earth can be almost completely eliminated if the kinetic-impact method is used before 2029, but some small danger would remain if the nuclear-explosion method is used after 2029. However, this probably is not the greatest difficulty faced by the nuclear method in the case of Apophis.

## V. Conclusions

If a collision with Earth in 2036 becomes likely, Apophis can easily be deflected before 2029 either by the kinetic-impact method or by a gravitational tractor. In fact, the cost of such a mission might not be more than the cost of a precursor mission to place a transponder on Apophis to find out if it needs to be deflected. However, a transponder mission can help in the case of kinetic-impact deflection by reducing the amount of deflection needed. A precursor transponder would help only slightly in the case of a gravitational tractor, by eliminating the wait for the tractor's own transponder to produce enough data after arrival to achieve the desired accuracy in the estimate of Apophis's orbit.

After 2029, deflection is more difficult, but in principle it can be done by means of one or more nuclear bombs. However, if deflection of Apophis turns out to be needed, it would be greatly preferable to do it before 2029.

## References

[1] NASA Near-Earth Object Program risk page for Apophis, URL: http://neo.jpl.nasa.gov/risk/a99942.html.

[2] Chesley, S. R., "Potential Impact Detection for Near-Earth Asteroids: The Case of 99942 Apophis (2004 MN4)," *Asteroids, Comets, and Meteors* (Proceedings of IAU Symposium No. 229, Aug. 7-12, 2005), edited by D. Lazzaro, S. Farraz-Mello, and J. A. Fernández, Cambridge University Press, Cambridge, England, 2006, pp. 215-228. (An almost identical version is available at http://www.b612foundation.org/papers/Chesley_paper.pdf.)

[3] Spitale, J. N., "Asteroid Hazard Mitigation Using the Yarkovsky Effect," *Science*, Vol. 296, 5 April 2002, p. 77.

[4] Schweickart, R. L., "A Call to (Considered) Action," National Space Society International Space Development Conference, May 20, 2005, available at http://www.b612foundation.org/papers/Call_for_Action.pdf.

[5] Holsapple, K. A., "An Assessment of Our Present Ability to Deflect Asteroids and Comets," paper AIAA-2004-1413, *Planetary Defense Conference: Protecting Earth from Asteroids*, Feb. 23-26, 2004. The Proceedings are available at http://www.aiaa.org/content.cfm?pageid=320, either online, paperback, or CD-ROM (*2004 AIAA Meeting Papers on Disc*, Vol. 9, No. 5), AIAA, Reston, VA.

[6] Lu, E. T., and Love, S. G., "Gravitational Tractor for Towing Asteroids," *Nature*, Vol. 438, 10 Nov. 2005, pp. 177-178.

[7] Izzo, D., Bourdoux, A, Walker, R. and Ongaro, F., "Optimal Trajectories for the Impulsive Deflection of Near Earth Objects," *Acta Astronautica*, Vol. 59, July-Sept. 2006, pp. 294-300.

[8] NASA Deep Impact Legacy Site, URL: http://deepimpact.jpl.nasa.gov/.

[9] ESA Don Quijote page, URL: http://www.esa.int/gsp/NEO/quijote/quijote.htm.

[10] Isakowitz, S. J., Hopkins, J. B., and Hopkins, J. P. Jr., *International Reference Guide to Space Launch Systems*, Fourth Edition, AIAA, Reston, VA, 2004.

[11] Delta Payload Planners Guides, available at http://www.boeing.com/defense-space/space/delta/delta2/guides.htm.

[12] Shafer, B. P., et al., "The Coupling of Energy to Asteroids and Comets," *Hazards Due to Comets and Asteroids*, edited by T. Gehrels, University of Arizona Press, Tucson, AZ, 1994, pp. 955-1012.

[13] Gennery, D. B., "Deflecting Asteroids by Means of Standoff Nuclear Explosions," paper AIAA-2004-1439, *Planetary Defense Conference: Protecting Earth from Asteroids*, Feb. 23-26, 2004. The Proceedings are available at http://www.aiaa.org/content.cfm?pageid=320, either online, paperback, or CD-ROM (*2004 AIAA Meeting Papers on Disc*, Vol. 9, No. 5), AIAA, Reston, VA. The paper is also available as a PDF file at http://home.earthlink.net/~dgennery/2004_1439.pdf.

[14] Schweickart, R. L., "The Real Deflection Dilemma," paper AIAA-2004-1467, *Planetary Defense Conference: Protecting Earth from Asteroids*, Feb. 23-26, 2004. The Proceedings are available at http://www.aiaa.org/content.cfm?pageid=320, either online, paperback, or CD-ROM (*2004 AIAA Meeting Papers on Disc*, Vol. 9, No. 5), AIAA, Reston, VA. The paper is also available as a PDF file at http://www.b612foundation.org/papers/Real_Deflection_Dilemma.pdf.

[15] Holsapple, K., Giblin, I., Housen, K,. Nakamura, A., and Ryan, E., "Asteroid Impacts: Laboratory Experiments and Scaling Laws," *Asteroids III*, edited by W. F. Bottke Jr., A. Cellino, P. Paolicchi, and R. P. Binzel, University of Arizona Press, Tucson, AZ, 2002, pp. 443-462.

[16] Asphaug, E., Ostro, S. J., Hudson, R. S., Scheeres., D. J., and Benz, W., "Disruption of Kilometre-Sized Asteroids by Energetic Collisions," *Nature*, Vol. 393, 4 June 1998, pp. 437-440.