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Potential impact detection for Near-Earth asteroids: the case of 99942 Apophis (2004 MN_4)

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Abstract. Orbit determination for Near-Earth Asteroids presents unique technical challenges due to the imperative of early detection and careful assessment of the risk posed by specific Earth close approaches. This article presents a case study of asteroid 99942 Apophis, a 300-400 meter object that, for a short period in December 2004, held an impact probability of more than 2% in 2029. Now, with an orbit based on radar ranging and more than a year of optical observations, we can confidently say that it will pass safely by the Earth in 2029, although at a distance of only about six Earth radii from the geocenter. However, the extremely close nature of this encounter acts to obscure the trajectory in subsequent years, when resonant returns to the vicinity of the Earth are possible. In particular, an impact possibility in the year 2036 has a roughly 5% probability of persisting through the very favorable 2013 radar and optical observing apparition. In the event that the 2036 potential impact has not been eliminated by 2013, a precise characterization of the Yarkovsky accelerations acting on the asteroid may become an important part of the orbit estimation and impact prediction problem. Even so, the sixteen years available to effect a deflection from 2013 until 2029, after which the problem would become intractable, are sufficient to respond to the threat should a deflection effort become warranted.

Keywords. minor planets, asteroids

1. Introduction

It has long been recognized that an integral part of preventing collisions of a Near-Earth Objects (NEOs) with the Earth is to discover them. This notion is well expressed by the old monster-movie maxim, "It's the ones you don't know about that you should be the most afraid of." Of course, a search and discovery effort alone would be ineffective unless the known objects are monitored continually and carefully for possibilities of future collision, allowing a timely warning of an impending calamity. This early warning capability is presently provided by two independent automatic warning systems, Sentry, operating at NASA's Jet Propulsion Laboratory, and CLOMON2, a part of the NEODyS system operated by the Universities of Pisa (Italy) and Valladolid (Spain). (See Milani *et al.* (2005) for a technical discussion of the operating principles of the two systems.)

During the Christmas holidays of 2004, near-Earth asteroid 2004 MN_4 startled the NEO hazard community when both Sentry and CLOMON2 reported a threat of unprecedented magnitude for an impact in 2029. While that particular threat was eventually ruled out by virtue of additional observations, this particular NEO—now named and numbered 99942 Apophis—still poses a moderate risk of impact in the 2030's, and so continues to receive considerable attention from amateur and professional astronomers, and even from the more-interested members of the general public.

This paper summarizes Apophis' history and outlines what the future may hold for this extraordinary asteroid.

2. Background on 99942 Apophis (2004 MN_4)

Asteroid 99942 Apophis was discovered by R. Tucker, D. Tholen and F. Bernardi at Kitt Peak, Arizona on June 19, 2004. Originally observed for only two consecutive nights and with observations plagued by astrometric reduction problems, the asteroid, provisionally designated 2004 MN_4, was lost until December 2004, when it was serendipitously recovered from Siding Spring, Australia by G. Garradd. At this point Apophis was recognized as a potentially hazardous asteroid, and indeed on December 20, with only a 1.7-day arc of December observations, the first run of Sentry, JPL's automated impact monitoring system, indicated an impact probability (IP) of 2×10^{-4} on April 13, 2029. Adding in the June discovery observations, which allowed a six-month arc of observations, confirmed a significant possibility of impact in 2029, but also revealed substantial astrometric errors in the original June observations. These errors, approaching 2 arcsec, were related to clock errors and a problematical plate solution (D. Tholen, priv. comm.).

Over the next two days D. Tholen obtained accurate remeasurements of the June Kitt Peak observations, and in the meantime a few dozen additional December observations were reported. This observation set, consisting of 55 observations over 187 days, indicated an IP of 0.4% and on December 23 those results were posted to the respective websites of NASA's Sentry and the Italian/Spanish NEODyS. On the subsequent day, ten new observations pushed the IP to 1.6% for an unprecedented rating of +1 on the Palermo Scale and 4 on the Torino Scale. Over the next four days the IP continued to inch upward, reaching a peak of 2.7% on December 27, when pre-discovery observations from March 2004—which eliminated any possibility of an impact in 2029—were reported by the Spacewatch survey.

However, the March 2004 observations, while removing any concern for a 2029 collision, also revealed that Apophis would certainly pass very close to Earth in 2029. An extraordinary flyby, some $10.1 \pm 2.6\ R_\oplus$ (three-sigma limits) from the geocenter, was indicated. ($R_\oplus = 6378$ km is the Earth radius.) Predictably, such a deep encounter allowed a wide range of possible post-2029 semimajor axes, including a number of values that led to resonant return encounters, and even potential impacts, in the years after 2029.

Later, radar ranging and Doppler tracking of Apophis, obtained in late January 2005 from the Arecibo observatory, were found to be inconsistent with then-current predictions (IAUC 8477). Notably, the radar astrometry indicated a much closer 2029 approach, some $5.6 \pm 1.6\ R_\oplus$ (three-sigma limits) from the geocenter (Giorgini, Benner, Nolan, *et al.* 2005). The discrepancy was traced to systematic errors in the March 2004 pre-discovery observations, and subsequent, independent remeasurements of these five observations brought them into line with the radar-derived orbit.

Optical observations of Apophis continued to be reported until early July 2005, by which time the asteroid was only 46° from the sun and moving into the daytime sky. On Aug. 7, 2005, just as the ACM 2005 Conference was getting underway, L. Benner and colleagues were able to obtain a single Doppler radar measurement at the Arecibo Observatory. Apophis passed within 9° of inferior conjunction on Aug. 11, 2005, during the ACM 2005 conference. The current prediction for the 2029 b-plane intersection, based on all observations received through August 2005, is depicted in Fig. 1. This prediction is for a 2029 encounter distance of $5.89 \pm 0.35\ R_\oplus$ (three-sigma limits).

Schweickart (2005) has suggested that a more or less immediate space mission may be necessary in order to place a radar transponder on the asteroid, which would allow it to be tracked with high-precision, just as interplanetary spacecraft are. The concern he raises is that, if one assumes the unlikely hypothesis that Apophis is indeed on a collision trajectory, it would not be clear that the impact was certain, or even very likely, until

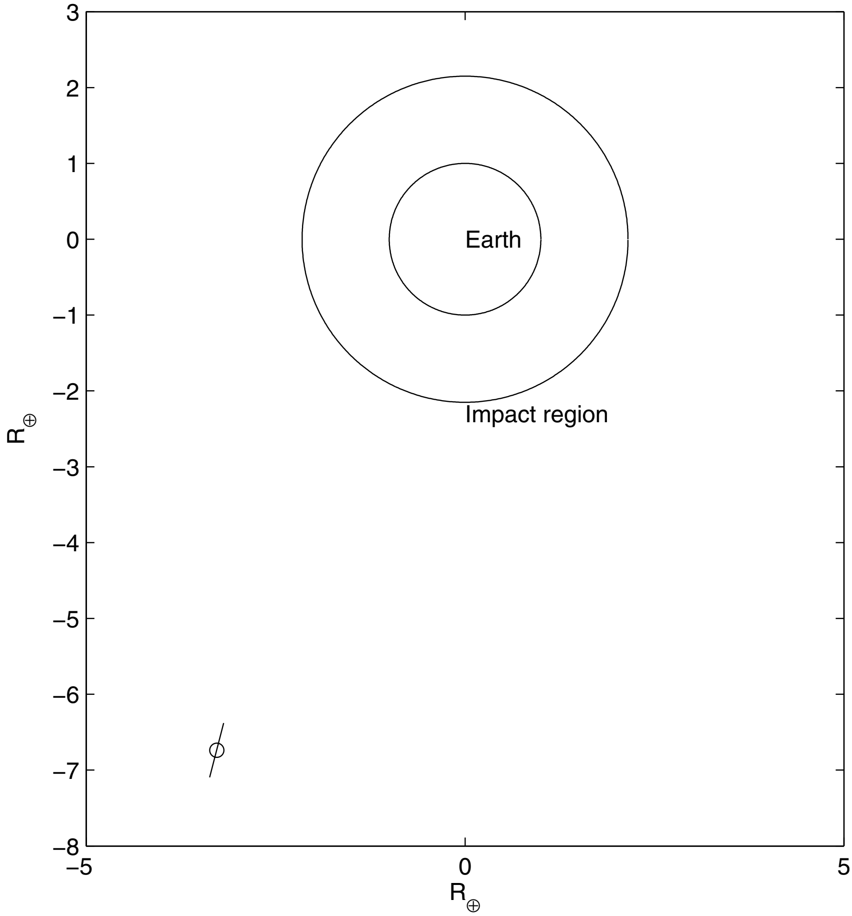

Figure 1. Depiction of the current 2029 b-plane footprint, with three-sigma extent. Note that, according to the definition of the b-plane, the positions shown are unperturbed target plane crossing distances. The fairly low encounter velocity of Apophis (5.86 km/s) causes the actual crossing distances to be somewhat closer. For example, the depicted nominal b-plane distance is 7.2 $R_\oplus$, whereas the nominal encounter distance is 5.7 $R_\oplus$. Similarly, the impact region is significantly larger than the figure of the Earth, as indicated.

quite late, perhaps too late to mount a deflection mission, which would in any case need to be complete before the 2029 close approach. Thus the call for a transponder mission, which would allow a much earlier recognition of the hypothetical impending impact.

3. Current Risk Analysis

A *resonant return* is an encounter that is, in a sense, spawned by a preceding encounter (Milani, Chesley & Valsecchi 1999). This occurs when the first encounter alters the asteroid's orbit so that its period becomes commensurable with that of the Earth. So, for example, if Apophis were to obtain a 426 day period (7:6 exterior Earth resonance) due to the 2029 encounter it would return near the same point in space 6 revolutions and 7 years later, at which point the Earth would also be there. Thus, a resonant return in 2036 would be obtained. Another key bit of terminology is the *keyhole*, which refers to the

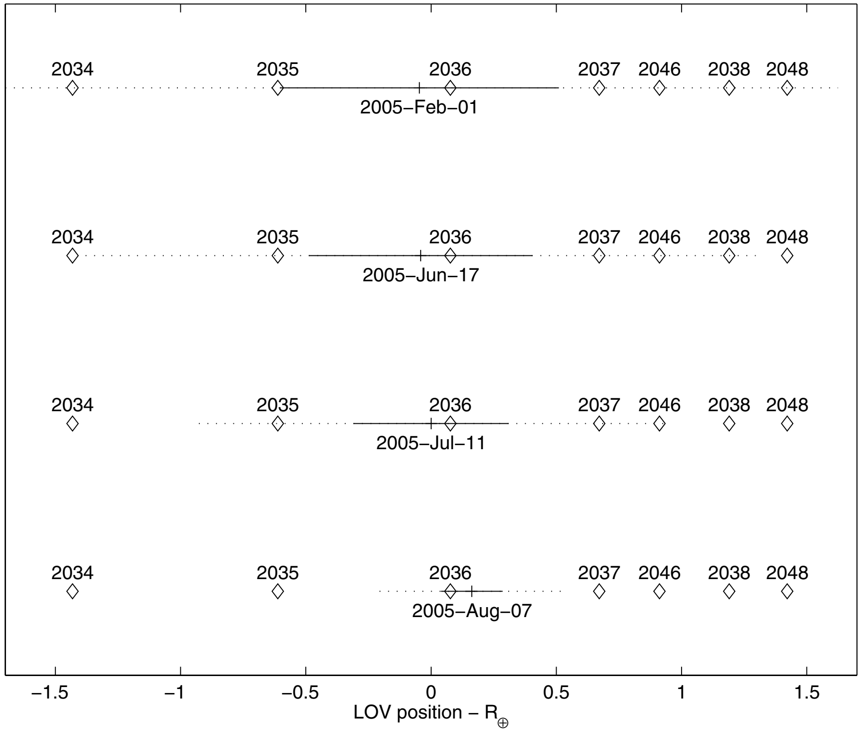

Figure 2. Recent evolution of the 2029 b-plane line of variation (LOV). Each horizontal line shows the one-sigma (solid) and three-sigma (dotted) LOV based on the observational data cut-off printed below the center of the respective LOV. The plot also depicts the LOV positions of the keyholes associated with the primary resonant returns from the 2029 encounter of Apophis. The 2038 keyhole, shown for completeness, allows an encounter distance no closer than 1.42 $R_\oplus$ and thus does not allow an impact. The Earth is located at approximately -7 $R_\oplus$ along the LOV in this depiction. The origin is arbitrarily selected.

small area on the target plane of the preceding encounter, in 2029 for Apophis, through which the asteroid must pass to obtain a resonant return collision (Chodas & Yeomans 1999). In other words, the keyhole is the region of collision orbits in the 2029 target plane and can also be interpreted as the preimage of the Earth in that space (Valsecchi, Milani, Gronchi, *et al.* 2003).

For Apophis there have been several primary resonant returns, tabulated in Table 1, in the years following the 2029 close approach. Additionally, there have been secondary resonant returns, which are spawned by primary resonant returns, as well as occasional non-resonant return impacts in October at the opposite node. Figure 2 depicts the recent evolution of the position and extent of the 2029 b-plane line-of-variation (LOV) with respect to the fixed positions of the keyholes.

Because of Apophis' very close encounter, the 2029 keyholes are far smaller, by orders of magnitude, than the Earth capture cross-section itself, and this is an important point because an impending impact can be averted simply by moving the asteroid trajectory away from the keyhole, and so a deflection becomes far more tractable than the case where there is no leverage from an intervening close approach. Conversely, the small keyholes can make it more challenging to ascertain that the object is actually on an impacting trajectory, if that is indeed the case. If the scale of a keyhole is at the sub-kilometer level, as is the case for Apophis (Table 1), then we need kilometer-level knowledge of the

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Table 1. 99942 Apophis Potential Impacts.

Primary Resonant Returns (from 2029)

Year	Resonance	Post-2029 Period (days)	Keyhole Size (km)
2034	5:4	457	0.56
2035	6:5	438	0.56
2036	7:6	426	0.61
2037	8:7	417	0.57
2046	17:15	414	0.66
2048	19:17	408	0.41

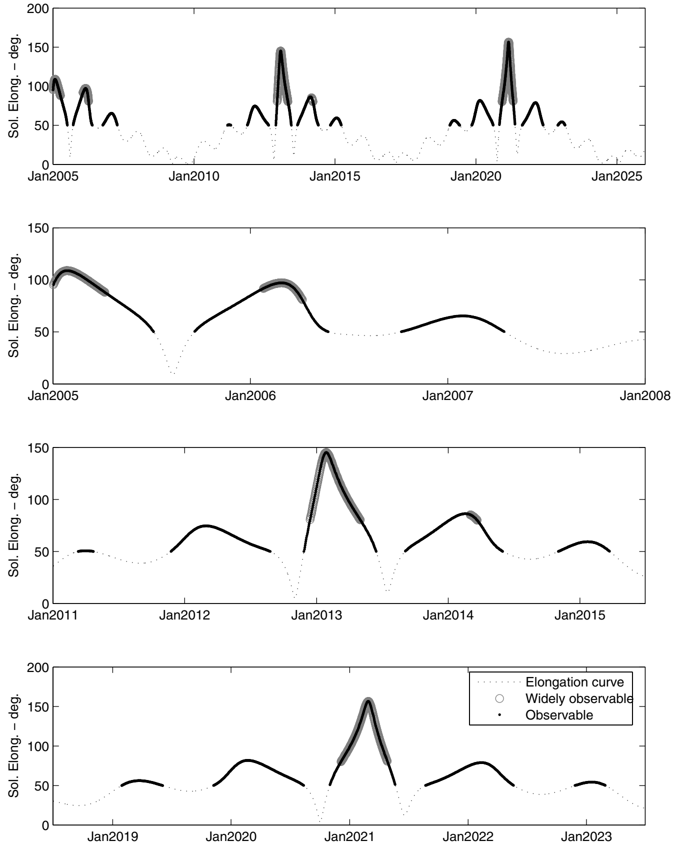

Figure 3. Optical observability of 99942 Apophis. The object is deemed observable if the solar elongation is greater than 50° and the visual magnitude is less than 23, and is considered widely observable if the solar elongation is greater than 80° and the visual magnitude is less than 20. We simulate one astrometric position with $0''.2$ standard errors on every second night when Apophis is widely observable and one such observation per lunation when otherwise observable.

asteroid state at the keyhole before we can say with some confidence that the object is on or near a collision path. Thus the small sizes of the keyholes associated with the 2029 Earth-Apophis encounter are a two-edged sword: A deflection mission becomes much simpler (if it can be accomplished before 2029), but the knowledge that such a mission would be required does not come until much later. However, since the 2029 keyholes are

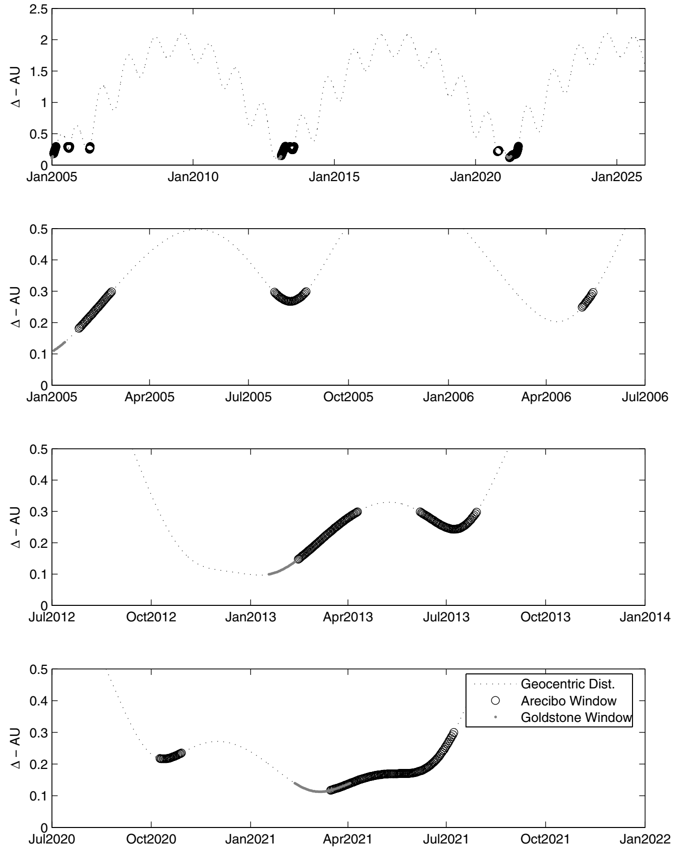

Figure 4. Radar observability of 99942 Apophis. Arecibo observability is assumed when the declination is between 0° and +36° and the range is less than 0.3 AU. Similarly, potential Goldstone windows are obtained when the declination is between −20° and +40° and the range is less than 0.14 AU.

widely separated, by 1000 km or more, it may be possible to *rule out* all potential impacts when the 2029 prediction uncertainty is still at the level of several hundred km.

4. Future observations

There are several considerations that need to be addressed in order to fully understand the very complex situation that Apophis presents. Chief among these is the question of how the 2029 prediction uncertainties will evolve under various observational scenarios and to address this issue we will assume a particular future observation schedule.

Figure 3 shows the times when optical observations can be reasonably expected. The optically observable periods are split into two categories according to the level of difficulty, and a less frequent rate of observations is assumed for the more difficult periods, as described in the caption to Fig. 3.

Of course, the possibility of radar ranging is of critical importance, and Fig. 4 depicts the periods when Apophis could potentially be observed by radar from the 305-meter Arecibo Observatory and from the Deep Space Network 70-meter antenna at Goldstone, California. From Fig. 4, five future Arecibo radar observing opportunities are apparent, and the measurements that presumably would be derived from each of those are listed

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Table 2. Simulated and Actual Arecibo Radar Apparitions for 99942 Apophis

Dates	Δ (AU)	SNR†	Delay sigma (μsec)	No. Range Pts.
2005 Jan 27-30	0.19	15	4.5	3
2005 Aug 07-08	0.27	4	-	0‡
2006 May 04-08	0.26	4	4.5	3
2013 Feb 14-20	0.15	40	1.0	7
2013 Jul 06-10	0.24	6	4.5	3
2020 Oct 09-12	0.22	8	4.5	3
2021 Mar 16-20	0.12	90	0.5	10

†Future Signal-to-Noise Ratios are inferred from the SNR actually obtained in Jan. 2005 and from the listed value of the topocentric distance Δ.

‡Due to transmitter equipment outage, only a single Doppler measurement of uncertainty 0.2 Hz was obtained at the August 2005 opportunity.

in Table 2. The two future Goldstone opportunities were not simulated because their contribution would be nil given the much stronger and contemporaneous echoes expected from Arecibo.

This study also considers the effectiveness of a radio tracking space mission, although, for reasons explained later, this year-long, simulated mission is assumed to begin operations in Jan. 2019, much later than proposed by Schweickart (2005). The mission simulation assumes that 365 daily pseudo-range measurements of 2 m accuracy to the center-of-mass of the asteroid would be obtained.

5. Force modeling

Another important consideration is the effect of force model uncertainties, and of particular concern for Apophis is an acceleration known as the Yarkovsky effect (Bottke, Vokrouhlický, Rubincan, *et al.* 2002). As an asteroid rotates, absorbed solar radiation is re-emitted in the thermal band in a direction offset from the sun direction. This induces a slight along-track acceleration, which in turn leads to an increase or decay in orbital energy and orbital period. Because the Yarkovsky effect causes a steady drift in semimajor axis, it manifests as a drift in the orbital anomaly that grows quadratically with time. The effect has been directly measured on the half-kilometer asteroid 6489 Golevka, which drifted approximately 15 km due to Yarkovsky accelerations in the first twelve years after discovery (Chesley, Ostro, Vokrouhlický, *et al.* 2003). Clearly, for the rather smaller Apophis, the Yarkovsky deflection over the 25 years from the first observations in 2004 to the close approach in 2029 could be substantial, especially in light of the kilometer-level predictions that are required to confirm a post-2029 impact.

The difficulty in predicting, even crudely, the Yarkovsky effect for Apophis is that we have no knowledge of the asteroid's spin pole direction, and yet the obliquity γ of the spin axis is the most crucial element for modeling the Yarkovsky acceleration. Small obliquities (i.e., direct rotation) tend to increase the semimajor axis, large obliquities (i.e., retrograde rotation) tend to decrease the semimajor axis, and intermediate values (near 90°) will typically have a smaller, potentially even negligible, effect. Thus, in the absence of a known obliquity we cannot even say whether the Yarkovsky effect is causing the asteroid to move ahead or fall behind in its orbit. Two additional parameters that are essential to predict the magnitude of the Yarkovsky effect are the bulk density ρ of the object and the thermal conductivity K of the surface material. Figure 5 shows how the mean semimajor axis drift rate depends upon γ and K. The drift rate also varies

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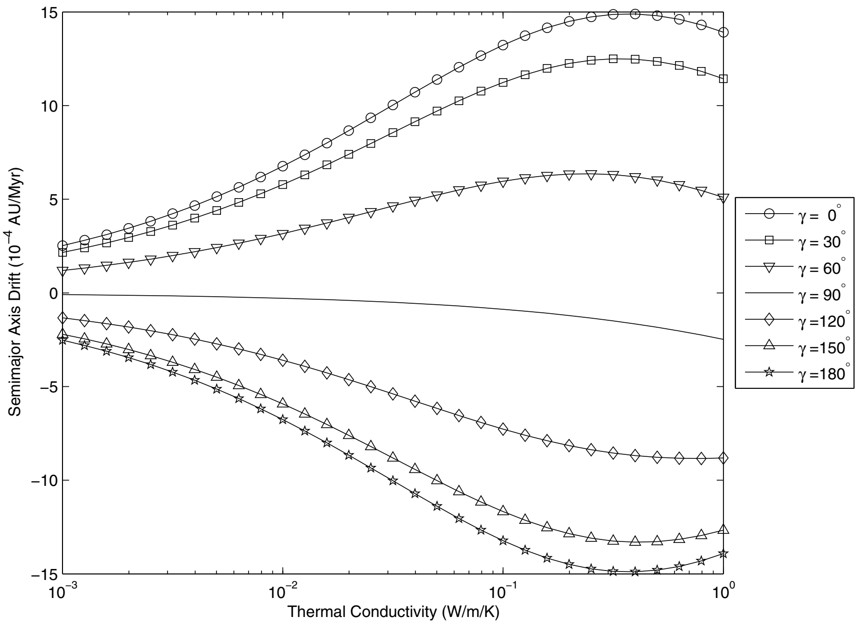

Figure 5. Mean semimajor axis drift rate of 99942 Apophis due to Yarkovsky acceleration. The model assumes a spherically symmetric body with spin period 30.6 hours (Gary & Reddy 2005) and applies a linearized heat diffusion model. See Vokrouhlický, Milani & Chesley (2000) for modeling details. Other assumptions include bulk density $\rho = 2.7$ g/cm^3, surface density $\rho = 2.0$ g/cm^3, surface heat capacity 680 J/kg/K and surface absorptivity (complement of Bond albedo) of 0.9.

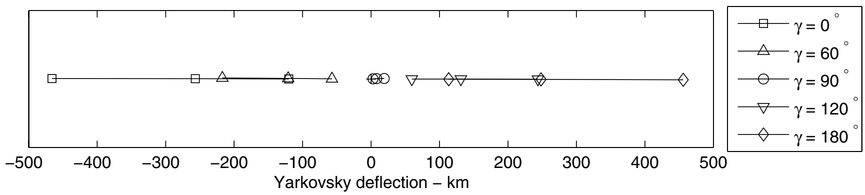

Figure 6. The extent of the Yarkovsky offset for 99942 Apophis in the 2029 b-plane. Five different values of obliquity γ are shown and for each obliquity three cases are plotted: a strong effect ($\rho = 2.0$ g/cm^3 and $K = 3 \times 10^{-2}$ W/m/K), a nominal effect ($\rho = 2.7$ g/cm^3 and $K = 10^{-2}$ W/m/K) and a weak effect ($\rho = 3.3$ g/cm^3 and $K = 3 \times 10^{-3}$ W/m/K).

inversely with ρ. Figure 6 provides an indication of how large the Yarkovsky effect could be when mapped from 2005 to the 2029 b-plane. From that figure it is apparent that deflections of up to 500 km are possible, although deflections less than 200 km appear much more likely. However, if the obliquity were known then the uncertainty related to Yarkovsky accelerations would be much smaller. Fortunately, the 2012–2014 radar and optical observing periods should provide ample opportunity to derive a spin axis orientation, and this paper assumes that that effort will be successful.

6. Prediction Uncertainty

With these pieces in place we are in a position to ask what will be the extent of the b-plane uncertainty region in 2029 as time passes and observations accumulate. Figure 7

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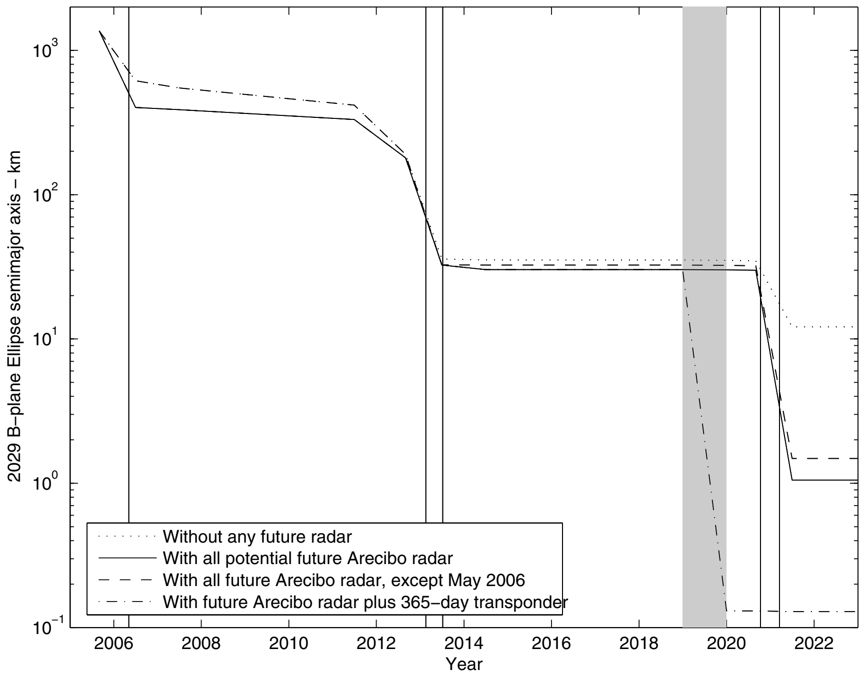

Figure 7. Predicted evolution of the uncertainty extent on the 2029 b-plane for 99942 Apophis. The four curves represent various observation scenarios. The contribution of the uncertainty in Yarkovsky modeling is included as described in the text. The vertical lines indicate the epoch of future Arecibo ranging opportunities. The gray region demarcates the time of a possible radio tracking mission, as described in the text.

shows the evolution of the 2029 uncertainty under the observational assumptions stated above. The uncertainty due to Yarkovsky is also incorporated into the plot by assuming a modest obliquity $\gamma = 60°$ and estimating the bulk density of the body.†

Although the obliquity probably cannot be determined prior to 2013, assuming an obliquity does not materially affect the result because prior to 2013 the uncertainties are dominated by measurement and orbit determination errors. Thus Yarkovsky is not a significant source of uncertainty during the period that the obliquity is unknown. However, after the obliquity is established, around 2013, the estimated uncertainty of the bulk density serves as a proxy for the contributions of the other unknown parameters, notably the thermal conductivity K. With this approach, the uncertainty of the Yarkovsky effect is found to be on the order of 15% in 2014, and this is the predominant source of uncertainty from 2014 to 2021. After the 2021 observations, the uncertainty in the Yarkovsky acceleration is less than 1%. This precision, coupled with the short mapping time from 2022 to 2029, leads to kilometer-level b-plane uncertainties in 2029. The inclusion of Yarkovsky-derived uncertainties does little to change Fig. 7 in the years before 2013 (when the uncertainty is dominated by measurement and mapping errors) and after 2021 (when Yarkovsky is well characterized and the prediction interval is short). In the intervening years from 2013 to 2021, however, Fig. 7 reveals an order of magnitude increase in uncertainty due to Yarkovsky.

While the use of radar imaging may be imperative for determination of the spin axis orientation of Apophis, which will enable improved Yarkovsky modeling and thus better

† The bulk density is estimated with a one-sigma *a priori* constraint 2.5 ± 1.0 g/cm^3.

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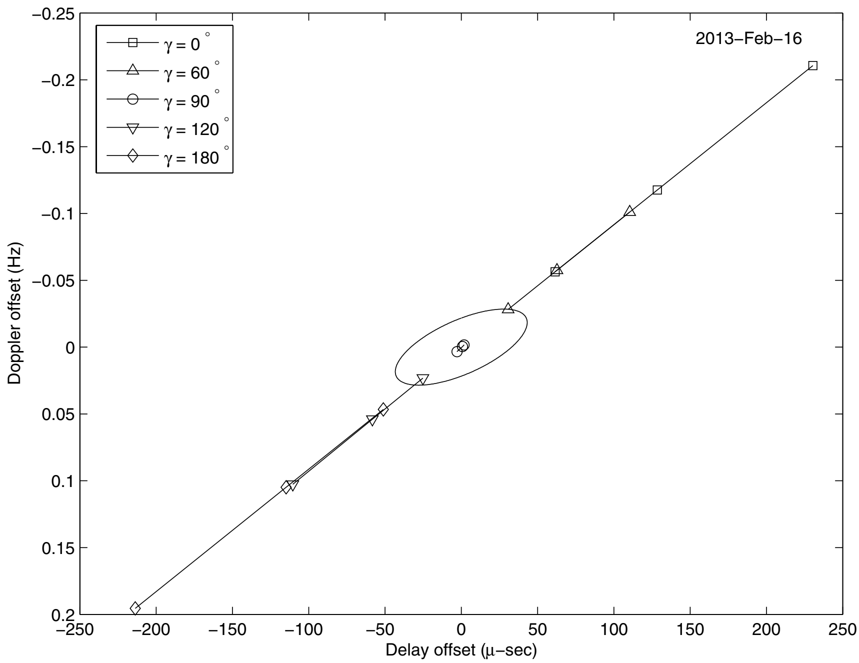

Figure 8. Yarkovsky-induced offsets in the space of radar observables at the Feb. 2013 radar ranging opportunity. The plotted ellipse depicts the 90% confidence region for a prediction with zero Yarkovsky acceleration, assuming expected optical and radar observations through Feb. 2013. The plotted Yarkovsky positions include weak, nominal and strong perturbations, as described in the caption to Fig. 6.

orbital predictions, the orbital improvement provided by future ground-based radar astrometry is otherwise rather modest. This is typical for asteroids observed over several years (Ostro & Giorigni 2004).

As mentioned above, the observations of 2013 can measure the Yarkovsky acceleration with good precision. Figure 8 reveals where the asteroid is predicted to appear in Feb. 2013 in the space of radar observables (delay and Doppler) for various Yarkovsky assumptions. As indicated by the plot, Yarkovsky accelerations may not be outright detectable in 2013. But even if the Yarkovsky signal is very weak this can be attributed to an intermediate obliquity, and in any case the magnitude of the effect is constrained.

To a large extent, the focus here has been on the uncertainty induced by the Yarkovsky effect because this will soon become the dominant source of prediction uncertainty. Still, there are other, smaller modeling issues that may need to be considered in the future. As the 2029 prediction uncertainty shrinks, the appropriate force model for making Apophis predictions will evolve. At present, with 1000-km+ uncertainties, the basic model with 13 perturbers (Moon and planets, plus Ceres, Pallas and Vesta) and a simple relativity formulation are sufficient. However, when the uncertainty begins to approach the kilometer level, more sophisticated models may become necessary, for example, consideration of additional asteroid perturbers, a more involved relativity formulation, and perhaps direct solar radiation pressure (Giorgini, Benner, Nolan, *et al.* 2005).

Another potential complication, more theoretical than practical, is that the spin state of Apophis is likely to change substantially as a result of tidal interactions during the 2029 close approach (Scheeres, Benner, Ostro, *et al.* 2005). In principle, this different spin state could alter the Yarkovsky accelerations enough to affect the impact prediction. However,

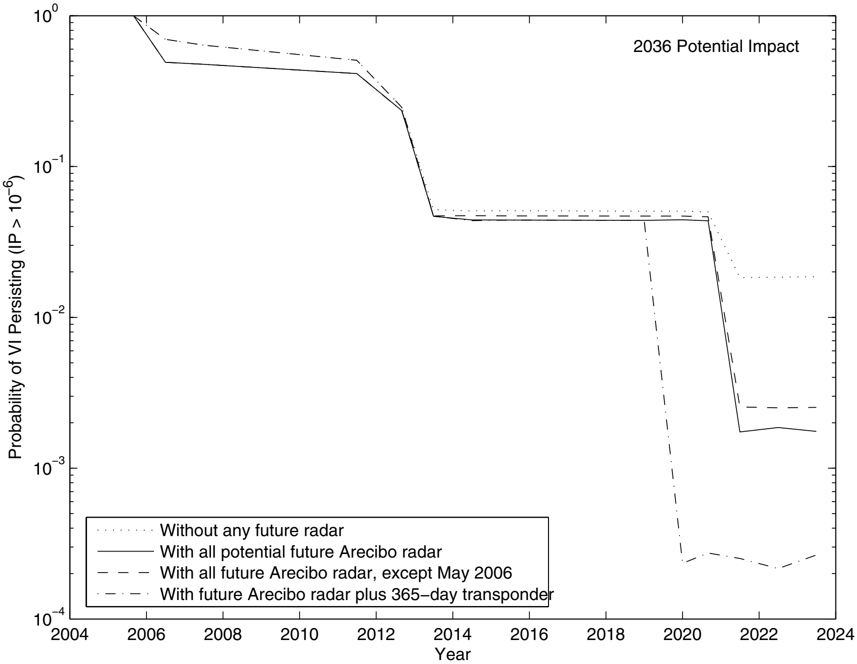

Figure 9. Probability that the 2036 potential impact will not be ruled out, i.e., the probability of persistence at IP $> 10^{-6}$, based on the uncertainties depicted in Fig. 7.

this would only be a concern should the trajectory pass near the edge of a 2029 keyhole, leading to a grazing post-2029 encounter. This because, from the 2029 encounter to, for example, the 2036 potential impact, the Yarkovsky effect can only alter the position by several kilometers or thereabouts. Mapped back to the 2029 b-plane, that effect would show up as a slight (sub-meter) displacement of the actual keyhole.

7. Impact prediction

What is the likelihood that a particular impact possibility will be ruled out or confirmed in future years? This is a crucial question in determining an appropriate course of action that will ensure that we are in a position to deflect Apophis in the unlikely event that it should be necessary. Given the size and current LOV location of a particular keyhole, for example that of the 2036 impact, we can use the 2029 uncertainty information from Fig. 7 to derive a likelihood that the 2036 impact will be ruled out with a given confidence by a given date. The approach is to randomly sample future nominal orbits according to the *current* (relatively large) Gaussian probability distribution, and then apply the smaller *future* Gaussian probability distribution, centered at each new nominal, to obtain a sampling of the future impact probability. The random samples can be collected to obtain a histogram of impact probabilities at a given time in the future. From this approach one can infer the likelihood that a potential impact will persist at a non-negligible IP into the future. This exercise has been done for the 2036 impact, which appears the most interesting at present. Figure 9 indicates a 5% probability that the 2036 impact will persist after 2013 and a 0.2% probability that it will persist beyond the 2021 radar opportunity, assuming a reasonable schedule of future ground-based radar and optical observations.

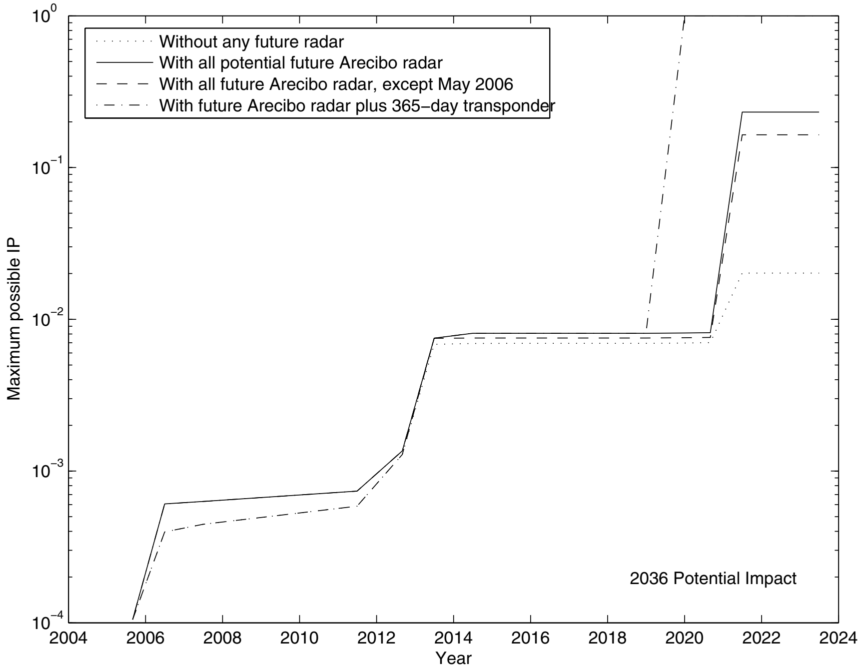

Figure 10. Maximum possible impact probability for the 2036 potential impact, based on the uncertainties depicted in Fig. 7.

Alternatively, if an impact possibility does persist, or if the object is actually on a collision trajectory, how grave might the situation appear at a particular time? In other words, what is the maximum possible IP for a given b-plane uncertainty? Figure 10 addresses this question, revealing that the 2036 IP could approach 1% after 2013, and reach roughly 20% after 2021, based on the assumed ground-based observation schedule.

The possible radio tracking mission reduces the 2029 uncertainty to about 100 m, which likely allow the 2036 impact to be conclusively confirmed with high confidence or ruled out altogether.

8. Deflection Considerations

Based on the foregoing analysis, one can paint a picture of how the situation might evolve, vis-a-vis the known potential impacts of Apophis. Obviously, either all possibilities of impact will eventually be ruled out or one of them will be confirmed. At present we can say with 95% confidence that the 2036 possibility of impact will be substantially eliminated by 2013. If, on the other hand, the post-2013 impact threat is deemed *significant* (a criterion that has yet to be defined) then some basic preparations for a space mission to deflect the asteroid could be initiated at that time. Such efforts could include a reconnaissance mission to the asteroid to characterize its shape, spin state, and material and structural properties. Naturally, such a mission would also be effective in refining the orbital predictions for the object (Fig. 7). Other post-2013 preparations, should they be deemed necessary, would probably include detailed mission and spacecraft design studies so that a deflection mission could be launched more quickly in the event that a decision is made to do so.

The leverage provided by the 2029 Earth encounter substantially eases the technical challenge of actually mounting a deflection mission. In a sense, one need only miss the 2029 keyhole, which means that kilometer-scale deflections would be sufficient if implemented before 2029. The most practical means of deflection for Apophis would likely be a kinetic energy impactor. In rough terms, a kinetic energy deflection mission causes an along-track position shift of

$$\Delta X = 3\,\Delta T\,\Delta V$$

where ΔV is the along-track component of the velocity change due to the impact and ΔT is the time after impact that the effect ΔX is measured (Ahrens & Harris 1994). Thus a modest along-track velocity change of 0.1 mm/s leads in approximately three years to a 25 km change in position, which is more than sufficient to avoid a keyhole. A ΔV of this magnitude can be readily obtained from a 1000 kg impactor with a relative velocity of just a few kilometers per second. Of course there are factors of safety and redundancy issues that need to be considered in detail, but this rough calculation indicates that a kinetic energy impactor would be a feasible option with current technology and available launch vehicles.

The experience of NASA's Deep Impact mission, which was schematically similar and progressed from preliminary planning to launch in only six years and from launch to a successful collision with a comet in six months, is instructive. An Apophis deflection mission could thus reasonably delay launch until the early 2020's, although detailed mission and spacecraft design studies may need to be completed earlier. Important design considerations for a deflection mission would include the possible need for backup missions and the availability of post-deflection radio tracking to verify success. Preliminary work on transfer orbits and deflection considerations has already been reported by Junkins *et al.* (2005) and Gennery (2005).

As an example deflection timeline, should Apophis persist as a significant risk beyond the 2013 apparition, a scientifically-oriented reconnaissance mission to Apophis may be called for in 2014 to arrive around 2019 as indicated in Fig. 7. Additionally, paper studies of deflection options could be conducted, but fabrication of the actual deflection spacecraft could be delayed until around 2020, depending on the results of those studies. After fabrication, launch could reasonably be delayed until after the 2021 apparition, with the actual deflection occurring around 2024, five years before the 2029 b-plane crossing. This example would need to be solidified with comprehensive mission studies, but the key point is that the deflection effort could be called off—at any point in time and after a minimum of investment—if it becomes certain that an impact will not occur. Throughout this scenario, the guiding principle should be to make all decisions and commitments as late as possible while carefully preserving the ability to prevent a potential impact.

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