AAS 12-227

THE SIROCO ASTEROID DEFLECTION DEMONSTRATOR

Claudio Bombardelli[*], Hodei Urrutxua[†], Andres Galvez[‡] and Ian Carnelli[§]

There is evidence of past Near-Earth-Objects (NEOs) impacts on Earth and several studies indicating that even relatively small objects are capable of causing large local damage, either directly or in combination with other phenomena, e.g. tsunamis. This paper describes a space mission concept to demonstrate some of the key technologies to rendezvous with an asteroid and accurately measure its trajectory during and after a deflection maneuver. The mission, called SIROCO, makes use of the recently proposed ion beam shepherd (IBS) concept where a stream of accelerated plasma ions is directed against the surface of a small NEO resulting in a net transmitted deflection force. We show that by carefully selecting the target NEO a measurable deflection can be obtained in a few weeks of continuous thrust with a small spacecraft and state of the art electric propulsion hardware.

INTRODUCTION

NEO impacts could be considered as the most severe of all possible natural disasters, though fortunately they are also rare ones. There is now overwhelming evidence that large impacts (of objects with dimensions in the order of kilometers) have had catastrophic consequences in the past.[1,2] While these impacts have been uncommon smaller objects are relatively more frequent and can cause significant damage when they hit the Earth at random intervals of hundreds or thousands of years. Many concepts of asteroid deflection missions have been proposed in the last years, and some are still actively investigated by space agencies such as ESA's Don Quijote mission.[3]

A new asteroid deflection concept is considered here to complement previous ones and complete the range of option under consideration by the community. The concept, proposed by the Technical University of Madrid[4,5] would be based on a single spacecraft using a high-specific impulse propulsion system aimed at the asteroid. In this way the plasma ions leaving the spacecraft at very high velocity would impinge on the surface of the NEA, transferring their momentum to the asteroid and changing its velocity. Over a long period of time and with sufficient propellant this effect would be large enough to change the period of the object in a measurable way and successfully deflect a sub-kilometer asteroid from a potential impact.

One interesting feature of this method is that it can be applied to very small NEOs, down to a few meters in diameter. Because these are easier to deflect and more abundant in our solar system, a relatively cheap deflection mission becomes possible. Low ΔV objects with good communication and visibility conditions from Earth are easy to find among the many small NEOs already detected so far. In addition, the position of the center of mass of a small object can be tracked with sufficient

[*]Research Fellow, Space Dynamics Group, Technical University of Madrid (UPM), Madrid, Spain
[†]PhD Student, Space Dynamics Group, Technical University of Madrid (UPM)
[‡]General Studies Programme, European Space Agency, Paris, France
[§]General Studies Programme, European Space Agency, Paris, France.

accuracy even with a hovering spacecraft and does not necessarily require an orbiter. This is because the uncertainty on the asteroid center of mass location will produce an error not exceeding a few times the diameter of the asteroid spherical envelope, as long as the spacecraft is equipped with a laser altimeter of reasonable accuracy and its position with relative to the asteroid surface is bounded. Another key advantage of working with very small asteroids is that they pose virtually no threat of impacting the Earth surface.

The first section of this paper describes the IBS technique and its application as an asteroid deflection concept. Next, key aspects and challenges of a deflection demonstration mission are discussed. In the third section we select a small NEA, with a diameter not exceeding a few tens of meters and favorable observing condition in the next 20 years. A small force of a few tens of mN is applied to the asteroid for a two months time and the resulting radial shift with respect to the unperturbed trajectory is computed with an accurate in-house orbital simulator and including all relevant perturbation forces. The effect of uncertainties due to initial orbit determination errors and unmodeled solar radiation pressure is taken into account and its implications in the measurement of a "deflection signal" are discussed. Finally we compute the required spacecraft mass resources needed in order to carry out the required deflection maneuver. Scientific opportunities compatible with the deflection mission are also proposed.

ASTEROID DEFLECTION WITH AN IBS

The ion beam shepherd concept (IBS) proposes a novel use of space electric propulsion in which the plasma accelerated by an ion thruster (or similar plasma propulsion device) is directed against the surface of a target object to exert a force (and a torque) upon the target from a distance of a few times its size. One of the most promising applications of the IBS concept is the deflection of Earth-threatening asteroids (Fig.1) as recently proposed.[4,5] In a typical asteroid deflection mission employing this technology a "shepherd spacecraft" rendezvous with the target asteroid sufficiently early in time before a predicted impact, and position itself at a safe hovering distance from the asteroid surface towards which one electric propulsion thruster is aimed. Ideally the shepherd should be placed as further away as possible from the surface (to avoid the unstable interaction with the asteroid gravitational field as well as reduce collision risks) but without exceeding a limit distance at which a considerable fraction of the thruster plasma plume misses the asteroid (due to plume divergence effects). As long as the ion beam emitted by the thruster(s) is correctly pointed at the target a deflection force arises from the variation of momentum of the plasma ions (typically xenon) impacting against the surface of the object and penetrating its outermost layers before being stopped. An essential element of the IBS is then the presence of a secondary propulsion system that compensates for the reaction force that the ion beam exerts on the shepherd and that would make it accelerate away from the asteroid.

This simple idea, in which the accelerated plasma is used to produce an action rather than a reaction, can be used to remotely maneuver objects in space without physical contact (docking) and has also been proposed for the active removal of space debris.[6] Similarly to space debris, asteroids can be problematic to dock to as they are typically in a spin state which, in addition to complicate a docking maneuver, constraints the direction of the thrust diminishing its effectiveness. Furthermore, many asteroids, even relatively small ones, are thought to be unconsolidated bodies (rubble piles) held together only by gravity and friction, which complicates the mechanical transmission of even a tiny deflection force.

As far as deflection performance the IBS has been compared to the gravity tractor concept (GT),

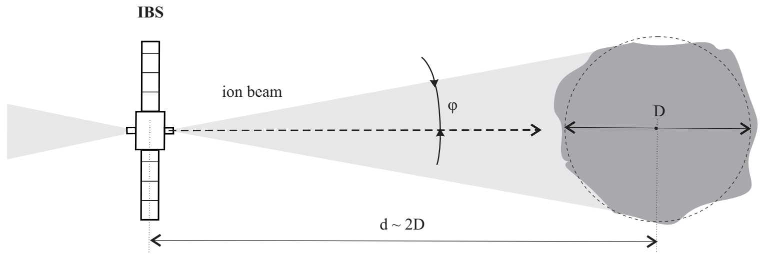

Figure 1. Asteroid ion beam shepherd concept (IBS)

a well known "contactless" deflection technique exploiting the spacecraft-asteroid gravitational interaction. It has been shown that, in the case of sub-kilometer asteroids, more than one order of magnitude decrease in required spacecraft wet mass at rendezvous can be obtained with an IBS of equal deflection capability.[4,5] IBS deflection simulations with real asteroids have also been carried out showing that an IBS of reasonable mass (<5 tons) could deflect a typical 140-m diameter Earth-approaching asteroid (e.g. $2009\mathrm{AG}_5$) by more than 2 Earth radii when the deflection maneuver is initiated ten years before the predicted impact.[5]

THE NEED FOR A DEMO MISSION AND ITS CHALLENGES

Any proposed asteroid deflection concept is of little use in a real threat scenario if it has not been at least partially demonstrated before. ESA's Don Quijote mission,[3] for instance, is aimed at demonstrating the deflection of a near Earth asteroid following the impact with a spacecraft made to collide with it at a relative speed of a few km/s.

In a way, one of the hardest part in designing an asteroid deflection demonstration mission, is to keep the mission budget and schedule to a reasonable demo-mission level. This is due to a number of intertwined factors which strongly depend on the type of deflection method employed and the choice of the target asteroid. Actually, a key factor contributing to the cost of a deflection mission is the *versatility* of the deflection method in dealing with different target asteroids, which is the main advantage of the IBS technique as it will become apparent in the following.

Because the very basic requirement of a deflection demonstration mission is to measure, with enough confidence, an artificially imparted deflection, one should first concentrate on two main objectives:

1) To maximize the *signal*, that is, the imparted deflection

2) To extract the signal from various sources of *noise* (e.g orbit uncertainties)

When looking at the maximization of the imparted deflection one immediately realizes the overwhelming influence of the asteroid size, as the deflection magnitude, for equal amount of deflection force or impulsively transmitted deflection momentum, is proportional to the cube of the asteroid diameter.

As far as the extraction of the deflection signal is concerned one has to consider the various measurement options available to estimate the deviation of a deflected asteroid from its unperturbed trajectory and understand their limitations. Direct ground-based tracking systems of the asteroid position must be employed before launch and during the cruise phase in order to facilitate the rendezvous (or impact) with the target. In addition, they can be useful before during and after the deflection takes place, in order to improve, when combined with spacecraft tracking, the estimation of the pre- and post-deflection asteroid trajectory. The effectiveness of these tracking systems depends on the asteroid absolute magnitude and its position relatively to the Earth and the Sun during the mission, which may strongly constrain the choice of the final target asteroid. Typically, higher accuracy orbital elements are available for larger asteroids.

When the spacecraft has come to a rendezvous with the asteroid very accurate tracking systems for the shepherd spacecraft position and velocity may be used to greatly improve the estimation of the asteroid orbit. The degree of improvement, however, depends on whether or not the spacecraft can be put on a sufficiently stable orbit around the celestial body with minimal use of thruster control. Typically, only relatively large asteroids can be orbited about in a reasonably stable manner while controlling a spacecraft in the vicinity of a small asteroid requires frequent thrusting maneuvers which spoil the measurements.

Nevertheless, when the asteroid is very small (a few meters in diameter) a reasonably good estimation of the asteroid orbit becomes possible as long as the spacecraft hovering distance from the asteroid surface can be kept within reasonable bounds. More precisely, the *position* of the asteroid center of mass is bounded by a sphere centered at the IBS spacecraft and with radius:

$$R = R_{ext} + d_{max} + \triangle d, \tag{1}$$

where R_{ext} is the radius of a spherical envelope containing the asteroid and centered at its barycenter, d_{max} is the maximum distance of the shepherd spacecraft from the asteroid surface throughout the pre- and post-deflection measurement phases of the mission and $\triangle d$ the uncertainty of the laser altimeter measurement (which strongly depends on the actual hovering distance). Because d_{max} is of the order of a few asteroid diameters it is reasonable to assume the maximum uncertainty in the asteroid center of mass position relative to the shepherd spacecraft to be less than a few tens of meters for a very small asteroid. In turn, the distance of the shepherd spacecraft with respect to Earth can be estimated with very high accuracy (cm level) with state of the art radiometric tracking techniques.

As far as the determination of the *velocity* of the asteroid center of mass it is more difficult to find a simple relation like (1) because the rate of distance between the asteroid center of mass and the laser altimeter footprint depends on the rotation state of the asteroid and its shape, which are in general unknown a priori. In the present analysis we will assume the relative velocity error between the asteroid center of mass and the shepherd is smaller than the asteroid surface escape velocity multiplied by a factor of ten. For a small 400-ton 7.2-m diameter asteroid as the one considered later this corresponds to about 4 cm/s. The velocity error of the shepherd relative to the Earth can be estimated to better than 1 mm/s with state of the art radar ranging techniques.

In the hypothesis that a measurable deflection of a chosen target asteroid can be achieved with a given deflection device there still remain the need to deliver the spacecraft to the right orbit in order to either impact or rendezvous with the target. Here the choice of the target becomes crucial as it is directly related to launch costs. The third main objective to be pursued in trying to reduce the total mission cost is therefore:

3) To minimize the total trajectory ΔV

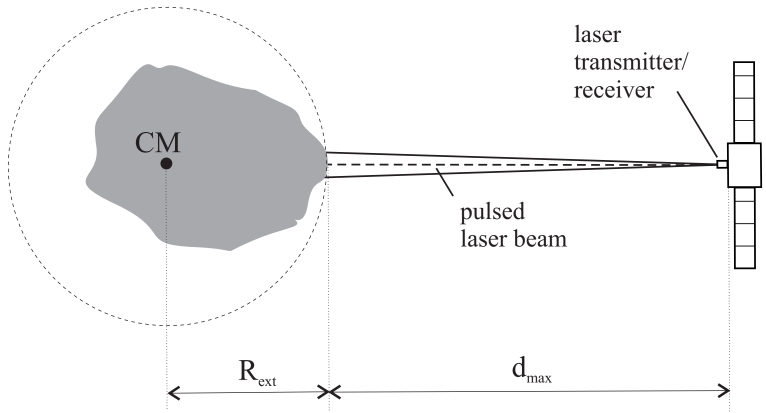

Figure 2. Laser altimeter metrology

To satisfy this last objective the choice of the asteroid orbit becomes paramount. In particular, when rendezvous missions are considered, the family of Earth-like orbits NEOs are the most easily accessible in terms of ΔV and, at the same time, are easily observable from the ground as they come in close proximity with the Earth every few years. One crucial aspect that must be realized when looking for lowΔV rendezvous orbits is their link with the asteroid size. The number of asteroids rises steeply with decreasing diameter with a size distribution roughly following a power law. As a consequence, even taking into account the current technology limitations in observing faint objects, the likelihood of finding a lowΔV object is higher the lower its diameter.

The conclusion from the above considerations is that smaller asteroids are strongly preferred for a demo mission, as long as their orbits can be estimated with sufficient accuracy and the chosen deflection method is compatible with the asteroid size. Both the gravity tractor and the kinetic impactor methods are not very suitable for small asteroids, which provide too weak a gravitational force for tractoring and are vary fragile when impacted at high relative velocity. On the other hand the IBS concept is completely insensitive to the asteroid size and is therefore ideal for deflecting small asteroids. Note, finally, that very small asteroids (say less than 15 m in diameter) are extremely unlikely to cause any damage when striking the Earth as they tend to be completely vaporized during atmospheric reentry.

DEFLECTING ASTEROID 2010UE_{51}

With a tentative launch date in the 2018-2022 window the small "Arjuna" asteroid* $2010\mathrm{UE}_{51}$ is a candidate target for the SIROCO mission for the following reasons:

- It is a small asteroid, with an expected diameter between 6 and 12 meters and a corresponding mass which is expected to be around 400 tons.
- It has, currently, quite an accurate orbit (compared to other objects of its family) thanks to a vary favorable observing geometry in the period from Nov 2010 to February 2011.
- It will be observable again starting from around July 2023, hence increasing its orbit accuracy before rendezvous.

*The Arjuna family includes low-eccentricity low-inclination asteroids with semimajor axis close to the Earth one. Often, radar observations have to be conducted to rule out technogenic objects.

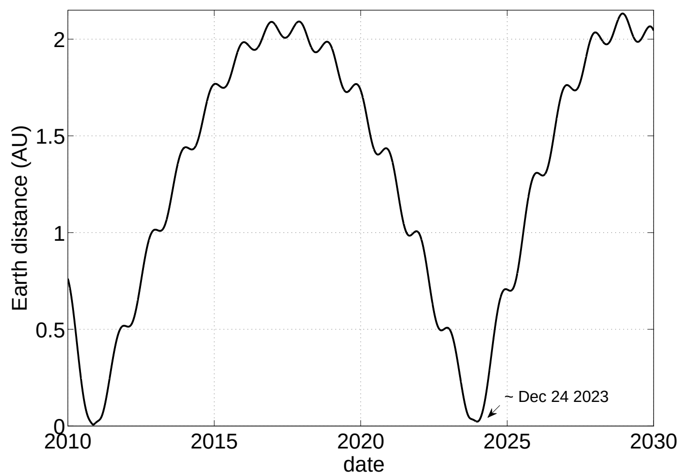

Figure 3. Earth distance of $2010\mathrm{UE}_{51}$

The main characteristics of the target asteroids are given in Table 1.

Table 1. Main characteristics of asteroid $2010\mathrm{UE}_{51}$

MJD	a(AU)	e	i(deg)	ω(deg)	Ω(deg)	M(deg)	H	d(m)	m(ton)
56000	1.0552	0.0597	0.6246	47.201	32.286	57.560	28.311	7.2*	400†

Figs. (3-4) show the relative distance with respect to Earth and the Sun-Earth-Asteroid angle (SEA) during 2 decades starting from 2010. Ideally, the SIROCO mission should be launched in an interplanetary trajectory before the asteroid enters opposition around mid 2023. When that happens a higher accuracy orbit becomes available for aiding the subsequent rendezvous phase. At that point the IBS spacecraft moves to a hovering position at a few meters from the asteroid surface when range and Doppler tracking data become available to further increase the accuracy of the asteroid orbit estimation. Once sufficient integration time is acquired and a sufficiently accurate initial orbit estimation is obtained the deflection maneuver begins.

As a numerical example we consider a constant thrust force of a few tens of mN applied for a time span of two months along the normal to the orbit. It can be easily verified that such solution, considering the present trajectory geometry and the relatively short push interval, is close to optimum (we have preferred using a constant thrust and constant direction magnitude to ease the reproducibility of our simulations).

The perturbed and unperturbed asteroid trajectory was propagated with a very accurate in-house model, which includes the gravitational perturbations of the Moon, all solar system planets and Pluto according to JPL DE405 ephemerides, as well as main relativistic effects and the solar J2 acceleration.

Fig 5 plots the relative trajectory in an Earth-centered synodic frame. A deflection maneuver is supposed to last from January 1st 2024 until March 1st.

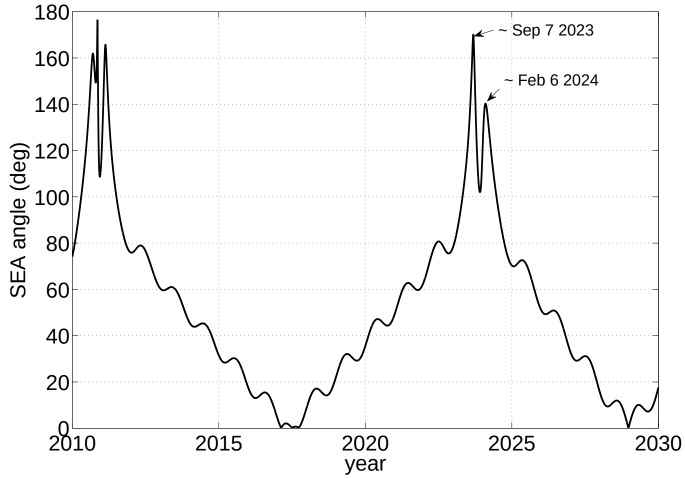

Figure 4. Sun-Earth-Asteroid angle of $2010\mathrm{UE}_{51}$

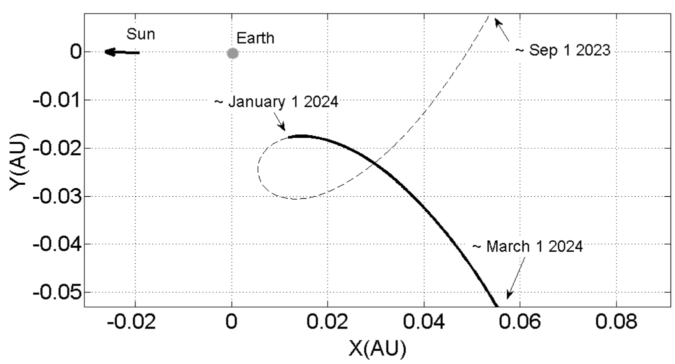

Figure 5. Asteroid $2010\mathrm{UE}_{51}$ trajectory in an Earth-centered synodic frame during the SIROCO rendezvous (dash curve) and deflection phase (solid curve)

Fig 5 shows the amount of deflection along the Earth line-of-sight during the thrust arc for various thrust magnitudes. The corresponding deviation caused by a velocity estimation error of 4 cm/s* of the asteroid trajectory at the beginning of the deflection campaign is added for comparison. The orientation of the estimated velocity error was taken as ~65 degree as this was seen to give rise to the highest radial position shift. Note that the influence of even a large (km-level) initial position estimation error would be negligible.

The other major source of uncertainty in the asteroid propagation comes from unmodeled non-gravitational perturbations, mainly solar radiation pressure (and to a lesser extent, thermal emission). A 7.2-m asteroid at about 1 AU is perturbed by a radial solar radiation force of less than 0.2

*This velocity estimation error was conservatively chosen as roughly 10 times the asteroid surface escape velocity. It is likely that a much smaller error can be achieved.

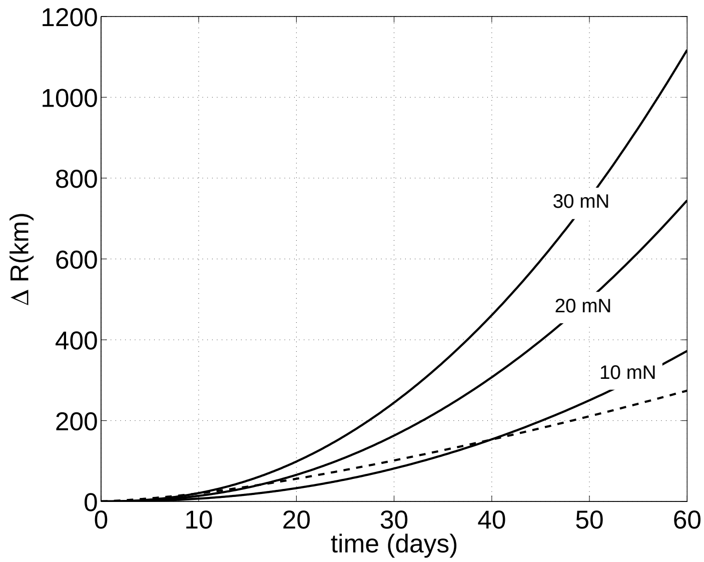

Figure 6. Earth distance variation of asteroid $2010\mathrm{UE}_{51}$subject to different level of constant thrust when compared to an unperturbed trajectory. The dash line represents the drift due to an initial orbit velocity estimation error of 4 cm/s in the orbit plane and rotated by +65 deg angle (around the orbit angular momentum direction) from the initial asteroid velocity (dash).

mN which has a negligible influence here. Non-isotropic thermal emission arising from a difference in temperature between the sun lit and shadowed asteroid surface would give rise, even in extreme conditions, to an additional but comparatively negligible force.

MASS ESTIMATE

A preliminary estimate of the minimum spacecraft mass at rendezvous required for the deflection obeys:

$$m_{tot} = 2\left[\frac{F\Delta t}{I_{sp}g} + \frac{\alpha F I_{sp} g}{2\eta}\right] + m_{pay} + m_{str}$$

where I_{sp} is the (constant) thruster specific impulse, g is the see-level gravity, η the thruster efficiency, α the (constant) inverse specific power, m_{pay} is the mass of a possible scientific payload and m_{str} the spacecraft structural mass (including mainly fuel tanks, thermal control units, aluminum spacecraft structure, ion thruster mass, communication and attitude control). The factor 2 reflects the assumption that the same propulsion system is employed for the primary and secondary thruster.

Taking as preliminary values $\alpha = 15\,\mathrm{kg/kW}$, $I_{sp} = 3400\,\mathrm{s}$ and $\eta = 64\%$ corresponding to a RIT-10 ion thruster[7] developed by Giessen University and successfully flown on the Artemis mission in 2002, one soon realizes the power and propellant mass employed in a typical 60-day deflection with 10 to 30 mN continuous thrust is only about a few tens of kilograms. An extensive analysis, including low thrust interplanetary trajectory optimization, will be required to come to a first estimate of the required mass at launch. Such analysis will be carried out in a following paper.

SIROCO SCIENTIFIC OPPORTUNITIES

An interesting scientific experiment, which may be easily accommodated within the SIROCO mission, was proposed by Lorenz in the early 90s.[8] The idea was to point an ion thruster towards the surface of an asteroid and collect and analyze the surface asteroid material that is sputtered back (at a few tens of eV energy) following the penetration of the impinging ions. This would result in a relatively simple, and quite ingenious, secondary ion mass spectroscopy experiment (SIMS) similar to the one proposed by Sagdeev et al. in 1984,[9].[10] Thanks to the relatively low current density of the ion beam footprint on the asteroid surface it is theoretically possible to obtain undamaged organic molecular compounds (when present) among the backsputtered material following a process known as *static* SIMS. Very small asteroids are very likely *regolith-free* objects, a class of celestial bodies never visited by a space mission.

Note that argon or krypton propellant, instead of xenon, would be recommended if attempts are to be made to determine xenon isotope abundance in the celestial body (xenon´s nine isotopes have been found in anomalous ratios in meteorite samples).[8]

CONCLUSIONS AND RECOMMENDATIONS

A possible slow-push asteroid deflection demonstration mission employing the ion beam shepherd technique has been investigated. The choice of a small-size "Arjuna" asteroid with a sufficiently accurate orbit and proper phasing conditions for Earth based observations during the mission is seen to be paramount in order to achieve the mission goals within the budget and schedule constraints of a small demo mission. The required deflection magnitude and duration is mainly driven by the uncertainty of the asteroid velocity at the beginning of the deflection phase. Assuming a velocity error not exceeding 4 cm/s a measurable deflection can be detected with a 20-30 mN thrust applied continuously for about 2 months.

Future studies will be needed to address the feasibility of performing a rendezvous maneuver with a small asteroid given the available orbit accuracy, as well as analyze the $\triangle$V cost of an optimized low-thrust interplanetary trajectory meeting the mentioned phasing requirements. The capability of improving the velocity estimation of a small asteroid with a hovering spacecraft will also need to be further analyzed.

ACKNOWLEDGMENTS

The study has been supported by the research project "Dynamic Simulation of Complex Space Systems" supported by the (former) Dirección General de Investigación of the Spanish Ministry of Innovation and Science through contract AYA2010- 18796. The authors are grateful to Dr. Ralph Lorenz from JHU Applied Physics Laboratory for providing a copy of his article.[8]

REFERENCES

[1] L. Alvarez, W. Alvarez, F. Asaro, and H. Michel, "Extraterrestrial cause for the Cretaceous-Tertiary extinction," *Science*, Vol. 208, No. 4448, 1980, p. 1095.

[2] C. R. Chapman and D. Morrison, "Impacts on the earth by asteroids and comets: assessing the hazard," *Nature*, Vol. 367, No. 6458, 1994, pp. 33–40.

[3] A. Gálvez and I. Carnelli, "ESA Studies on the Don Quijote NEO mission: dealing with impact uncertainties," Paper IAC-05-Q.P.21, 56th International Astronautical Congress, Fukuoka, Japan, October 2005.

[4] C. Bombardelli and J. Peláez, "Ion Beam Shepherd for Asteroid Deflection," *Journal of Guidance, Control, and Dynamics*, Vol. 34, No. 4, 2011, pp. 1270–1272.

[5] C. Bombardelli, J. Pelaez, E. Ahedo, H. Urrutxua, and M. Merino, "The Ion Beam Shepherd: a New Concept for Asteroid Deflection," *2011 IAA Planetary Defense Conference, 9-12 May 2011, Bucharest, Romania*.

[6] C. Bombardelli and J. Pelaez, "Ion Beam Shepherd for Contactless Space Debris Removal," *Journal of Guidance Control and Dynamics*, Vol. 34, No. 3, 2011.

[7] R. Frisbee, "Advanced space propulsion for the 21st century," *Journal of propulsion and power*, Vol. 19, No. 6, 2003, pp. 1129–1154.

[8] R. D. Lorenz, "Remote Asteroid Surface Analysis using Exhaust from an Ion Thruster," *41st Congress of the International Astronautical Federation, 6-12 October 1990, Dresden, GDR*.

[9] R. Sagdeev, G. Managadze, I. Shutyaev, K. Szego, and P. Timofeev, "Methods of remote surface chemical analysis for asteroid missions," *CRIP H-1525, Budapest 114 POB 49 Hungary, KFKI-1984-82*.

[10] G. Managadze and R. Sagdeev, "Chemical composition of small bodies of the solar system determined from the effects of solar-wind interaction with their surfaces," *Icarus*, Vol. 73, No. 2, 1988, pp. 294–302.