A Permanently-Acting NEA Mitigation Technique via the Yarkovsky Effect

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Abstract

In the later stages of a combined exploration/mitigation mission to a hazardous Near Earth Asteroid (NEA), and once sufficiently detailed tracking, orbit prediction, mass distribution and physical properties data have been accumulated; it may be desirable to implement a “slow push” mitigation technique that is capable of altering the NEA orbit continuously and permanently. This possibility was suggested in a companion paper that outlined an archetypal exploration/mitigation mission to the NEA 99942 Apophis. In this scheme, long term mitigation is achieved using a novel albedo change approach. This paper describes the details of the albedo modification technique and apparatus.

The albedo change technique described here is the penultimate phase of the exploration/mitigation mission concept, and relies on thorough scientific exploration in the previous mission phases. To continually alter the orbit of Apophis (or similar NEAs), far beyond the mission lifetime, and eventually eliminate the threat of impact altogether, we propose to alter the NEA albedo to either diminish or enhance the Yarkovsky effect. Detailed calculations show that within reasonable bounds for the absorptivity and mass, and depending upon the spin state, a 5% change in the albedo of Apophis, starting in May 2029, and using less than 25 kg of surfacing material, will deflect Apophis between 17 and 45 Earth radii by 2036.

At present, the albedo change mechanism that appears the simplest and most effective involves a device that dispenses, in a controlled fashion, ionized powder onto Apophis’ surface – which is itself ionized by ultraviolet radiation. Electrostatic attraction provides the dominant force that will distribute and bind the powder to the surface.

The albedo change dispenser described here is based upon triboelectric powder dispensing technology and contains two supply canisters containing either very high or very low albedo powders. Either one or the other will be used, depending on the albedo/thermal emission data and the tracking/orbit prediction data collected during the exploration phase of the mission. We describe the design details and the constraints on particle size (to prevent electrostatic levitation and escape) and dispensing speed (to achieve the desired coverage zone and prevent particles from orbiting or escaping).

Introduction

As Near Earth Asteroids (NEAs) are discovered and concern is increasingly raised, a plan to mitigate these potential hazards must be developed. The Apophis Exploration and Mitigation Platform (AEMP) employs two mitigation techniques to deflect the Aten class NEA 99942 Apophis from a possible collision course with Earth. The first mitigation technique applied is the gravity tractor, which is a short term technique that will prevent an impact in 2036. This paper focuses on the second of these methods, an albedo change mechanism (ACM), which will serve as a long-term mitigation strategy for the asteroid, altering the orbit to prevent future impacts.

Discovered in June 2004, Apophis crosses the orbit of Earth every seven years, making it a periodic threat. At 270m diameter, Apophis presents the possibility of regional destruction. Initially believed to pose a threat to Earth in 2029, Apophis briefly reached a record high rating of 4 on the Torino impact hazard scale with an estimated impact probability of 1 in 300 [2]. After further analysis, researchers concluded that Apophis has a negligible impact probability in 2029, but that there is a 1 in 45,000 chance it will pass through a gravitational keyhole at that time. This keyhole would alter Apophis' trajectory toward Earth impact in 2036 [3]. Though Apophis is now believed to present a minute threat, it can serve as a critical test subject for experiments concerning mitigation techniques for use in the future against more hazardous NEAs.

The AEMP mission will be launched during the close approach of Apophis in January - March 2022. The goals of this mission are to study Apophis, test mitigation techniques, and demonstrate an archetypal template that will guide future missions [1]. Both before and after the short-term mitigation strategy is implemented, orbital, structural and thermal data will be collected and analyzed. This information will determine a more defined strategy for long-term mitigation [4].

Presently, the uncertainties in Apophis' trajectory prevent a more precise knowledge of the risk of impact in 2029 and 2036. Tracking Apophis during the mission will reduce these uncertainties through constant, periodic measurements. Application of the long term mitigation technique relies upon precise measurements, so continuous monitoring of Apophis throughout the mission is critical. All future modified orbit crossings of Earth and Apophis must be a greater distance than the determined uncertainty.

A secular force called the Yarkovsky effect is driven by the amount of light reflected from a celestial object's surface. The AEMP mission will augment or diminish this force by changing Apophis' albedo. The Yarkovsky effect will gradually alter the asteroid's semimajor axis, ultimately resulting in an orbit that will never place Earth in peril.

Albedo and Yarkovsky Effect

Albedo is a surface property of any material that describes the relative amount of incident light diffusely reflected; it may be considered a more specific representation of reflectivity. Apophis is estimated to have a geometric albedo of 0.33 [6]. This surface quality indirectly influences a non-gravitational recoil force called the Yarkovsky effect.

The Yarkovsky effect is the result of anisotropic heating of a celestial object. The amount of heat absorbed by the object is closely related to its albedo; as uneven heating occurs, the warmer surfaces radiate more thermal energy and a resulting net force acts on the object. For instance, the side of an asteroid that faces the sun will be heated. As the sunlit side of the asteroid rotates away from the sun, the warmer "dusk" side radiates more energy than on the cooler "dawn" side. The resulting net force acts in a direction that is determined by the asteroid's spin axis, rotation rate, and orbital period. Note that, as illustrated in Figure 1, an asteroid rotating prograde emits higher energy photons along the velocity vector, while one rotating retrograde exhibits the opposite behavior [5].

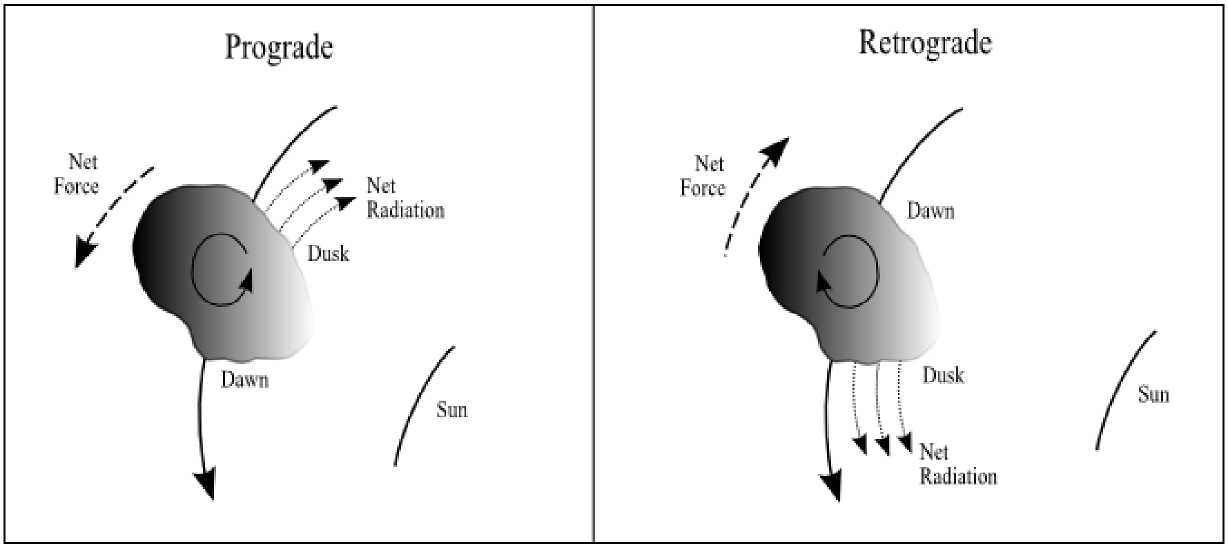

Figure 1: Dependence of the direction of the Yarkovsky force upon asteroid spin state

The Yarkovsky effect gradually alters an object's trajectory over time. Both the orientation and rotation rate of the spin axis (diurnal variant), as well as the mean motion frequency of the object revolving around the sun (seasonal variant) are the major factors driving the Yarkovsky effect [5]. The thermal radiation model for the body is represented by a quartic term, so its effect may only be represented as linear if carefully simplified. A highly eccentric orbit will affect the seasonal variant because of uneven heating through one revolution about the sun. A nonlinear heat diffusion analysis would be much more precise and reduce the uncertainty in its orbital determination.

The Yarkovsky effect plays a role in the dynamical evolution of asteroids and has been observed to influence metastable orbits of small asteroids by imparting a secular change in the semi-major axis [7,8]. Changing the albedo of Apophis will alter the magnitude of the Yarkovsky effect, allowing the secular term of the semi-major axis perturbation to be controlled. AEMP will use a detailed analysis of Apophis' trajectory to determine the change in albedo necessary to prevent any future collisions with Earth. The AEMP albedo change subsystem has been sized to produce a three Earth radii orbit deflection by 2036. This investigation will be conducted during phases of the mission before the albedo change technology is applied. Trajectory information collected about the asteroid at close range will allow for a more accurate examination than is possible from Earth-based observation. The method by which the albedo is changed must be verified before any action is taken to prevent undesired results. Currently, the surface properties and rotational dynamics of Apophis are only conjectured through the reflectance spectrum. As these properties will be discovered during the mission, a high and a low albedo material shall be on board the spacecraft for flexibility [9].

General mathematical models have been developed for small celestial bodies affected by the Yarkovsky effect, but two assumptions are generally made; the body temperature over the entire object is assumed to be the average value, and the body is modeled as an ideal sphere [8]. These models have the advantage of simplicity; however, the thermal model for Apophis, as well as for other hazardous NEAs, will require a much more precise analysis. The thermal model will need to be refined as data is collected during the observation phases of the mission in order to allow for less uncertainty in the determined effect of the albedo change mechanism. Heat diffusion must be modeled in three dimensions throughout the asteroid for complete thermal characterization. Specifically, the Yarkovsky effect parameter calculations of thermal conductivity, thermal capacity, and density will be adjusted in-flight as more thermal measurements are collected. The mathematical models are complicated by general factors such as a highly non-spherical and irregular shape, a high orbital eccentricity, and an unusual spin axis rotation [7].

Apophis' Physical Properties

Apophis is determined to be a Sq-class asteroid composed of mainly olivine and pyroxene. This classification indicates a strong similarity to the spectral properties of LL chondrite meteorites; small-scale physical characteristics of these celestial bodies are studied in laboratory environments. Apophis is estimated to have a porosity of 40% and a grain-size parameter of 6.1. Additional characteristics include average values of 3.5 g/cm^3 grain density, 3.2 g/cm^3 bulk density, 7.9% micro-porosity, and 20% macro-porosity [10]. These physical properties of Apophis will greatly influence the long term mitigation strategy of the AEMP mission.

Predictions of the future trajectory of Apophis are well characterized and based on the Standard Dynamical Model. However, Earth-based observation errors resulting in these forward propagations increase nonlinearly with time, driving a need for more precise dynamical observation during the mission. Improved knowledge of the asteroid's orbital path will be obtained during exploration portions of the mission [10].

Measurement Techniques

Using a series of optical images, a surface mapping of the asteroid will be constructed, and the spin state will be determined. The images will be correlated to provide the geometric shape of Apophis. The average bond albedo will be estimated by imaging each area at a variety of phase, α, incidence, θ_i, and observance, θ_o, angles, as shown in Figure 2. Due to the likely non-homogeneity of the surface and the rotation of the asteroid, an entire rotation of the asteroid must be imaged from each phase angle to provide an accurate average bond albedo. Since bond albedo is the measure of the reflection of all wavelengths from all phase angles, albedo measurements must account for the imager spectral limitations.

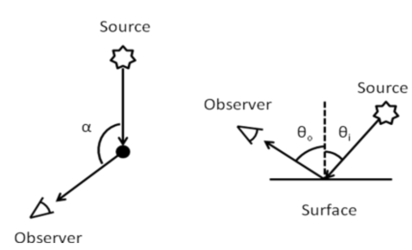

Figure 2: Definition of Phase, Incidence, and Reflection Angles

A study of the bond albedo determines the energy balance on Apophis. The energy balance is estimated via the surface temperature. Measurements of surface temperature via an onboard micro-bolometer will provide insight to the energy emission properties of the asteroid. The magnitude of the Yarkovsky effect can be measured directly by summing the emission vectors over the asteroid. The net emission imbalance can be calculated and combined with the information on the spin state to provide an accurate model of the Yarkovsky effect and associated perturbations on the asteroid's orbit. Due to the Yarkovsky O'Keefe Radzievskii Paddack (YORP) effect (a second-order version of Yarkovsky), the spin state of the asteroid will change over time [8]. The evolution of the spin state will be monitored and correlated with thermal emission measurements to better model thermal emissive phenomena.

In order to properly analyze the results of the ACM, it will be necessary to track the changes in the trajectory following the application of the ACP. The spacecraft performing the mission will already be employing an on-board beacon with the Deep Space Network (DSN). The baseline design uses pseudo-noise ranging as the ranging method, as opposed to the more precise Delta-Differential One-way Ranging (ΔDOR) methodology, because the more precise measurements will not yield significant advantages. The following analysis uses an unscented Kalman filter to directly estimate the magnitude of the Yarkovsky force. Figure 3 shows the standard deviation of the estimate of the Yarkovsky force for three cases: tracking using ΔDOR methodology, tracking using pseudo-noise ranging, and ground-based tracking [11, 12].

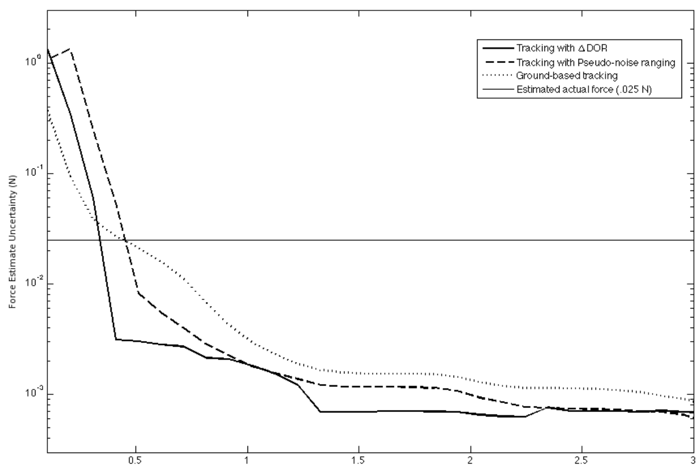

Figure 3: Estimated Standard Deviation of Yarkovsky Force

The results show that the final estimate is equally precise for all tracking methods; the difference is apparent in the speed at which an adequate measure is achieved. Because adding additional time to the end of the mission increases costs and risk, it is desirable to reduce the time required for the spacecraft to complete its mission. Given the unnecessary complications of the addition of ΔDOR tracking, an extended mission life of one year for tracking should be considered before switching to ground-based tracking over the next three to five years to reach the best case sub-mN precision. By considering the final tracking portion as extended mission life, there is a higher probability of spacecraft failure during this period. However, the same precision is eventually achieved using ground-based tracking.

Albedo Change System

The albedo change system is a device to be utilized by the spacecraft during the long-term mitigation phase. The objective of the mechanism is to modify the albedo of the asteroid. The device should minimize the spacecraft mass when on-station at Apophis while providing sufficient modification. Based on observability requirements, a baseline bond albedo modification of ±0.5% is considered sufficient according to Giorgini, et al [3].

The primary candidate for surface treatment is a dispenser that deposits a fine powder on the surface of the asteroid from a supply canister mounted on the spacecraft. Chondritic bodies, such as Apophis, have an innately high electrical resistivity and tend to accumulate static charge. Solar wind and UV-induced radiation positively charges the sunlit surface of the asteroid (Region 2), with a sheath of negatively charged particles levitated above the surface (Region 1) [13]. Figure 4 illustrates this configuration. The electrostatic repulsion in Region 1 is considered negligible in comparison with the electric field of the positively charged surface. As a result of this phenomenon, electrostatic attraction is an efficient option to adhere the powder to the surface.

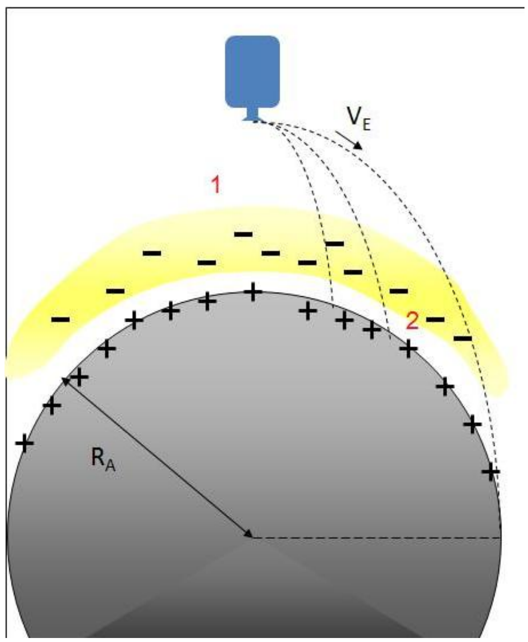

Figure 4: Schematic depiction of the charge distribution and s/c location

The albedo change particles (ACPs) can be charged in various ways. The selected method is tribocharging, an electrostatic deposition technique used in industrial applications to coat objects using negatively charged powder. Electrostatic charging can be imparted through cold plasma, called corona charging, or through frictional contact, called tribocharging [14]. Tribocharging is favored for greater simplicity, reliability, and reduced power requirements. Furthermore, tribocharging does not generate free ions, which form Faraday cages that prevent further deposition. Another possibility is to break an ionic compound, such as ammonium chloride, into its constituent ions. However, methods for breaking such bonds require immense amounts of heat or separation in polar solvents such as liquid water, which are not viable aboard a spacecraft [15].

A tribogun charges the powder particles through electrostatic friction with the gun barrel. For creating negatively charged particles, the most popular barrel material is nylon 6/6 with polytetrafluoroethylene (PTFE) powder. PTFE is a naturally white synthetic fluoropolymer that is nonreactive and resistant to degradation until 260°C [16]. However, since PTFE can be color treated, any albedo can be achieved. Nylon 6/6 is the strongest standard variety of nylon with a high melting point, strong abrasion and thermal resistance, and a long lifetime [17]. These materials provide an attractive option as both are widely available and inexpensive.

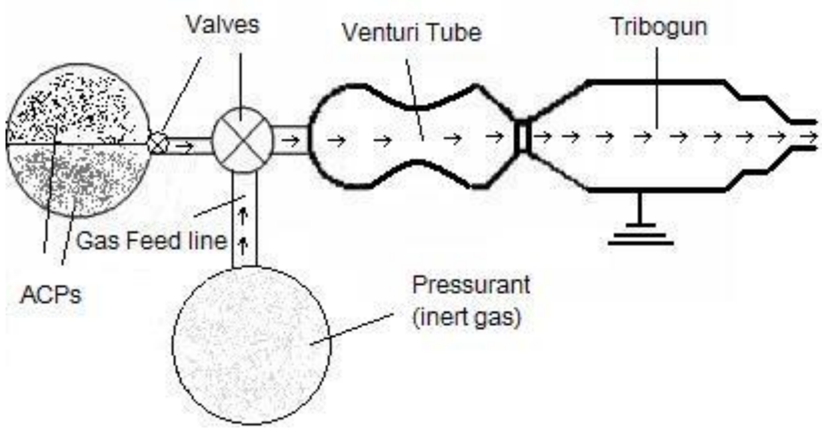

Figure 5: Schematic of cold gas and tribogun system

A simple design concept for accelerating the powder through the gun uses a low-pressure cold gas thruster, as illustrated in Figure 5. The high albedo ACPs and low albedo ACPs are stored in two separate tanks with a common tank of pressurize, inert gas. When commanded, the appropriate valve opens, and the ACPs flow into the tribogun. As the ACPs flow through the tribogun, contact with the nylon surfaces charges them.

During the long-term mitigation phase the spacecraft will maneuver to an inertially-fixed position approximately 100 m from the surface of Apophis. As Apophis rotates beneath the spacecraft, ACPs will be deposited on the surface at preselected regions until sufficient modification is achieved. During deposition an optical navigation camera will aid in tracking and monitor particle distribution.

Several design constraints should be addressed. If evenly distributed, the maximum area covered by a given number of ACPs is proportional to the square of their diameter, D_P^2, while the total mass is proportional to D_P^3. Hence, the smallest possible particle size gives the greatest albedo change per unit mass. However, the size must be large enough to prevent dust levitation. On the sunlit side, the finest surface particles, upon acquiring a positive charge, can be levitated above the surface and subsequently escape. According to Lee, particles must be greater than 100μm in diameter to prevent such levitation [13]. These constraints recommend an ACP size of 100-200 μm.

The speed at which the particles are ejected from the spacecraft present additional limits. The first requirement is that particles must not go into orbit or escape. In a limiting case, the dispenser is considered to have a wide dispersal angle such that ACPs can be ejected as much as 90° from nadir. To meet the above requirement and ensure that the ACP deposition can be monitored from the spacecraft, the particles are required to travel no further than point B as indicated in Figure 6. Hence, we can define an upper limit to the dispensing speed, V_E, as a function of the dispensing altitude, H, above the surface:

$$V_E < \sqrt{\mu_A R_A} \big/ \left(R_A + H\right)$$

R_A is the radius of Apophis (modeled as a sphere) and μ_A is the gravitational constant of the asteroid.

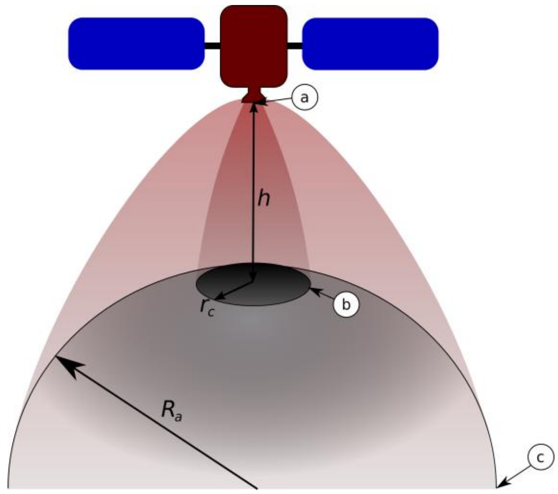

Figure 6: Limiting trajectories resulting in the dispensing speed bounds

A minimum desired coverage area of radius, r_C, presents a lower bound for the dispensing speed. The area of coverage is defined to allow for even distribution without clumping or overlapping. Again, assuming a limiting-case where ACPs are ejecting 90° from nadir, as illustrated in Figure 6, particles should land between points B and C. This case implies a lower bound for V_E:

$$V_E > \sqrt{\mu_A \frac{R_A\left(1-\cos\left(r_C/R_A\right)\right)}{\left(R_A+H\right)\left(R_A\left(1-\cos\left(r_C/R_A\right)\right)+H\right)}}$$

Please note that coverage is still intended for the circular area with radius r_C lying precisely below the spacecraft. The ACPs will still likely land within the circular region given this velocity constraint if they are not ejected 90° from nadir, which is the vast majority of cases. This restraint merely reduces the probability that the ACPs land within this region to the extent that excessive overlapping is avoided.

The necessary coverage area is only ~40mx40m (22m radius circle) as discussed in Giorgini, et al. if the mission is launched in 2018 [3]. Since AEMP will be launched four years later, the coverage area is most likely larger though on the same order of magnitude [13]. Using the "nominal case" parameter values given by Binzel, et al., R_A = 135 m and $M_A = 2\text{x}10^{10}$ kg, and assuming a desired coverage area with circular radius 40m, the dispense speed is then constrained to within the boundaries shown in Figure 7 [10]. These fairly tight restrictions limit the dispensing speed to between 2 cm/s and 6 cm/s for the a spacecraft at approximately 100m above the asteroid surface.

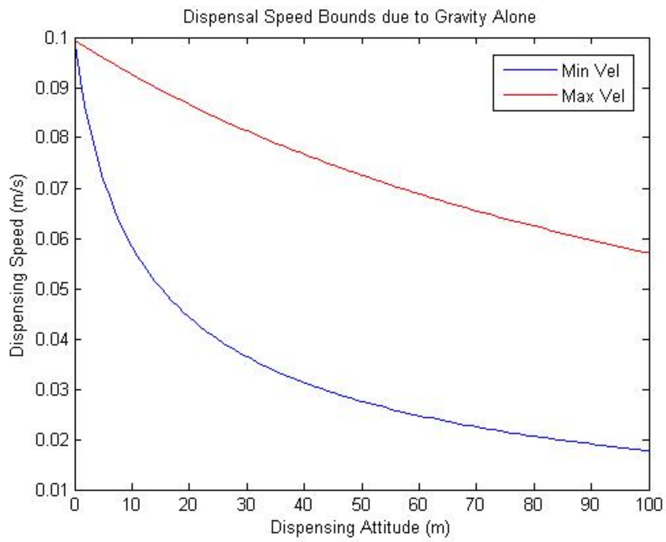

Figure 7: Upper and lower bounds on dispensing speed

A rough estimate of the amount and mass of the material needed to change the albedo of Apophis is easily derivable knowing the ACP composition [16]. The mass of the ACPs can be calculated via the equation

$$M_T = \frac{\pi R_A^2 w \rho_T \left|\Delta x\right|_{(2036)}}{\Gamma \left|\alpha_T / \alpha_0 - 1\right| R_\oplus}$$

The thickness *w* is the same as the largest ACP diameter size while ρ_T is estimated based on an average of the bulk density of several Dupont Teflon powders [19]. A distance of three Earth radii from Earth along the orbital track is considered a safe margin by the year 2036. Γ is a dimensionless quantity that depends on spin state, the average albedo, and the asteroid mass [3]. For numerical calculations, there are two extreme cases with different Γ and bond albedo, α_0, as defined in Giorgini, et al. due to current ambiguity of the exact composition of Apophis. All variables and their respective quantities are outlined in Table 1. Notice that there is no explicit dependency on the coverage area in the mass equation.

Table 1: Mass calculation of ACPs

Variable	Quantity	Description
R_A	105-175 m	Radius of the asteroid
W	100 μm	Thickness of the covered layer
ρ_T	400 kg/m^3	Bulk density of ACP
$\|\Delta x\|_{(2036)}$	3 R_{Earth}	Distance from orbital track by 2036
α_T	0.05 – 1	Geometric albedo of treated surface
Γ	200-1450	Orbit sensitivity factor
α_0	0.1383-0.1613	Bond albedo

For the least sensitive case (maximum mass, minimum albedo, $\alpha_T = 0.05$), the ACP mass needed is ~90 kg; for the most sensitive case (minimum mass, maximum albedo, $\alpha_T = 1.0$), the ACP mass needed is ~0.55 kg. The mass of the albedo change mechanism is yet to be determined. For nominal values of the parameters ($R_A = 135m, \alpha_T = 0.1521$) the mass required is ~51 kg.

An optimal application strategy will be decided pending the results of the exploration. Trajectory refinement and spin state define the desired direction of change in semi-major axis. Surface mapping would allow for maximum effectiveness by applying high albedo particles to lower albedo regions on the asteroid or the reverse. Spin state and surface geometry also allow for maneuver planning.

Evaluating the Effectiveness

An important aspect of the AEMP mission is to assess the effectiveness of the mitigation techniques applied. While direct measurements of the asteroid's trajectory are useful in determining the effectiveness of the gravity tractor method and Yarkovsky force manipulation, these measurements provide little insight to the reflective/emissive phenomena occurring on the surface of the asteroid. By measuring the reflectivity, surface temperature, and spin state of Apophis before and after the mitigation events, the dynamics and orbital perturbations can be modeled more precisely.

During the pre-mitigation exploration phase of the mission, the asteroid will be tracked over an extended period. This tracking will provide an improved trajectory as well as potential measurement of current absorptive/emissive effects. These improvements to the trajectory propagation will aid in determination of mitigation efforts and provide a better understanding of the asteroid's evolution. Also during the pre-mitigation exploration phase, the surface will be mapped for reflectivity and surface temperature. The models generated from these measurements and the known effects on the asteroid's trajectory will allow planners to design the mitigation events and project the effect of those events.

Following the application of the ACPs, the tracking must be continued for an appropriate amount of time, and the surface remapped. The efficacy of the ACPs will be quantified and the success of the application method reviewed. This pre and post-mission study of the asteroid will yield both scientific and technological benefits for future encounters with hazardous NEOs.

Conclusion

The AEMP design will follow a strict *do no harm* policy while experimentally verifying the efficacy of two mitigation techniques. The short term gravity tractor technique will retire impending threats, while the long term method described in this paper is intended to prevent all future impacts. The advantages of controlling the Yarkovsky effect through manipulating the asteroid's albedo include direct observations of the resulting changes and a semi-permanent adjustment in Apophis' trajectory.

The ACM has many desirable characteristics. A tribogun design uses techniques that are commonly used and well understood. Because the ACM uses powder to cover the surface of the asteroid, the mass is much less than that of any liquid-based alternative. A tribogun design uses few movable parts, greatly reducing the risk of in-flight failure. Additionally, this technology will be validated in laboratory settings and a LEO experiment prior to the development of the spacecraft.

The effectiveness of the ACM technology will be tested on 99942 Apophis and can be refined for other hazardous NEAs; in the case of a certain impact, the design time and cost for a mitigation mission will be drastically reduced.

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