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THE SHADOW MISSION
DEFLECTING APOPHIS WITH A FLOTILLA OF SOLAR SHIELDS

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ABSTRACT

The orbit of asteroids like APOPHIS is difficult to extrapolate on the long term mainly due to the uncertainties upon the effect of non gravitational forces. The Yarkovsky Effect (YE), which is the main unknown, is a tiny but permanent thrust, the intensity and direction of which are directly related to the nature of the soil, the rotation characteristics and the physical properties of the asteroid.

The SHADOW mission we propose would be phased in the following way:

- as soon as possible, send a probe to rendezvous with APOPHIS and provide the requested data to assess the YE. The probe itself being tracked from the ground, the characterization of the resulting thrust can be achieved after a few months flyby.

- after assessing the risks of Earth impacts for the coming decades, a decision can be made about the possible mitigation techniques.

- if the YE is proved to be important, cancelling it will be sufficient to avoid a collision with the Earth. This can be achieved by shadowing and cooling the asteroid with a flotilla of solar shields.

We propose to name this strategy YES: Yarkovsky Effect Shadowing.

1. THE YES STRATEGY

All the rocks, dust and grains that have been accumulated during the last billion years have produced what is now the Earth we live on.

The Earth is one of the eight planets of our Solar System. To deserve to be called a planet [1], the Earth had to clean the neighbourhood around its orbit. Unfortunately, the clean up is not yet completed and there are still some hazardous celestial bodies wandering in space.

Thousands of such Near Earth Asteroids (NEAs) are being catalogued. We can assume that, in a few decades, the inventory of NEAs will be completed. Among them a few hundreds are expected to pose some concerns for our future. What can be done with those that will be suspected to threaten the Earth with a devastating collision?

Before doing anything, the collision issue has to be investigated in depth, in order to quantify the risk more precisely. The prediction of the collision of two space objects (the Earth and one NEA) is a fully deterministic problem once the forces that apply to the objects are sufficiently well known. As the Earth ephemeris are well known (a few hundred meters accuracy), the assessment of a collision risk with a NEA is completely dominated by the uncertainty on the NEA orbit.

The orbit determination process of any space object relies on two equally important pillars: force models and measurements. In the case of a dangerous NEA, two kinds of forces have to be taken into account: gravitational and non gravitational forces. The gravitational forces are well defined so the main difficulty is to assess properly the magnitude of non gravitational forces. The Yarkovsky Effect (YE) is the origin of the most important non gravitational force to determine for enabling accurate orbit propagation.

The measurements can be of two types: ground based or space borne.

Current ground-based optical measurements are efficient for NEA detection but their accuracy for orbit determination is very poor: several thousands of kilometres at least, depending on the distance and direction of the incoming NEA with respect to the Earth. Ground based radar measurements can be only done when the distance to the NEA is sufficiently low, typically under 0.3 AU to allow Arecibo measurements [2].

The combination of only ground based measurements and the ignorance of the YE leads to orbit errors in the range of hundreds to thousands of kilometres for the short future.

Space borne measurements are routinely used with interplanetary probes. The most accurate system presently available is Delta DOR [3] which consists in measuring the angle between the radio transponder of the probe and a well defined quasar. The typical accuracy is 4 km at a distance of one Astronomical Unit. Once again, two possibilities are offered: placing the transponder on the soil of the NEA or keeping it onboard a probe that hovers over it. While following a NEA, the same probe can carry a set of instruments that provide the physical data needed to determine the non gravitational forces that are in effect, especially the above mentioned YE.

A single spy probe can thus shadow the asteroid and simultaneously (*i.e.* within a few months) provide the necessary data for determining its orbit and refining the models of non gravitational forces needed for further extrapolation.

When this orbit determination process has provided reliable data, the situation can be:

- no future collision risk exists
- there is still some probability that a collision will occur in a far future
- there is a high probability for a collision within a few decades.

The case we are considering here is the third one, where something has to be done in a limited time frame.

The first possibility of action is to modify the asteroid orbit so that it passes out of a so called 'keyhole'. A keyhole in the present context is a region close to the Earth which is acting like a trajectory deflector. Passing through one of them would place the incoming asteroid on an orbit with a period commensurable with that of the Earth, making a further impact very likely to occur. The size of such keyholes is of the kilometre level. After passing through it and assuming that a resonant orbit is reached, then depending on the resonance ratio, a longer time can be available for action. In case of bad luck, anyway, only a few years will remain to mitigate the threat. Then more aggressive methods than YES can be required.

The dilemma is whether to act before passing through the keyhole in order to move the asteroid path out of it or after when a better knowledge of the future orbit is achievable. In the latter case, a much larger deviation will be needed to make sure the threat has been cancelled.

Several deflection strategies can be implemented in order to get rid of any collision risk. Each of them has pros and cons. The one that is proposed here is a 'soft' one, which does not require new technological developments and is not destructive. Contrary to all the mitigation techniques that have been proposed up until now, it does not consist in adding a force to change the NEA orbit: instead it cancels one of the effects that apply to the NEA, the YE. This can be done simply by shadowing the NEA with a flotilla of solar shields. The cooling that would result from this shadow would dramatically reduce the thrust due to the YE.

The pressure due to the YE on an asteroid like APOPHIS can be compared to the one exerted by a butterfly landing on a nuclear aircraft carrier. It seems ridiculous but when integrated even over a few years, it can be sufficient to modify the asteroid trajectory by several kilometres, enough to avoid huge havocs on Earth.

2. THE YARKOVSKY EFFECT

The YE is the radiation thrust due to the anisotropic radiation of heat radiated by an illuminated rotating body. On a rotating body, such as an asteroid, the surface is warmed up when illuminated by the Sun.

During an asteroid day, the surface cools down during the afternoon and early night. The result is that more heat is radiated on the "dusk" side than on the "dawn" side, leading to a net radiation pressure thrust in the opposite "dawn" direction.

A seasonal effect due to a possible north/south asymmetry can also exist but its order of magnitude for asteroids larger than100m is one order of magnitude below the diurnal effect.

In this paper, we only refer to the diurnal Yarkovsky Effect under the abbreviation YE.

The YE depends on the flux received from the Sun which is easy to determine. The radiated flux providing the YE is much more complex and is the result of several properties of the asteroid:

- geometry
  - the radius provides a first order of the amount of solar flux that is intercepted by the asteroid,
  - the shape can be quite different from the ideal sphere. The intercepted flux will vary in time during a full rotation depending on the asteroid shape,
  - the spin rate is one of the key parameters to evaluate the YE. If it is too slow, the YE will exert a thrust close to the Sun direction and its effect on the orbit period will be quite negligible, so there would not be a lot of interest in cancelling it. If it is too fast, the YE thrust will be split in almost all the directions so the result too will be negligible. The YE is a function of the thermal inertia, the angular velocity of the asteroid rotation and the temperature of the sub solar point [4],
  - the sense of rotation: if it is prograde, the YE will increase the semi-major axis and the asteroid will spiral away from the Sun. A retrograde rotation will cause an inward spiral.
  - the spin direction constrains the orientation of the YE thrust. If it is perpendicular to the orbit plane (zero obliquity) all the YE effect will apply to the in plane orbital parameters (*a, e*). A different orientation will add an out of plane effect. A spin axis in or close to the orbit plane will increase the role of the seasonal YE compared to the diurnal effect.

- thermal properties
  - the two main thermal parameters to be determined are the soil temperature in the sub solar area and the thermal inertia. The first is related to the surface albedo, the second also depends on the nature of the soil and the peripheral layers.
  - the sub solar temperature T_{ss} is of paramount importance since the YE is proportional to the equilibrium temperature cube T_{eq}^3 and the deviations of temperature from the equilibrium.
  - the range of variability of the thermal inertia is very large (4 orders of magnitude) depending on the internal nature of the body.

- dynamical features
  - the mass is obviously essential to evaluate the acceleration resulting from the YE and thus calculate accurately the orbit
  - the moments of inertia of the asteroid are not requested, a priori, for the characterisation of the orbit but they will be helpful to constrain the internal structure model used by the thermal models.

Depending on the shape of the asteroid (the closer to a sphere the simpler), the calculation of the YE will have to be done on a wide set of phase angles with respect to the Sun since the YE can be quite different along a rotation of an irregular shape body. Ideally, the temperature distribution on its surface dependant of time (ie phase angle) is needed for the complete characterization of the YE. The resulting effect on the orbit will then be estimated as the mean of the different phase angle YE.

Several theoretical publications are discussing in detail the theory of the YE. Whichever is used, a comprehensive thermal characterization of the asteroid from its surface (albedo) to its core (propagation of the thermal waves) will be needed for an accurate estimation of the magnitude and direction of the YE.

3. THE CASE OF APOPHIS

Theoretical approach: In a paper published in 2001 [5], the authors establish a theory for the calculation of YE impact on the semi-major axis for a ‘perfect’ asteroid. Applying this theory to 1 km stony asteroid at 1 AU gives an offset of 15,000km in 100 years [6]. When applying this evaluation to APOPHIS which could be approximated by a 400 m diameter sphere, a 7000 km deviation can be obtained after 20 years considering that APOPHIS will be further from the Sun after its 2029 Earth close flyby.

From the observations: The YE has been observed for the first time on the asteroid GOLEVKA [7]. An offset of 15 kilometres after 12 years between the observed position and the theoretical position in absence of YE has been evidenced.

If we make the assumption that the characteristics of APOPHIS with respect to the YE are the same as those of GOLEVKA, the main differences are the mass and the surface temperature.

	GOLEVKA	APOPHIS	RATIO	Effect on YE
Mass	2. 10^{11} kg	4 10^{10} kg	5	x 5
Temperature	176 °K	395°K	2	X16

The average solar flux received by APOHIS is 6.25 times higher than the one received by GOLEVKA due to the difference of orbits. The YE, which is varying with T^4, could then be 16 times higher for APOPHIS than for GOLEVKA if we assume that the subsolar region temperature is the same as on the Moon. If YE on APOPHIS is 80 times higher than on GOLEVKA, the resulting thrust will produce a position shift of about 2100 km in 24 years.

When fixing some of the YE parameters and taking only the obliquity as variable, the effect on the position can be as high as 1000 km in 24 years [2], the most probable values ranging in the 100 km – 200 km span.

From a few hundreds to a few thousand kilometres in about 20 years, there is a large span of estimations of the YE on an asteroid like APOPHIS. The case of APOPHIS is recent (2004) but similar discoveries are very likely as a worldwide sky monitoring is expected to run.

The first opportunity to test and qualify in space any mitigation strategy will be offered by APOPHIS, which has been recently discovered (2004) and which will come back close to us (less than 40,000km) in a reasonable future (2029) after two periods (2013 and 2021) when the distance to Earth will be around 0.15 AU during several weeks.

This asteroid could be the right target to validate the Yarkovsky Effect Shadowing (YES) strategy.

The principle of the YES technique is based on two distinct steps: collect all the needed parameters about the asteroid in order to characterize the YE and operate the adequate solar shield to perform the job.

What does it mean in the case of APOPHIS ?

Asteroid 99942 APOPHIS is estimated to have a 320 meters diameter and a mass of 4.6×10^{10} kg [2]. APOPHIS is currently (2007) predicted to have a close approach to Earth in 2029 (30,000 km on April 13). If it passes within a 600m wide “keyhole” then it would be placed on a resonant (7:6) orbit with the Earth and the likelihood of impacting the Earth exactly seven years later (April 13, 2036) would largely exceed the “background” impact probability 10^{-6}/year [8].

The strategy to prevent any risk of impact in 2036 is thus in two steps:

- improve the accuracy of orbit determination while preparing a mitigation mission. In 2013 (January) the closest approach from APOPHIS will still be 0.096 AU (same as 2004) and in 2021 (March) it will be 0.113 AU. The orbit accuracy that can be expected from these two passes will still be in the 100 km order of magnitude for the 2029 pass. The SHADOW PART ONE will enable to reduce this uncertainty to a kilometre level, the scale of the keyhole.
- if the likelihood of crossing the keyhole is confirmed then the SHADOW PART TWO mission should follow to deflect APOPHIS as far away as possible from the 2029 keyhole (while avoiding any longer term keyhole), thus eliminating any impact risk for the future.

Assuming that the YE causes the APOPHIS semi-major axis *a* to change at a constant rate *da/dt* (which is quite realistic due to its low eccentricity), the miss-distance with respect to the Earth *D* is varying linearly with *da/dt* and like the square of the integration time of the YE.

Considering a small 10 meters/year decrease of a, this leads to 100 meters after one year, 400 meters after two years. That means that the keyhole can be avoided after cancelling the YE in only in a few years long period of time.

Under these assumptions of low level YE, this method is not efficient enough to modify the orbit in less than the 7 years separating the 2029 and the 2036 passes (*D* ~ 5 km for *da/dt*=10m/year) but cancelling the YE within a few years before 2029 so that APOPHIS miss the fateful keyhole is feasible.

4. THE SHADOW MISSION, PART ONE: THE OBSERVATION PHASE

4.1 Rendezvous with APOPHIS

Propulsion: Considering that the probe will always cruise about 1 AU from the Sun and that the observation mission will require a long flyby of APOPHIS and very high navigation accuracy in its neighbourhood, we choose to use SEP (Solar Electric Propulsion) for this mission. Thereby the spacecraft is assumed to be equipped with a plasmic engine (PPS1350 type) with the following characteristics:

Specific impulse, Isp = 1900s
Thrust magnitude, F = 0.1N
Electrical power, P = 1.6kW

Launcher: The Launch Vehicle (LV) used for this mission is a Soyuz Fregat 2-1b LV. The performances associated with the departure conditions presented below allow an initial spacecraft mass of 1200kg. This value is computed taking into account the mass of the launcher adaptor and some launcher margins.

Trajectories: Direct ballistic trajectories towards APOPHIS are too energetic: the hyperbolic excess velocity required for the Earth's escape is equal to 5.33km/s. So we introduce an Earth swing-by during the heliocentric cruise in order to reduce this value from 5.33km/s to 3km/s.

Two options are proposed corresponding to a launch date in 2011 or in 2019. These options are detailed in the table below. The projection onto the ecliptic plane of the heliocentric trajectory associated with the 2011 option, respectively 2019, is presented in figure 1, respectively figure 2. Low thrust phases are plotted in bold lines.

	2011 option	**2019 option**
Departure date	Dec. 14, 2011	Dec. 5, 2019
Departure conditions	v-inf = 3km/s, dec-inf = -20.4deg	v-inf = 3km/s, dec-inf = -18.4deg
Launch mass	1200kg	1200kg
Date of the Earth swing-by	Apr. 18, 2013	Apr. 11, 2021
Characteristics of the swing-by	h_p = 78000km, v-inf = 4.38km/s	h_p = 60000km, v-inf = 4.50km/s
Date of the rendezvous	Mar. 5, 2014	Jan. 18, 2022
Total cruise duration	813 days (27 months)	775 days (26 months)
Total Delta-V	1520m/s	1350m/s
Xenon mass	95kg	85kg
Final S/C dry mass	1105kg	1115kg

Table 1: Characteristics of the trajectories in 2011 and 2019

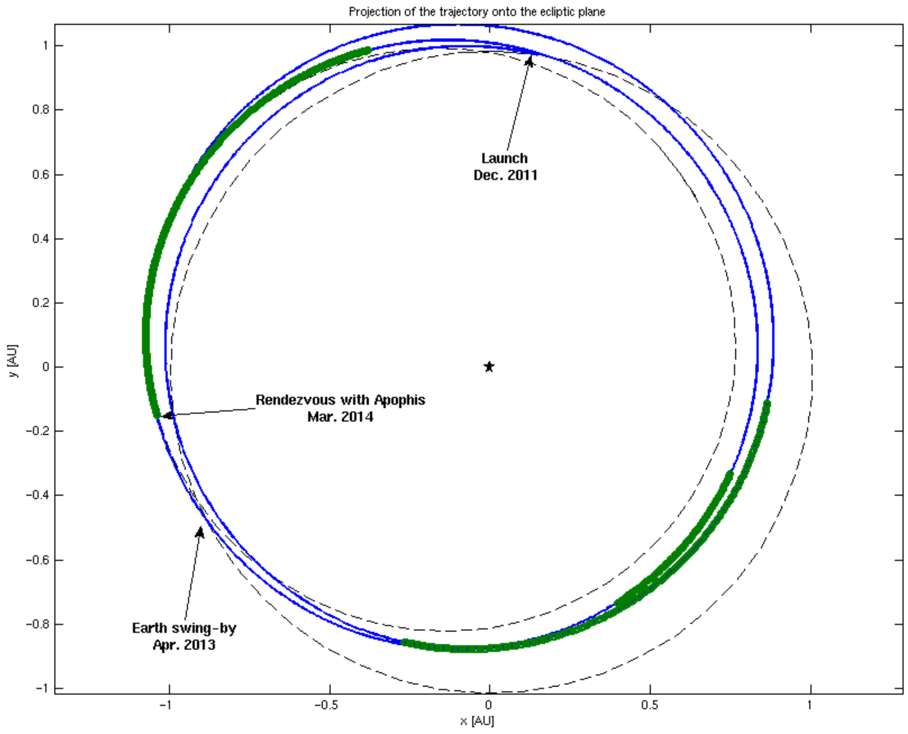


Figure 1: Trajectory towards APOPHIS – 2011 option (ecliptic view)

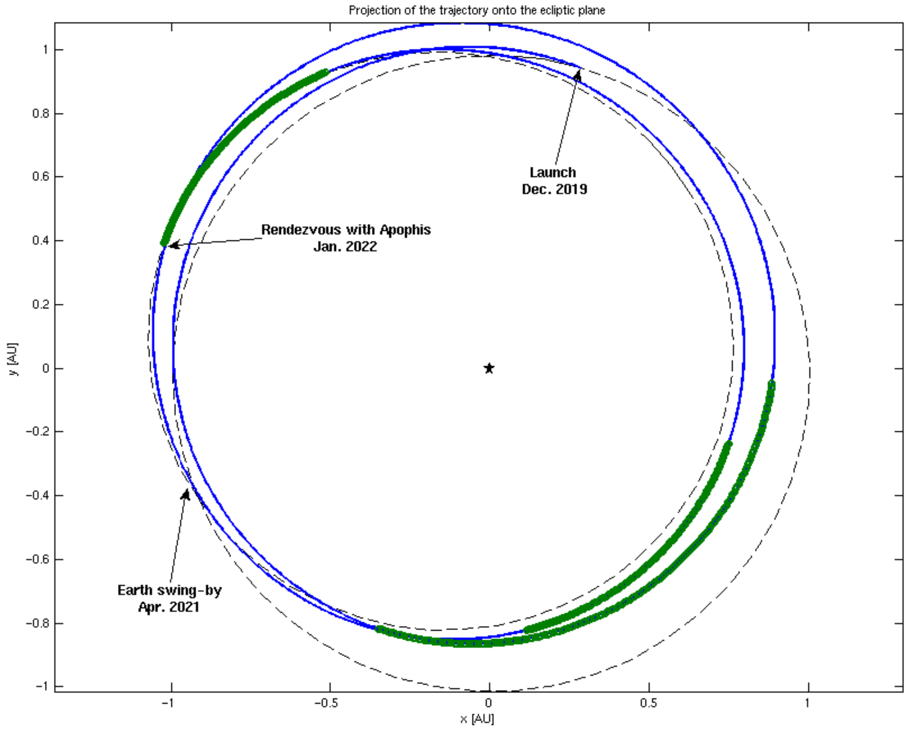


Figure 2: Trajectory towards APOPHIS – 2019 option (ecliptic view)

Asteroid APOPHIS may be reached within 27 months by means of a Soyuz Fregat 2-1b launcher and a spacecraft equipped with a plasmic propulsion system. About 100kg of Xenon are required to ensure the final rendezvous. The spacecraft dry mass is greater than 1000kg. This allows a sufficient payload mass for remote sensing and/or in situ measurements.

Onboard instrumentation: The instruments needed onboard the probe fall in two categories: remote sensing of the asteroid and precise orbit determination.

Remote sensing instrumentation: the purpose of this package is to provide the knowledge of all the physical data that are needed at least for the characterization of the YE. This includes a thermal camera (at least in two IR wavelengths) and a visible camera [4].

Merging the information acquired by these two kinds of cameras will allow to determine the geometrical and dynamical parameters (dimensions, rotation axis and velocity), thermal maps that will be transmitted and processed on ground in order to determine the characteristics of the YE.

The observation strategy will be defined once the main rotation parameters (velocity, direction) have been identified. Some flexibility in the final observation programme is then required. The typical altitude over the asteroid will be a few asteroid radii over the surface. The thermal mapping program will require keeping a variety of observation positions. The reference position of the probe can be defined as located in the asteroid equator plane in the direction of the Sun.

Additional instruments, for instance for scientific studies, can be accommodated as a second priority, according to the remaining resources.

Orbit determination package: the ultimate goal of this part of the mission is to provide an improvement of the asteroid ephemeris to a hundred meter level, in accordance with the size of the keyholes. It could be envisaged to deliver a transponder at the surface of the asteroid but this is not our favourite solution: landing and powering a transponder on an asteroid is not that easy and is a risky operation. Furthermore, there is no reason to believe that the geometry of the link to the Earth is optimal with respect to the transmitting system. Even an omni directional system can be unavailable during a long period of time due to the combination of the rotation parameters of the asteroid with the direction of the Earth seen from its surface.

The orbit determination process will then rely on two legs: determine the absolute position of the probe in an inertial heliocentric reference frame (J2000 for instance) and determine the relative position of the asteroid centre of mass in a probe centred frame. The absolute position of the asteroid in the reference frame will then be straightforward.

Determination of the probe orbit: the best instrument for determining the probe orbit is using a Δ-DOR system. It can be the NASA's DSN one or the new ESA system. Such systems provide angular measurements. In the most favourable conditions (that are met in 2013 and 2021 when the probe – Earth range is about 0.1 AU), the expected accuracy is 400 m. When the probe is far from the Earth, the position error can increase up to 8 km.

Relative positioning of APOPHIS: the position of the asteroid relative to the probe can be provided by a radar altimeter. A radio altimeter can be preferred to a laser altimeter because it would also allow determining the gravity field of the asteroid by performing some sequences of free fall where the acceleration due to the asteroid could me measured through its Doppler signature. This information is not needed to assess the YE but can be very useful to prepare the station keeping of the solar shields for the possible second phase.

Timeliness: The best periods for accurate positioning measurements of the probe are summarized below.

Date	Earth-probe range (AU)	Expected positioning accuracy (km)
April 2014	0.38	1.5
January 2020	0.44	1.8
March 2021	0.11	0.44
April 2022	0.55	2.2

In the mission scenario we have studied, the best choice is to launch according to the 2011 option, in order to reach APOPHIS in March 2014, just before the first favourable period and to hover over APOPHIS at least up to January 2020, ideally up to March 2021, thus covering a full year survey.

If this 'fast track' scenario cannot be fulfilled, the loss will be twofold: the launch opportunities will be less favourable and the expected orbit determination accuracy will also deteriorate. So it is important not to miss the 2011 launch opportunity.

5. SHADOW MISSION, PART TWO: THE MITIGATION PHASE

Decision making process

Let us consider now the worst case where the first part of the SHADOW confirms that APOPHIS will pass through the 2029 keyhole [9].

Even taking into account the propagation of a high YE, the size of the keyhole does not change radically from the estimated 600 m diameter. For instance, a *da/dt* of 1km/year would mean, after 7 years, a 500 km increase of the initial radius value of 15,000 km in the *b*-plane that is retained as the Earth impact area. The objective of the second part of the SHADOW mission is to deflect APOPHIS from its natural orbit by at least 6 kilometres.

The justification of the 6 kilometres target is that the YES method is not symmetrical: by cancelling the YE thrust, the *b*-plane crossing point can be displaced only in one direction. The worst situation would be that the keyhole is near one side of the error ellipse and that it could be displaced only by crossing the whole keyhole. In that case, somebody would have to accept to increase the impact probability during a part of the mission.

Another tricky aspect is that the lower the YE, the longer in advance a decision has to be made.

Let us consider that even in the bad case of keyhole crossing, the good news is that cancelling YE can only move APOPHIS away from the keyhole.

Mission overview

This second part of the SHADOW mission will consist in positioning a set of solar shields on the sun lit side of APOPHIS. The thermal repartition at the surface will be smoothed rapidly and the YE will fall to a negligible value.

The size of the asteroid is estimated to be around 300 metres in its largest dimension. It is not necessary to shadow the regions where the sun rays are grazing. We assume that it is necessary to cover an area of 30,000 m^2 because it is the one contributing the most to the YE. Due to the possible irregular shape of APOPHIS and for reliability reasons, we prefer to use a flotilla of individual solar shields instead of a single large one. For instance, a set of 12 to 16 square or hexagonal sails, each with a 50 metre diameter, can be used. These shields facing the Sun will behave like solar sails which means that the solar photonic pressure will tend to modify their orbit, as well as the gravitational attraction of APOPHIS, both in the same anti sunwards direction. This thrust will have to be counterbalanced by an orbit control system onboard each shield (or sail). The closer to the asteroid surface, the more important the gravitational pull will be.

Mission design

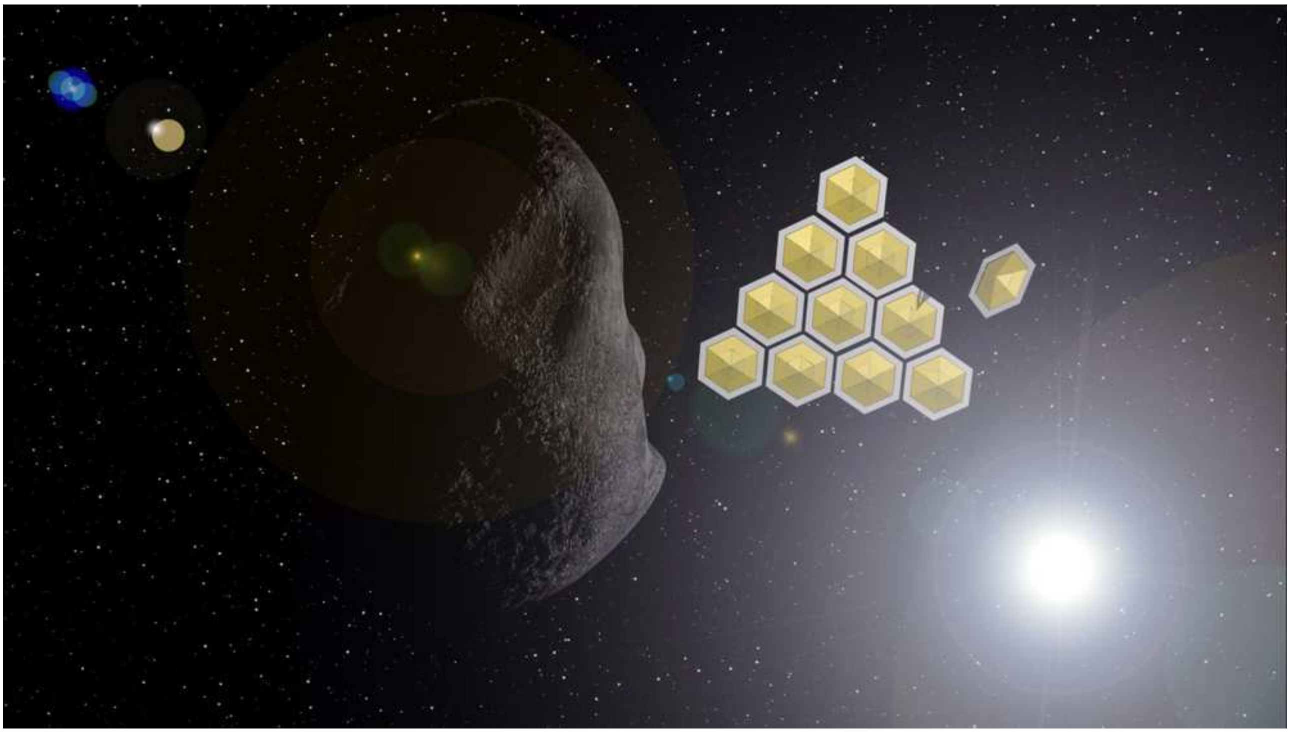
There are two very distinct phases in this mission: the first one is the cruise from the launch up to APOPHIS and the second is the hovering over it. The resources that are needed during these two phases are very different:

- for the cruise:
  - high ΔV from the launch up to the APOPHIS rendezvous
  - electrical power for the SEP system
  - high reliability needed
  - direct communication link with the Earth
- for the hovering phase:
  - autonomous control of the formation level
  - autonomous control at the individual sail level
  - several sails can be kept in reserve so the reliability requirement can be lowered

If we consider a launch in 2019, APOPHIS can be reached in 2022 (Table 1). The maximum duration of the hovering phase is then 7 years.

Station keeping requirement

The individual sails will have to counteract the action of the solar photonic thrust and the gravitational attraction of APOPHIS.
The photonic pressure will be at its maximum near the perihelion (0.75 AU). If we consider a sail area of 2,500 m^2 and a reflectivity of 0.1 for a 200 kg object, the resulting acceleration is 1. 10^{-5} m/s^2. If the sail is located at 1 km over APOPHIS, the gravitational pull will be around 3 10^{-6} m/s^2. The average continuous thrust required to balance these two effects is then about 13 10^{-6} m/s^2 corresponding to an average daily ΔV of 1.1 m/s in the perihelion vicinity.
It is then fundamental to adapt the sail design to the duration of the mission and the asteroid surface that we really need to shadow. For instance, at the end of the observation phase, it can be that the shape of APOPHIS is such that only a part of its surface has to be shadowed but during a long period of time or vice versa.



Preliminary system design

The choice is naturally to use a dedicated transfer module (TM) for the cruise. This TM will carry the bundle of solar sails that will be unfolded one by one only when the final station keeping location over APOPHIS is reached.

The Transfer Module (TM)

As for the first part of the mission, Solar Electric Propulsion is envisaged for the Transfer Module.

When the APOPHIS area is reached, the sails are jettisoned one by one and deployed. The whole formation is controlled by the TM. In order to avoid any collision, the formation can be ordered in different layers (two or even more), each sail being given a flight level. The position restitution of each sail is performed by the TM which sends them individual thrust commands.

Individual Solar Sail

As a consequence of the important role of the TM, each individual sail can be quite simple. Their only function after being deployed is to cast their shadow on the asteroid surface. Doing this requires only a simple AOCS and limited power and communication systems.

Power is easy to provide since the sails are always facing the Sun at a distance that rarely exceeds one Astronomical Unit.

No direct link with the Earth is required. Only communications with the TM are needed. Distances are quite short, a few kilometres at most. Some sort of Wifi link can be used to exchange the command/control and position keeping data.

A very preliminary mass budget allocation can be:

Solar shield	40 kg
Bus, comms, power	20 kg
AOCS	40 kg
Fuel	100 kg

Such a sail would be able to deliver about 1500 m/s of total ΔV with a traditional chemical propulsion system and could then keep hovering APOPHIS during about three years.

Spare sails: Depending on the available launch resources, a few extra sails can be delivered to APOPHIS, in order to have some back up in case of a deployment failure (for instance). The spare sails that are still available at a given time of the mission can be located at the L1 or L2 Lagrangian points of the Sun-APOPHIS system. Given the low mass of the asteroid, these points are located only about 15 km from the asteroid. The sails that would be stored in these locations would have to be oriented perpendicularly to the Sun direction so as not to be perturbed by the solar photonic pressure. In such an orientation mode, they would not need any significant fuel for their station keeping while waiting to be eventually displaced in a hovering position.

Mass budget : considering the result of the mission analysis from the table 2, a single Soyouz Fregat launcher can deliver into orbit one TM (mass 400 kg) carrying four 200 kg solar sails.

For shadowing the full surface of APOPHIS with 12 sails, a total of 3 Soyouz launches is needed. Instead, a single ARIANE V or DELTA IV can do the job.

Reliability: The reliability requirement for the mission is very high. If there is a 100% probability that APOPHIS will hit the Earth while on its natural trajectory, then the deflection mission must have a very stringent reliability requirement, 1 in 1 million probability of failure to be coherent with the ‘background’ risk of Earth impact. To cope with possible failures at some critical stages of the mitigation mission (launch, cruise, sail deployment) it should be envisaged to double the amount of launched sails.

Technical readiness: The first part of the SHADOW mission does not present any particular technical difficulty. It is very similar to a mission like DAWN that is to be launched very soon.

The second part is more complex. The technical challenges are:

- deployment of large structures. At the difference of what is required for solar sails, the mass reduction is not so important for SHADOW as it does not impact on the final performance. This means that conservative solutions can be adopted where needed, priority being given to reliability. Demonstration of in-flight solar sail deployment needs to be done before undertaking this mission. Flights in Low Earth Orbit would be fully representative.

- autonomous formation flying: several Formation Flying are presently planned (PRISMA by Sweden, SIMBOL X by CNES and ASI, PROBA 3 by ESA). Extending formation flying technology from two objects to more than ten is maybe not a trivial question but it should be well mastered within a few years.

- relative positioning : there can be up to a few dozens of objects flying in a limited volume in a well defined location with respect to a passive body. A reliable strategy and an efficient measurement system have to be developed and flight proven.

6. YES COMPARED TO OTHER APPROACHES

When coming to the mitigation phase, should it be necessary, the YES method has some advantages with respect to the already identified strategies [10].

Two families of mitigation techniques have been proposed up until now: Impulsive techniques (conventional or nuclear explosive, kinetic impactor) or ‘slow push’ techniques (Yarkovsky Effect enhancement by changing the asteroid albedo, asteroid tug, gravity tractor, solar sail tractor...).

The first category can pose several problems from an ethical and political point of view since they can be suspected to be a pretext to send weapons into space.

The second category is certainly less spectacular but, provided it is planned sufficiently in advance, it is well suited for small displacements of impact region with respect to keyholes. When at least one of these methods is sufficiently well mastered, it can be envisioned to use it to deliberately send the incoming asteroid on a trajectory where it will definitely escape from any future approach or alternatively, will crash on the Moon.

The most promising and technically feasible of the 'smooth' techniques seems to be the Gravity Tractor (GT) [10]. R being the asteroid radius, the GT efficiency is varying with $1/R^5$ (*$1/R^3$ from the mass to radius ratio multiplied by $1/R^2$ gravitational attraction when considering that the GT has to hover at an altitude proportional to R*) while the YES efficiency is varying like 1/R (*ratio of the YE in R^2 to the acceleration in $1/R^3$*), so the GT becomes inefficient much faster than the YES method.

Neither of these techniques is excluding the other one. During the first phase of the mission, once all the needed information is acquired, the probe can be used as a GT as long as there is enough fuel available. This can perform part of the deflection task, the remaining needed deflection being supported by the YES phase 2. It can be desired to prevent the plasma plumes to impact the soil of the asteroid. This can be done without tilting the axis of the thrusters from the axial direction of the probe just by choosing a zigzag trajectory of the probe in front of or behind the asteroid, depending on the requested change of its orbital velocity. This sort of 'gravity scull' would only oblige a regular turn of the probe, once per hour as an order of magnitude, so that it remains close to the natural path of the asteroid.

The YES method is not the first one to be based on the idea of changing the YE to modify the orbit of an asteroid [11] but compared to the ones that have been proposed (paint it in black, in white, add dust to darken the surface…) cooling the asteroid by a flotilla of solar shields is certainly cheaper, faster and more reliable.

On the other hand, the YES method is not applicable to any asteroid: the YE has to be strong enough so that cancelling it makes a difference within an acceptable period of time. The fuel that is needed to compensate for the solar photonic pressure is a limitation to the method. In the case of APOPHIS, due to the high value of its orbit eccentricity (0.191), the YE is nearly two times higher near the perihelion than near the aphelion. Shadowing APOPHIS only in a part of the orbit but during several perihelion passes can be a good strategy. We can also think about deploying a mesh instead of a solar sail so that the photonic thrust would be reduced while the shadowing would be maintained at a sufficient level and would behave as a kind of space 'moucharaby'.

One other possible weakness of YES is that there can be situations where the displacement of the impact area with respect to the keyhole obliges to cross it first. The impact probability would then be increased before being cancelled. Should a failure happen at this critical moment, the situation would be serious.

7. CONCLUSIONS

The YE is the main unknown parameter for the extrapolation of NEAs orbit. Any effort to improve this knowledge is a necessary first step. Whatever effort is made from ground observations, it will never be able to provide the necessary information concerning any asteroid with the sufficient level of detail. It is needed to send remote sensing and positioning instruments close to the asteroid and let them collect data during a few months at least by hovering over the asteroid.

It is worth noting that similarly to DAWN which will soon visit VESTA then CERES, a single probe can be targeted on a sequence of NEAs. Collecting information even on asteroids that are no threatening the Earth will be very helpful to improve models, draw statistics about their physical features and calibrate ground based observations.

Such a space mission aimed at characterizing asteroids and especially the YE are not that expensive. They fall into the category of class M mission of ESA for instance, around 300 M€, which is also the order of magnitude of the DAWN mission.

Technological developments should be undertaken for the deployment of large surfaces in space. The shadowing requirements are very similar to solar sail requirements with respect to deployment and large surface control, so they could benefit both types of missions.

An internationally supported initiative [13] [14] where the best expertise would be collected worldwide will be a very efficient way to show humanity that space can not only improve the quality of life but also save million of lives with a single space mission.

REFERENCES

[1] IAU General Assembly – Resolution 5– Prague – 14-25 August, 2006
[2] Potential Impact Detection for Near-Earth Asteroids: The Case of 99942 Apophis Steven R. Chesley Asteroids, Comets, Meteors Proceedings IAU Symposium No. 229, 2005
[3] Delta-DOR A new technique for ESA's deep space navigation ESA Bulletin 128 November 2006
[4] Determining the Physical Properties of Nearr-Earth Objects D.P.Cruikshank et al.
[5] Numerical Evaluation of the General Yarkovsky Effect: Effects on Semimajor Axis J. Spitale ICARUS 149 (2001)
[6] Asteroid Hazard Mitigation using the Yarkovsky effect J. Spitale Science -5 April2002
[7] Direct Detection of the Yarkovsky Effect by Radar Ranging to Asteroid 6489 Golevka - Chesley Science 302 (2003)
[8] Threat Characterization: Trajectory Dynamics(White Paper 039) Russel Scweickart et al. B612 foundation
[9] Near-Earth Object Survey and Deflection Analysis of Alternatives NASA Report to Congress March 2007
[10] Comparison of the Efficiency of Various Hazard Mitigation Techniques Gabe Rogers, Noam R. Izenberg JHU/APL
[11] Threat Mitigation: The Gravity Tractor (White Paper 042) Russel Scweickart et al. B612 foundation
[12] NEA Hazard Mitigation using the Yarkovsky Effect – J.N. Spitale Lunar and Planetary Science XXXIII (2002)
[13] Deflecting NEAs: A Pending International Challenge Russel L. Schweickart, Association of Space Explorers-Presentation to the 44th COPUOS session
[14] Interim report of the action team on Near Earth Objects A/AC.105/C.1/L.290 44th COPUOS session Vienna 2007