Deflecting a Hazardous Near-Earth Object

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INTRODUCTION

This short report on Near-Earth Object (NEO) hazard mitigation strategies was developed in response to a request for information by the U.S. National Research Council's Space Sciences Board on December 17, 2008 and for the Planetary Defense Conference that took place 27-30 April 2009 in Granada Spain. Although we present example simulations for specific techniques that could be employed to deflect an Earth threatening NEO, our primary goal is to discuss some of the general principles and techniques that would be germane to all NEO deflection scenarios. This report summarizes work that was carried out in early 2009 and extends an earlier, more detailed study carried out in late 2008 [1].

STUDY OVERVIEW

Because of the wide range of possible sizes, trajectories and warning times for Earth threatening NEOs, there will be a corresponding range in the levels of challenge in providing an appropriate mitigation response. Unless there are decades of warning time, hazardous NEOs larger than a few hundred meters in diameter may require large energies to deflect or fragment. In these cases, nuclear explosions, either stand-off or surface blasts, might provide a suitable response. For the far more numerous objects that are smaller than a few hundred meters in diameter, and provided there is a sufficient warning time, a kinetic energy (KE) impactor spacecraft might be sufficient to deflect the hazardous NEO so that it would miss the Earth at the time of a predicted impact. These mitigation options have been discussed in some detail (for example, see [2]). This current report will discuss some of the other issues that have not yet been fully addressed, including the deflection of a NEO when the predicted Earth impact is preceded by a close Earth approach a few years earlier, the verification of a successful deflection, and the need for NEO "trim maneuvers" to ensure deflection success.

To illustrate some of these NEO mitigation issues, we consider Apophis, a NEO that will make a very close Earth approach on April 13, 2029 (to within 5 Earth radii of the Earth's surface). Although it is an extremely unlikely scenario, we will assume that Apophis will pass through a narrow 610 meter region in space (a "keyhole"), that would cause it to be perturbed by the Earth into a resonant return, complete 6 revolutions about the sun and collide with the Earth on April 13, 2036. We then consider the deflection option whereby a rendezvous spacecraft (S/C) is sent to Apophis several years in advance of the 2029 close Earth approach. The combination of S/C tracking and imaging of Apophis from this rendezvous S/C would allow the ephemeris positions of Apophis to be greatly refined. Hence this S/C would be capable of verifying the 2036 impact possibility. We then assume this same S/C could act as a gravity tractor [3] to slightly trim the asteroid's velocity by mutual gravitational interaction, enough to avoid the 2036 keyhole as well as any secondary keyholes that could allow Apophis to impact the Earth at a return subsequent to 2036. That is, the S/C could act as a gravity tractor (GT) in 2022 to slowly move Apophis away from the 2036 and secondary keyholes that are present at the time of the 2029 Earth close approach. At the same time, the tracking of the S/C would allow the orbit of Apophis to be refined to the sub-kilometer level so that a successful deflection via the GT could be verified.

We begin this report by defining some necessary terminology, stating our hypothetical Apophis impact scenario, and outlining the design of a viable Apophis rendezvous/gravity tractor mission. We then summarize how ground tracking of the rendezvous S/C combined with onboard asteroid imaging can greatly refine the orbit of Apophis and verify that it is headed for the 2036 keyhole in its 2029 passage by the Earth. Next, we discuss strategies for choosing the target location for the deflection, so that both the primary 2036 keyhole and the neighboring secondary keyholes can be avoided during the 2029 close Earth approach. A discussion of the geopolitical considerations of deflection is then included, followed by some considerations for using a kinetic energy impactor in combination with the rendezvous GT spacecraft. Finally, we provide a summary of our key points.

B-Planes and Keyholes

The orbit of an asteroid at a given time can be uniquely identified by a set of 6 parameters called orbital elements. The orbit is solved for iteratively by finding the element set which best fits the available astrometric observations of the asteroid. (The current set of observations for Apophis numbers well over 700.) No orbit solution will match all the observations perfectly because they contain small random measurement errors. The uncertainty region or ellipsoid is the volume of 6-dimensional orbital element space containing all orbital solutions which satisfy the observations sufficiently well (i.e., to within the expected level of measurement errors). The region is often also projected into 3-dimensional position space; for Apophis, at the time of its most recent observation, the position uncertainty region was less than 100 km in extent. The size of the uncertainty region depends on the number, timing and accuracy of the observations; it shrinks as observations are added to the data set. On the other hand, when the region is projected into the future, differential orbit dynamics cause it to spread in the along-track direction, while uncertainties in the cross-track direction remain relatively small. The current Apophis uncertainty region projected to the time of its 2029 close approach is typical: a long thin region aligned along the orbital path. The axis of this region is often called the Line of Variations (LOV) to indicate that the various possible locations of the asteroid lie along this line. As more and more ground-based observations of Apophis are made in the coming decade, the uncertainty region will significantly shrink. And the region would shrink even more dramatically if the asteroid were observed from a nearby spacecraft.

Position uncertainties during a close approach are best analyzed when projected into the so-called b-plane (also called the target plane). The b-plane is defined as the plane centered on the planet and perpendicular to the incoming trajectory asymptote. If the uncertainty region projected into the b-plane intersects the Earth's capture cross section, then an impact is possible. The Apophis uncertainty region in the 2029 b-plane is currently a 3500-km long swath less than 100 km wide, and it does not overlap the Earth's cross section, which is tens of thousand of kilometers distant on the b-plane. But impacts can still occur through keyholes. Keyholes are narrow strips within the b-plane confidence region that are entrances to corridors in which Earth's perturbation puts the NEO on a resonant return that impacts the Earth on a subsequent close approach [4]. There is currently a small possibility that during its 2029 close approach Apophis could pass through the so-called "2036 keyhole," through which it would be perturbed onto a trajectory which impacts the Earth in 2036. This trajectory would lie in a 7:6 resonance: while the Earth revolved about the Sun 7 times, Apophis would go around 6 times, bringing the two bodies back to the same position on April 13, 2036 for a collision.

Near the 2036 keyhole we can expect secondary keyholes that lead to Earth impacts in years beyond 2036. A secondary keyhole is simply a primary keyhole in the b-plane of one close approach (e.g. 2036) mapped backwards to the b-plane of the previous close approach (i.e. 2029). The secondary keyhole leads to an impact because of a resonance after the second close approach (i.e., after 2036 in this case).

The Impact Scenario

In all likelihood, the ground-based optical and radar observations of Apophis planned for the January 2013 and March 2021 Earth approaches will rule out the possibility of passage through the 2036 keyhole. Nevertheless, for the purposes of this study, we assume that these observations and the subsequent orbit refinements do not rule out the impact. In fact, we make the worst-case assumption that as observations shrink the uncertainty region, it converges onto the 2036 keyhole and a 2036 impact therefore becomes very likely.

AN APOPHIS RENDEZVOUS/GRAVITY TRACTOR MISSION

We examined a wide range of launch and arrival-date options for an Apophis rendezvous S/C over the next two decades. A number of good mission options were found in the 2021-2022 time frame, with the best ones having launch dates in March and April of 2021. We selected mid-April 2021 as our nominal launch date, with a C3 of 28.5 $(km/s)^2$, a flight time of nearly eight months, and arrival in early January 2022 with an arrival delta-V of about 400 m/s. A twenty-day launch period would be available, from April 10 to April 30, for a modest increase in C3 to 30 $(km/s)^2$, and with a still-reasonable arrival delta-V of 900 m/s in mid to late December 2021. This rendezvous could be achieved through the use of a small solid rocket motor; alternatively, low thrust ion propulsion could be used starting soon after launch to shape the transfer orbit leading to a rendezvous.

After arrival, a month or so would be allotted for rendezvous operations to place the spacecraft in a stable orbiting or hovering location near Apophis. This time period would also be used for initial checkout and calibration of the instruments. Soon thereafter, a high accuracy shape model of Apophis would be generated using camera images; this step is a key process that allows accurate positioning of the orbiter relative to Apophis. The Apophis tracking phase would then begin, with the objective of greatly improving knowledge of the asteroid's trajectory and therefore dramatically shrinking its position uncertainties in the 2029 b-plane.

Tracking Apophis to Verify That It Will Impact

Verifying that the asteroid is on an impacting trajectory is particularly difficult in our scenario because of the 2029 close approach. We must determine whether the asteroid is headed for a very narrow keyhole in the b-plane, not the much larger impact region of the entire planet, as we would have for a direct impact. The uncertainty region would have to shrink down to become approximately the same size as the keyhole in order to verify impact, and this could be accomplished only with highly accurate measurements. It has been suggested that the best way of obtaining such measurements is to land a transponder on the asteroid and track it as if it were a spacecraft. In our previous study [1], however, we have shown that camera imaging data from a spacecraft orbiting or hovering near a small asteroid can be used to measure the asteroid's position, and these data can be combined with normal ground-based spacecraft tracking to provide accurate tracking of the asteroid very comparable to that obtained from landing a transponder. In particular, the optical images of the asteroid from the spacecraft could give sub-meter level positioning with respect to the asteroid. The radiometric data could then provide an accurate heliocentric determination of the spacecraft. This scenario has the advantage of avoiding the additional costs and risks of carrying a separate landing system to place a transponder on the surface of the asteroid. Moreover, a landed transponder poses serious thermal and power challenges due to seasonal and diurnal dark periods at the landing site. Communication and tracking are also more difficult for a landed transponder.

We assume that the Apophis tracking campaign begins on February 14, 2022, using continuous radiometric tracking of the orbiter for several weeks. A high fidelity uncertainty analysis was performed using this scenario to determine the improvement in Apophis' trajectory that can be obtained from in situ tracking, beyond what can be obtained from ground-based astrometry up to this time. The analysis used simulated tracking data incorporated into a least squares fit of the Apophis orbit and produced an estimate of the uncertainty in the orbit parameters. These uncertainties were then mapped forward to the b-plane of Apophis' flyby of Earth in 2029.

The results are shown in Fig. 1, which plots the semi-major and semi-minor axes of the uncertainty ellipse in the b-plane. Starting from a very conservative uncertainty ellipse in the 2029 b-plane (580 x 15 km) that is based upon only current ground-based optical astrometry, the analysis shows that tracking the spacecraft for 20 days would reduce the Apophis position uncertainty to about 5 x 0.6 km. After a period of little change, the uncertainties further reduce to about 360 x 180 m after 65 days. Additional tracking does not seem to improve the results, so it is assumed that this represents the best orbit that can be determined at this time period.

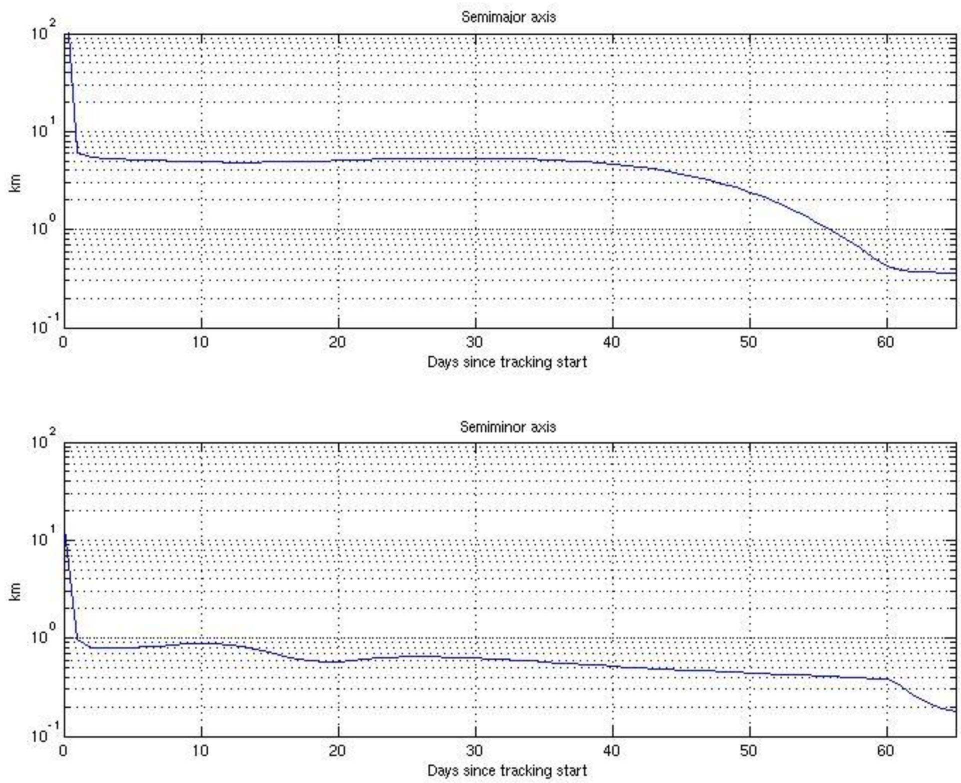

Fig. 1: 1 sigma Apophis Orbit Uncertainty at the Earth 2029 B-plane

The Apophis Physical Model

To ensure that the gravity tractor spacecraft is sized to have enough fuel on-board to complete the required deflection, we adopt a conservative physical model for Apophis, one that is at the large end of the range of possibilities. The asteroid is modeled as a tri-axial ellipsoid with arbitrarily selected axial ratios of 1.4 x 1.2 x 1. In [5], the diameter of the visible disk of Apophis is estimated to be 270 +/- 60 meters. If a viewing geometry is assumed where only the maximum and minimum dimensions are visible, the above axial ratio suggests a maximum Apophis size with semi-major axes of 195 x 167 x 139 meters.

The maximum expected density for Apophis is estimated assuming that it is of spectral type Sq [6], with a microporosity level consistent with meteorites of that composition [7], and zero macroporosity (i.e., a monolithic asteroid). This maximum density estimate is 3.4 g/cm^3. Given the maximal density and shape model, the mass (M) of our maximal Apophis model is 6.49×10^{10} kg (or a GM value of 4.33×10^{-9} km^3/s^2).

A retrograde rotation pole (RA = 270 deg, DEC = -65 deg relative to the Earth Mean Ecliptic of J2000 coordinate frame) was chosen for Apophis (arbitrarily) and a uniform rotation rate around this pole was assumed with a period of 30.6 hours.

Demonstration of a Translational Motion Control Law for Tractoring

It is important to demonstrate that a gravity tractor spacecraft can safely maintain sufficiently close proximity to Apophis for a sufficient time to exert the required ΔV to avoid the keyhole passages in 2029 (see Fig. 3). A high-fidelity software simulation of the translational spacecraft dynamics has demonstrated that it is feasible to control the gravity tractor translational dynamics in close-proximity to our Apophis model. This simulation uses the shape and gravity model for Apophis, realistic thrust levels, realistic uncertainties in spacecraft position and velocity, and solar perturbations on the spacecraft. In the simulation, tractoring begins on July 4, 2022. Tractoring for durations of up to 6 months is shown to be well-controlled under autonomous dead-band thrust control logic developed in a previous study [1]. A significant amount of additional detail on the simulation software, the control law, the simulation outputs, thruster configuration, and tractoring range selection can be found in [1].

We have attempted to use plausible parameters in our simulation to model our gravity tractor (GT) spacecraft, though we haven't gone as far as doing a detailed spacecraft design. The mass of the spacecraft at the beginning of the gravity tractor phase is 1000 kg. We assume the GT spacecraft has 5 throttle-able fixed-direction SEP thrusters (not including backups) of which any three can be operated simultaneously. Each thruster is modeled after the ion thrusters used on the Dawn spacecraft, providing a maximum of 90 mN of thrust at a specific impulse (Isp) of 3100 seconds (Dawn spacecraft website, 2008). The orientation of the thrusters is illustrated notionally in Figure 2. Each thruster is represented by a red conical "nozzle" on the grey square spacecraft. With this thruster orientation, the spacecraft has the capability to apply control thrust in any direction in three-dimensional space [1]. The pair of thrusters labeled 'T1' and 'T2' are the primary thrusters for tractoring. They apply force at the "thruster canting angle" β away from the spacecraft centerline which prevents impingement of the thruster outgassing on the asteroid surface (which degrades tractoring performance). The remaining thrusters are used to maintain spacecraft position at the desired tractoring location.

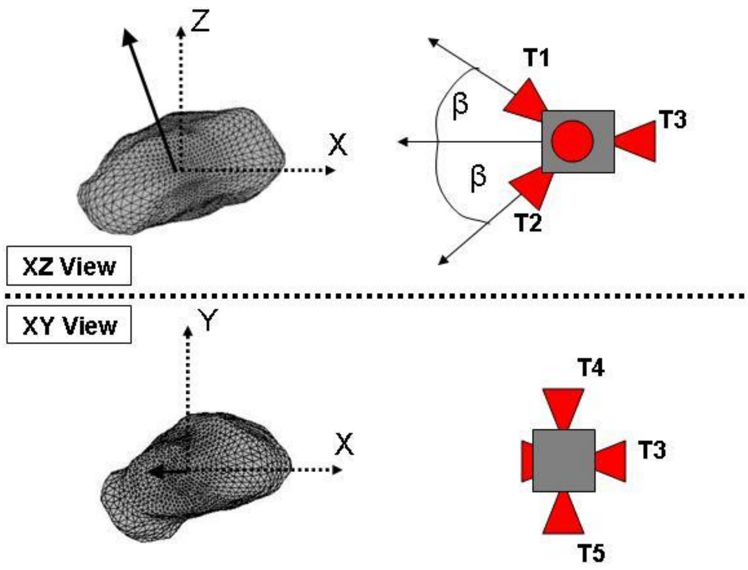

Fig. 2. Diagram of the fixed thruster orientations on the gravity tractor spacecraft relative to the target asteroid (not to scale).

For these simulations, the desired spacecraft tractoring position is chosen to be 250 meters from the Apophis center-of-mass along the positive velocity direction of the asteroid (the largest orbit change is effected by tractoring along the asteroid velocity vector). A thruster canting angle of 54 degrees is used, which avoids plume impingement on the surface at this range. The dead-band control law used in these simulations permits a maximum excursion from the nominal position of -10 or +60 meters in the (roughly) radial direction and ±25 meters in the (roughly) transverse directions.

The results for this tractoring scenario show that the asteroid will be perturbed by ~2.9 μm/sec on average for each month of tractoring performed (~1.14 x 10^{-12} m/s^2). About 9.9 kg of fuel would be used by the spacecraft to maintain position for each month of tractoring.

In order to verify the success of a deflection, the deflected orbit must be determined to an accuracy similar to that of the original orbit. An important advantage of the GT deflection method is that it is a high-precision procedure. The asteroid trajectory will be known to high precision throughout the entire process, and the progress of the deflection can be closely monitored. Uncertainties should not grow much beyond their pre-tractoring levels, and may well decrease. At the completion of the deflection, the spacecraft will move to a standoff position and undertake an asteroid tracking campaign similar to the one performed before deflection. Although we have not explicitly analyzed the post-tractoring uncertainties in the 2029 b-plane, our earlier study [1] indicates that even if the asteroid uncertainties grew during the tractoring, they would return to their pre-tractoring levels shortly after completion. These are the uncertainties we will use in our deflection targeting strategy.

The Deflection Strategy – Finding a Safe Harbor

Any comprehensive asteroid deflection strategy must consider the problem of keyholes: the deflection may avert an impact, but it could move the asteroid into a keyhole which leads to impact at a later time. In the case of Apophis, with its 2029 pre-impact close approach, the objective of the deflection is to move the trajectory away from the 2036 primary keyhole in the 2029 b-plane, because this leads to an impact. The question is where to move the trajectory so that it avoids not only the primary keyhole but also any potential surrounding secondary keyholes (i.e., the primary keyholes in the 2036 b-plane mapped back to the 2029 b-plane). To address this question, we have computed a detailed map of the keyhole structure in the 2029 b-plane.

The map was produced by systematically probing the major axis of the current Apophis uncertainty region to produce a series of orbit solutions which trace along the weak direction of the confidence region, while being constrained by the actual Apophis observations in the off-axis directions. The set of orbits were mapped forward to the year 2100 by numerical integration, and the closest Earth approach was noted for each. We considered a set of 100,000 solutions centered on the solution which passes through the center of the 2036 keyhole. Differential orbital dynamics from the current epoch to 2029 effectively separate the solutions into a string in the along-track direction. Projected into the 2029 Öpik-b-plane [8], the solutions trace a 580-km-long line segment parallel to the ζ-axis. The keyhole map in Fig. 3 plots the minimum post-2029 close approach distance for each solution versus position along the confidence region in the 2029 b-plane. The smooth upper envelope of this plot is due to the primary post-2029 resonances, while the narrow downward spikes are caused by secondary resonances surrounding the primaries. Points below the horizontal dotted line lie represent impacting solutions and therefore lie within keyholes. Resonances with minima above the dotted line cannot lead to impact and do not represent keyholes.

Fig. 4 displays a close-up of the keyhole map around the 2036 keyhole. The 610-m width of the 2036 keyhole is quite apparent at this scale, while it is clear that the secondary keyholes are extremely narrow. Our analysis shows they range in width from 3 meters down to the centimeter level. Additionally, there are certainly many tertiary and higher order keyholes that are far below our resolving power. Special efforts have been made in the keyhole search to extrapolate all potential keyholes down to their minimum close approach distances by interpolating points in their respective b-planes and projecting back to the 2029 b-plane.

Since the small asteroid deflections considered in this study move the object almost entirely in the along-track direction (along the Line of Variations), they essentially affect only the ζ-coordinate in the 2029 b-plane. The question is how much should the orbit be changed and in which direction. What should be the target ζ-value? Assuming the worst case of a trajectory down the middle of the 2036 keyhole, a naive strategy would be to choose a minimum deflection in ζ of just the radius of the keyhole (305 m). But of course, the entire uncertainty region of Apophis must be moved out of the keyhole with a high level of confidence, say 6 standard deviations (i.e., 6 sigmas). Using the post-tractoring sigmas from a previous section, and assuming the major axis lies in the along-track direction, we would choose a target ζ at least 2.5 km away from the center of the keyhole (6 sigmas plus the radius of the keyhole). The 2029 close Earth approach will provide a multiplier for the 2.5 km offset from the 2036 keyhole and move the nominal miss distance in 2036 to 13 Earth radii, and the 3-sigma boundary of the uncertainty region on the near side will pass no closer than 6.9 Earth radii.

This minimal deflection of ~3 km is well within the capability of the gravity tractor. Fig. 5 shows the deflection obtained in the 2029 b-plane as a function of tractoring time, assuming tractoring begins on July 4, 2022. The minimal deflection discussed above can be achieved with only 2 months of tractoring. Larger deflections can clearly be obtained with reasonable extensions of the tractoring time.

The next question is which direction to deflect the asteroid. The keyhole map in Fig. 4 provides a useful tool in making this decision, since it shows the positions of the secondary keyholes, which also should be avoided. One important question is which direction to shift the NEO. The simplest answer is to move towards the nearest edge of the keyhole, accomplishing the deflection as quickly as possible and using the least amount of fuel to get the job done. But as the keyhole map shows, there are nearby secondary keyholes which must be taken into consideration in order to avoid a subsequent impact. For Apophis, it would seem that the better strategy is to move the trajectory to the right of the 2036 keyhole (towards increased ζ-values), since the nearby region on that side is less densely populated with secondary keyholes and they are for impact times somewhat more removed from 2036. (The nearest one on the right is a full 23 years after the 2036 close approach.) Furthermore, the keyholes on the right are narrower: we estimate the 2059 keyhole to be only 5 cm wide in the 2029 b-plane, while the 2040 keyhole on the left is about 12 cm wide. If we choose to go to the right, a minimal deflection would move the nominal asteroid trajectory to ζ = +2.5 km relative to the 2036 keyhole, and the secondary 2059 keyhole would then lie at the 2.8 sigma point on the b-plane within the post-tractoring confidence region, yielding an acceptable impact probability of about 1 in a million. Other possible deflection targets are fairly wide clear regions around ζ = -8 km and ζ = +8 km, the latter region being marred only by the very remote 2099 keyhole pair.

It is interesting to itemize the sequence of steps that lead to the deflection. To move Apophis to the right in Fig. 4, the gravity tractor would have to tow the asteroid on its leading side, pulling it into a slightly larger orbit, which would cause the asteroid to pass slightly farther from the Earth than the impacting solution during the close approach in 2029. This in turn leads to a slightly smaller boost to the orbital energy, which would cause the asteroid to lead slightly ahead of the impacting solution after 2029, and in 2036 pass slightly ahead of the Earth instead of impacting.

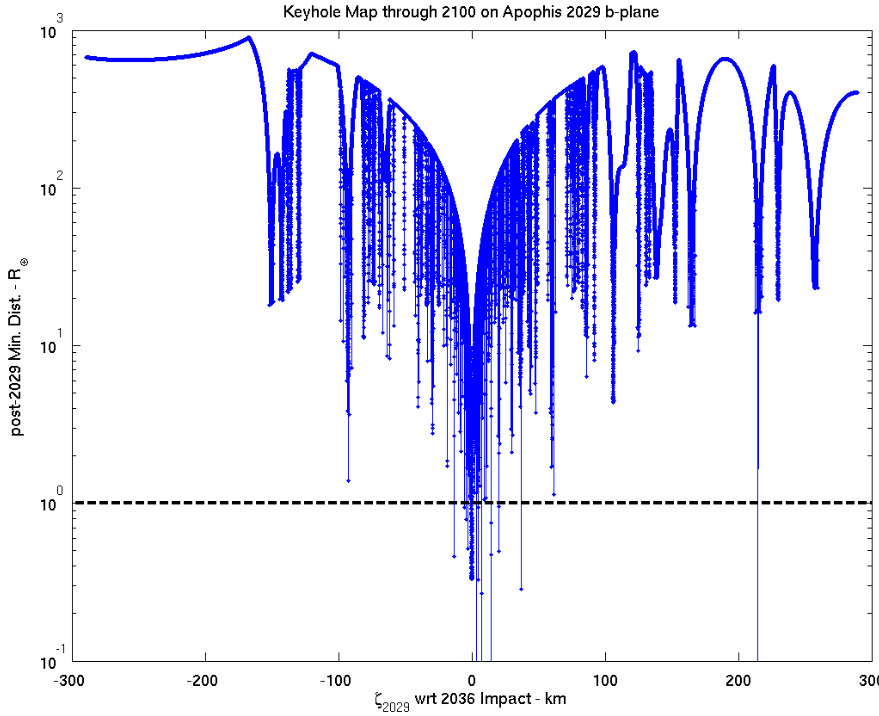

Fig. 3. Keyhole map for a 600-km segment of the Apophis uncertainty region in the 2029 b-plane.

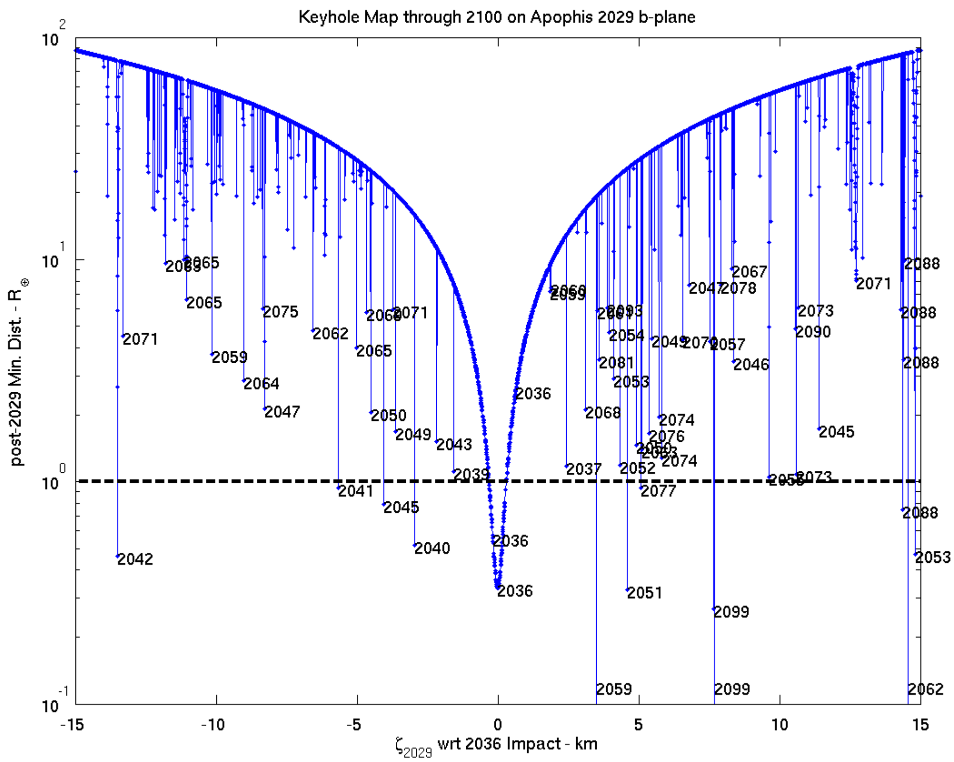

Fig. 4. Close-up of the keyhole map for Apophis around the 2036 keyhole. The 610-meter width of the main keyhole is immediately evident. Year labels have been placed on resonances which lead to close approaches within 10 Earth radii.

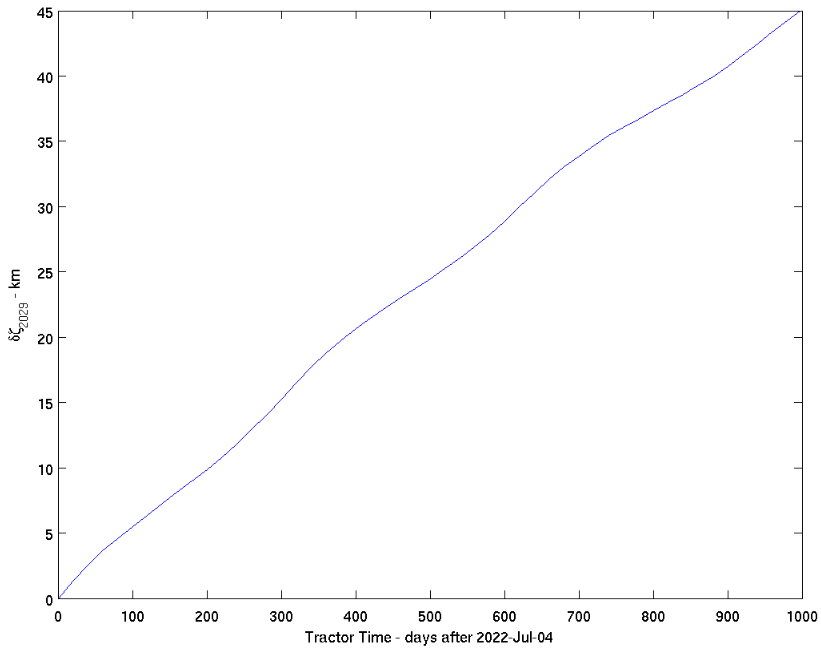

Fig. 5. Deflection in the 2029 b-plane as a function of tractoring duration.

Although the deflection leverage provided by a pre-impact keyhole passage can be impressive, and this is especially true for our Apophis test case, one might ask what fraction of the impacting population has a keyhole passage prior to an Earth impact. To gain some insight into this question, we examined the close approach histories of a representative population of 990 Near-Earth impactors. Fig. 6 summarizes the results by plotting the percentage of impactors that have a pre-impact close approach within a given distance as a function of time before impact. Let us assume, for example, that pre-impact close approaches within 10 lunar distances (10 LD) are close enough to produce keyholes which provide enough leverage to be useful in deflections. From Fig. 6, we can see that over 30% of the impactor population passes within 10 LD during the 50-year interval prior to impact. We would therefore expect that about a third of the impactor population will pass through a keyhole within 50 years of impact. However, further analysis has shown that not all of these close approaches have sufficient leverage to produce small keyholes. To gain further insight into this issue, we computed the leverage provided by these representative close approaches in order to determine the fraction of the impactors which have small keyholes. We found that about 4% of the impactor population has keyholes with widths narrower than about 15 km within the 50-year interval before impact. Since none of the close approaches in our sample population had a leverage within 10 years of impact as high as that of the 2029 close approach of Apophis, which is only 7 years before impact, we conclude that Apophis is a very unusual case.

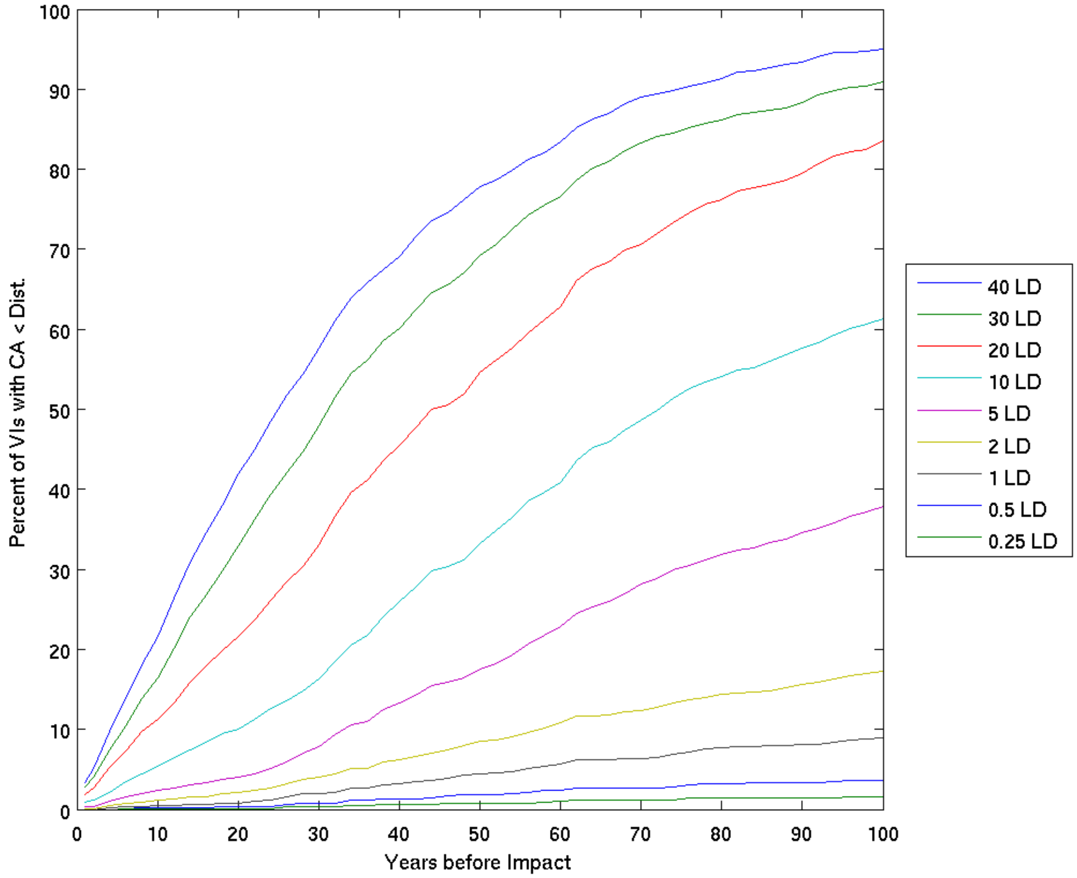

Fig. 6. Plots of the percentage of impactors with pre-impact Earth close approaches within a given distance as a function of time before impact.

Geopolitical Considerations of Deflection

Another useful tool to use in deciding the best strategy for an asteroid deflection is the so-called "risk corridor," which is the projection of the LOV onto a map of the Earth, showing the possible impact points as a function of ζ. The geopolitical implications of an aborted or failed deflection attempt must be considered.

During a slow deflection (GT or other) any failed deflection attempt will result in the nominal impact point being dragged along the risk corridor toward the leading or trailing edge of the Earth only to be "dropped" at a new impact location at the time of the failure. Of course, it is not merely the nominal impact point which is deflected, but the entire uncertainty region, and in our Apophis scenario, this is larger than the diameter of the Earth. Nevertheless, populations living along the risk corridor will, during a deflection, be placed at temporarily increased levels of risk until the NEO deflection drags the entire uncertainty region off the surface of the planet and the risk drops to zero for everyone. This consideration raises many challenging geopolitical questions of the criteria to be used to decide the ultimate direction of the deflection. The minimum cumulative population within the risk corridor in each direction would seem a simple solution; however other less objective geopolitical considerations will likely be introduced.

This issue of risk shifting during deflection applies to all deflection schemes since deflection situations yielding less than the minimum safe total impulse can cause similar shifting of the impact point along the risk corridor. The question of targeting a deflection is therefore a complex issue which must be more fully studied in both its technical and geopolitical dimensions.

The Combination Kinetic Energy/Gravity Tractor Mission Scenario

As mentioned earlier in this report, the Apophis case is most unusual in that the 2029 Earth encounter provides a tremendous leverage for pre-2029 deflection attempts, effectively multiplying the effort by a factor of 45,000. While amplifications of this level are rare, it is not too unusual for an impacting asteroid to have an Earth close approach in the few decades preceding an impact, and this may provide at least a moderate level of deflection amplification. Nevertheless, we cannot rely solely on the gravity tractor approach for asteroid impact mitigation in general. When a more powerful technique is required, the kinetic energy (KE) deflection approach will often prove sufficient. However, as we discuss below, the KE mission will require a rendezvous spacecraft to be on station prior to the deflection in order to, among other things, ascertain the post-KE deflection magnitude.

The deflection imparted on a NEO by a KE impactor is given by $\Delta V = \beta\ (m/M)\ V_\infty$, where m is the S/C mass, M is the asteroid mass, V_∞ is the S/C relative velocity at impact and β is the momentum enhancement factor (ref. 9). For $\beta = 1$, we have a plastic collision, with the impactor absorbed into the body without producing ejecta. For $\beta = 2$, the collision is elastic, with the ejecta momentum equal and opposite to the impactor momentum. Super-elastic collisions ($\beta > 2$) are considered likely, and sub-plastic collisions ($\beta < 1$) where the material spalled from the back of the asteroid carries more momentum than that of the crater ejecta, are considered very unlikely. We assume here that $1 < \beta < 5$ and that, nominally, $\beta = 2$.

For the present Apophis scenario, there are available mission designs for the KE option, although we have not selected a specific mission and trajectory. Rather, we assume for the moment that an impactor trajectory can be designed that will provide an impact velocity with an along-track component of 5 km/s. Using the conservative asteroid mass mentioned earlier (6.5×10^{10} kg) and a S/C mass of 2400 kg, the deflection $\Delta V = \beta\times0.185$ mm/s.

Fig. 7 plots the 2029 KE deflection capability for $\Delta V = 0.37$ mm/s (β=2) as a function of the deflection epoch. The ordinate corresponds to the zeta (ζ) direction in the 2029 b-plane, which in the heliocentric motion frame is the along-track direction. The wavy nature of the curve reflects the fact that an impulse at perihelion is more effective than an impulse at aphelion. For example, a KE deflection in April 2022 would produce a 200 km deflection in the 2029 b-plane for the given assumptions, which could place the trajectory into the two very clear regions ("safe harbors") found at that distance, both to the left and to the right, in Fig. 3. However, the uncertainty in the KE effectiveness, as indicated by the assumed uncertainty in β, allows for the actual 2029 deflection to be anywhere in the range of 100-500 km, and there may be secondary keyholes in that range.

With so much uncertainty in the net effect of the KE mission, policy makers will likely want to ascertain the post-KE trajectory through the use of a rendezvous S/C with a radio transponder. Moreover, the KE mission will have a much higher likelihood of success if the rendezvous spacecraft is in position early enough to provide to the KE spacecraft team precise estimates of the asteroid shape and spin state to aid the terminal guidance maneuvering. If the rendezvous spacecraft also has the capability to act as a gravity tractor by hovering in close proximity to the asteroid, it could in principle be used to move the asteroid out of any secondary keyholes that may fall within the uncertainty region following a KE deflection.

However, this latter possibility is extremely remote since secondary keyholes become less dense as the distance from the primary keyhole increases. For example, a KE impactor that deflects Apophis somewhere in the region of 100 to 300 km to the right of the 2036 keyhole in Fig. 3 would have a probability of passing through the single secondary keyhole equal to the width of the keyhole (~1 m) divided by 200 km or 5×10^{-6}. Policy makers might consider this an acceptable risk.

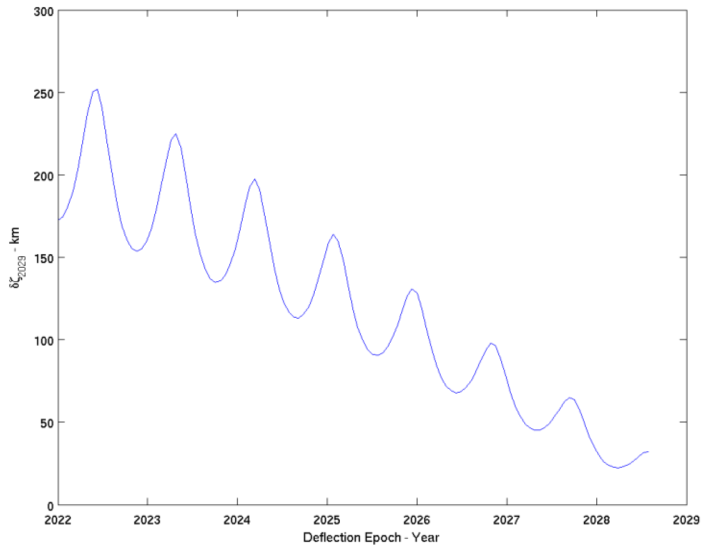

Fig. 7. Deflection of Apophis on the 2029 b-plane (i.e., on the abscissa of Fig. 3) for an impulsive 0.37 mm/s along-track ΔV, as a function of the deflection epoch.

SUMMARY OF KEY POINTS

The following are our study conclusions, augmented by additional conclusions from [1]:

- By far the most important requirement of a successful mitigation campaign is a warning time sufficient to carry out the mitigation mission. As a result, the most important aspect of mitigation is finding the hazardous objects many years in advance.
- Some primary impulsive deflection techniques (e.g., the kinetic energy impactor) provide relatively uncertain amounts of deflection (e.g., the momentum multiplier β is poorly known).
- An effective mitigation campaign not only needs to deflect an Earth threatening asteroid from the predicted Earth impact but it must also ensure that the deflection does not place the asteroid into a so-called keyhole which would lead to a secondary impact some years later.
- A pre-impact close approach usually multiplies the effect of an earlier deflection. It is usually preferable to perform a deflection prior to this close approach to take advantage of the leverage it provides. At the same time, however, the pre-impact close approach usually magnifies orbit uncertainties, making it more difficult to verify or rule out the impact.
- Although the Apophis case considered in this study is quite unusual because of its extreme close Earth approach only 7 years before impact many potential impactors will have at least moderately close pre-impact close approaches within 50 years of impact. We estimate that up to 4% of the impactors will have pre-impact keyholes with widths narrower than 15 km.
- Asteroid close approach trajectories and their associated uncertainties are best analyzed when projected into the b-plane. In the b-plane of the impact encounter, the overlap of the uncertainty region with the circle representing the capture cross-section of the Earth determines the impact probability.
- If the asteroid has a pre-impact close approach, the asteroid trajectory and associated uncertainties should be analyzed in the b-plane of this pre-impact encounter. An analysis of the location of keyholes in this b-plane would be an important part of any deflection strategy. Secondary keyholes around the primaries should also be considered.
- For the Apophis case considered in this study, the deflection to avoid impact in 2036 can be thought of as deflection out of a keyhole in the 2029 b-plane, which is approximately 610

meters wide. We have formed a detailed map of the secondary resonances and keyholes around the 2036 keyhole in the 2029 b-plane, and found over a dozen secondary keyholes with widths ranging from a few meters down to a few centimeters.

- A useful tool that should be used in establishing a deflection strategy is the risk corridor across the surface of the Earth. The geopolitical implications of an aborted or failed deflection attempt must be considered.
- We have performed a preliminary design for a viable Apophis rendezvous mission which could be launched in mid-April 2021 and arrive at Apophis in early January 2022 with only a moderate arrival delta-V.
- The combination of ground-based radiometric tracking of an orbiting or hovering spacecraft, combined with optical imaging of the asteroid from the spacecraft, is sufficient to improve the knowledge of the asteroid's orbit to the sub-kilometer level, enough to discern whether or not the asteroid is truly threatening. It is not necessary to place a transponder on the surface of the asteroid to acquire this high precision tracking.
- The amount of time it takes to realize these dramatic improvements in the knowledge of the asteroid's orbit ranges from a few days to a couple months. A spacecraft need not be in place for years for these improvements to take place.
- We have outlined a design for a rendezvous spacecraft which could operate as a gravity tractor should a deflection be found necessary. The 1000-lb spacecraft would carry 5 throttle-able fixed-direction SEP thrusters, and would hover over Apophis at a distance some 50 meters greater than the asteroid's maximum dimension.
- We have analyzed the performance of this gravity tractor mission and determined that it could deflect Apophis out of the 2036 keyhole after only two months of operation, assuming towing started in 2022. Larger deflections are obtainable for reasonable mission durations.
- An important advantage of the gravity tractor deflection method is that it is a high-precision procedure. The asteroid trajectory would be very accurately known throughout the entire process, and the progress of the deflection could be closely monitored.
- In other scenarios which use much more energetic deflections (such as the kinetic energy deflection method), a gravity tractor spacecraft would still be useful, both for determining the magnitude of the primary deflection and for providing an asteroidal trim maneuver in the event the primary deflection maneuver was unsuccessful or the asteroid was headed for a keyhole.
- Each potential Earth impact is a unique scenario that may require a tailor-made mitigation response.

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