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EFFECTIVE APPROACH NAVIGATION PRIOR TO SMALL BODY DEFLECTION

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The largest threat for asteroids impacts on Earth is currently posed by small bodies of diameter less than 40 m. Even though incapable of causing a global catastrophe, they can still potentially cause significant local and regional damage. One of the main challenges for deflecting asteroids in this size range is the precise orbit determination and approach navigation prior to implementing any deviation mechanism. This paper addresses this particular problem and presents an approach strategy that was proposed for the contactless deflection technology demonstrator SysNova challenge of ESA.

I. INTRODUCTION

After the recent events of a bright meteor being spotted and causing minor damage in Chelyabinsk, there has been considerable public attention to the possibility of an undetected impact of a small asteroid or comet. When considering the threat of an asteroid impact against the Earth in the near future, the current impact risk is largely posed by the population of small undiscovered objects,[1] and thus various methods have recently been discussed to provide subtle orbital changes to these small objects, as opposed to large-scale interventions, e.g., the use of nuclear devices.[2] Many of this latter batch of deflection methods, such as low thrust tugboat,[3] or gravity tractor[4] have in common a slow final approach phase, when compared to the use of more “traditional” methods such as a kinetic impactor.[5] They all involve a long duration operational phase in the close proximity area of the asteroid, be it orbiting, hovering or consisting of a (relatively) soft landing.

This final approach phase faces the difficulty of detecting such small objects, given the uncertainty in their orbits and their faintness.

The SysNova Challenge

ESA’s General Studies Program started at the end of 2012 the SysNova initiative: a series of technological challenges for academia, research institutions and industry teams aimed at developing new technologies in the space field. Bearing the NEO threat in mind, one of the challenges consisted on a “Contactless asteroid orbit modification system” with the objective of presenting a technology demonstrator mission proposal for contactless deflection of a small body. The main specifications of the challenge was to impart at least 1 m/s ΔV over the course of three years to a small asteroid of size 2-4 meters diameter (or 130 tons of mass referring to the average density of a silicate asteroid). Further constraints limited the target asteroid’s orbital elements to have a perihelion (r_p) larger than 0.7 AU, an aphelion (r_a) smaller than 1.4 AU and an inclination smaller than 5 degrees. Fictitious asteroids were allowed to be considered but teams were encouraged to actually present a solid mission concept with an existing real asteroid in a 25 year timeframe.

A consortium led by the University of Strathclyde, which included the University of Southampton, Astrium Stevenage and GMV-Skysoft, carried out a detailed study proposing a laser ablation demonstrator to deflect the target asteroid: Light-Touch[2].

Based on Strathclyde’s expertise in the field,[6, 7] the solution presented in January 2013 consisted of a small class spacecraft, called AdAM (Asteroid Ablation Mission), which will fly in formation with the asteroid and apply laser ablation. The Light-Touch[2] concept study showed that laser ablation is an efficient technology for such a mission, and that the target 1 m/s of variation of velocity can be achieved in less than one year of push time even with a relatively low power laser.

However, one of the main challenges that the team faced was due to the difficulty of detecting, characterizing and determining the orbits of small objects of the targeted size both from Earth and from the spacecraft itself. The small size of the asteroid and the fact that its ephemerides are not known with great accuracy required the definition of an advanced navigation strategy to discover, detect, approach and rendez-vous with the asteroid, while simultaneously improving the knowledge of its ephemerides. Advanced GNC techniques were devised to control the spacecraft in the proximity of the asteroid during ablation and to measure the achieved deflection and modification of the rotational state of the asteroid.

This paper presents the detection challenge for small asteroid impact threat and the proposed final approach and navigation novel strategy to circumvent this problem. For a more detailed description of the AdAM mission proposal, please refer to the final report.[8]

One of the main advantages of the strategy presented is that it is independent of the deflection method to be implemented (as long as it requires an operational phase in close proximity to the asteroid and not a kinetic impact) and even of the type of mission. It could be applied for exploration, sample return, or even capture or resource exploitation missions. It is also not limited to small objects (or equivalently dim larger but fainter/darker objects, or asteroids farther from Earth), and it can be extended to medium size asteroids with poorly determined orbits.

II. TARGET SELECTION AND THE CHALLENGE OF DETECTION

As of 20th August of 2012, 9016 NEOs were known. The smallest object among the surveyed asteroids is estimated to be of only a few meters diameter, while the largest is of 32 km diameter (i.e., Ganymed). The surveyed portion of the NEO population is only a small fraction of the total existing population, especially at very small sizes, on the order of a few meters diameter, for which the surveyed fraction is well below 1%. [9]

For the vast majority of known asteroids only the orbital data and the absolute magnitude H (i.e., intrinsic brightness) of the object are available, and in most cases with large associated uncertainties. Given the absolute magnitude, a simple formula provides a first insight into the asteroid size:

$$D = \frac{1}{\sqrt{p_v}} \cdot 1329[\text{km}] \times 10^{-H/5} \qquad [1]$$

where p_v is the asteroid's albedo, which can be assumed to be 0.154 as the average value for the standard near Earth asteroid.[10] However, this rough estimate can easily be inaccurate by an order of magnitude, and light curve analysis, radar campaigns or spacecraft encounter data would always be more reliable, but they are rarely available.

At the time of the challenge, 189 NEOs were known in the required range of orbital elements according to JPL Small Body Database Browser, ten of which fall within the range of sizes of the SysNova challenge, assuming the above albedo to calculate the equivalent spherical diameter for their magnitude. Table 1 shows the orbital elements, absolute magnitude and estimated size of these objects. None of these objects are Potentially Hazardous Asteroids because of their size; however they all have small Minimum Orbit Intersection Distance (MOID). If we assume brighter bodies, the number of NEOs in that region under 5 meters increases to 13 for an albedo of 0.25, and to 40 NEOs for very bright objects of albedo 0.50 (intended for icy objects).

Considering the latest near Earth object population estimates, i.e., NEOWISE,[11] close to 20 thousand million NEAs with diameter ranging from 2 to 4 meters diameter should exist. From these, close to 1 million should also have orbital elements within the specified operational orbit constraints: r_p>0.7 AU, r_a<1.4 AU and inclination <5 degrees. Since only 10 were known at the time of the challenge, from which 6 were discovered over the course of the past year, this represents an enormous potential for discovery of new target candidates for the contactless asteroid orbit modification challenge. Moreover, a consequence of the goal to catalogue 90% of all the 140 meters near Earth objects by 2020*, and the effort by the new generation of all-sky surveys such as Pan-STARRS and LSST to fulfil this, is that an enormous increase of the population of small objects should be expected for the next years.[9]

The Minor Planet Centre defines an Uncertainty parameter (U) or Orbit Condition Code (OCC) which gives an indication of the uncertainty in a perturbed orbital solution for a minor planet. It is expressed as an integer between 0 and 9 indicating how well an object's orbit is known on a logarithmic scale, with 0 indicating an extremely low uncertainty, and 9 a very high one. Objects with OCC larger than 5 can be considered effectively "lost" for the purpose of a rendez-vous mission, unless new radar or optical observations become available, as the uncertainty on the position would increase largely with time.

DESIGNATION	*H*	*q* [AU]	*Q* [AU]	*i* [deg]
2012 AQ	30.698	0.9598	1.1821	2.856
2011 CA7	30.319	0.7686	1.3930	0.121
2012 FS35	30.286	0.9686	1.2290	2.338
2008 WO2	29.779	0.8323	1.2182	2.010
2011 JV10	29.706	0.9095	1.3701	1.404
2011 AM37	29.690	0.9385	1.2626	2.629
2008 JL24	29.572	0.9276	1.1489	0.550
2006 RH120	29.527	1.0080	1.0585	0.595
2008 UA202	29.440	0.9624	1.1042	0.264
2012 EP10	29.165	0.9285	1.1721	1.033

Table 1: Possible candidates for contactless deflection

Considering valid OCC below 4, only two small bodies from the previous list can be shortlisted as the most suitable targets for a deflection demonstrator: 2008 JL24 (OCC=3) and 2006 RH120 (OCC=1). Table 2 summarizes both known orbital and physical data on objects 2008 JL24 and 2006 RH120. These objects will both undergo a very close approach to Earth in the coming decades: asteroid 2008 JL24´s closest approach occurs during 5th March 2026 with a minimum distance to Earth of only 0.061 AU; while asteroid

* National Aeronautics and Space Administration Authorization Act of 2005 (Public Law 109-155), January 4, 2005, Section 321, George E. Brown, Jr. Near-Earth Object Survey Act.

2006 RH120's closest approach occurs during 9th October 2028 with a minimum distance of 0.027 AU. Both objects can be assumed to be 4 m diameter asteroids with a mass of 130 tons. Given this mass and size the estimated average density is 3879.4 kg/m^3 for both objects, a bit higher than S-class asteroids and lower that M-class asteroids. Table 3 reports the typical estimated density of S-class, C-class and M-class asteroids and their albedos along with the density and estimated albedos of the selected targets.

2008JL24†

Orbital Elements at Epoch 2456200.5 (2012-Sep-30.0) TDB Reference: JPL 10 (heliocentric ecliptic J2000)			
Element	Value	Uncertainty (1-sigma)	Units
e	.106559869181477	7.2705e-06	
a	1.03826844970543	2.8956e-06	AU
q	.9276306995295643	5.0396e-06	AU
i	.5501064109470443	4.6053e-05	deg
node	225.822449694026	0.00026854	deg
peri	281.9655686889383	0.00038643	deg
M	124.186109529154	0.0073006	deg
t_p	2456067.198991958747 (2012-May-19.69899196)	0.0072788	JED
period	386.4229508179025 1.06	0.0016165 4.426e-06	d yr
n	.9316216835413743	3.8973e-06	deg/d
Q	1.148906199881296	3.2042e-06	AU

Absolute Magnitude: 29.572

Rotation Frequency~18.6 rev/h

2006RH120‡

Orbital Elements at Epoch 2456200.5 (2012-Sep-30.0) TDB Reference: JPL 45 (heliocentric ecliptic J2000)			
Element	Value	Uncertainty (1-sigma)	Units
e	.02447403062284801	4.2401e-05	
a	1.033252056035198	1.0251	AU
q	1.007964213574672	1	AU
i	.5952660003048117	9.4379e-05	deg
node	51.14334927580387	3.8304e-05	deg
peri	10.14353817485877	0.092984	deg
M	221.2498016727181	206.48	deg
t_p	2456348.356001016605 (2013-Feb-24.85600102)	1	JED
period	383.6258328667335 1.05	570.89 1.563	d yr
n	.9384143854377558	1.3965	deg/d
Q	1.058539898495724	1.0502	AU

Absolute Magnitude: 29.527 ± 1.2

Rotation Frequency~ 21.8 rev/h

Table 2: Orbital elements and physical characteristics of 2008 JL24 and 2006 RH120

Even with their low OCC, the ephemerides of both objects are relatively uncertain and a rendezvous may pose a serious challenge. Indeed, if the asteroids are visible from Earth before the rendezvous, the ephemerides of these objects may be updated and the uncertainty significantly reduced. If radar observations can be scheduled before the encounter, some physical characteristics may be extrapolated such as its shape. Unfortunately, as shown in Table 4, no radar observations will be possible in the coming two decades and only 2006 RH120 will be visible from Earth during June 2028.

A more detailed account of the visual magnitude of the objects as seen from the Earth and the spacecraft during a possible rendezvous trajectory is shown in Figure 1. The SC trajectory assumed is one of the possible transfers for each asteroid calculated during the course of the study. It can be seen, for example, that asteroid 2008 JL24 approaches the Earth twice during 2026. The best transfer opportunity for 2008 JL24 requires departing from the asteroid just before the second close approach, and as the spacecraft approaches the asteroid the visual magnitude of the asteroid as seen from the spacecraft (red line) decreases very quickly. 2008 JL24 reaches only a minimum magnitude around 25 as seen from Earth, slightly above 24, which is the minimum required to be detected by Earth based surveys with current assets (horizontal blue dashed line). Assuming a narrow angle camera with a standard limiting magnitude of 13-14 (horizontal yellow dashed line) the spacecraft would be capable to see the asteroid only during the last few days before rendezvous. On the other hand, 2006 RH120 appears to be a more advantageous target since both the asteroid and the spacecraft can be seen from Earth during the approach.

	ρ (kg/m^3)	p_v
C-class	1,300	0.06
S-class	2,700	0.18
2008JL24	**3,879.4**	**0.1637**
2006RH120	**3,879.4**	**0.1707**
M-class	5,300	0.12
Standard NEA	2,600	0.154

Table 3: Density and albedo of 2008 JL24 and 2006RH120. The values are also compared with typical asteroid data as in Chesley et al. [10].

DESIGNATION	2008 JL24	2006 RH120
H [mag]	29.6	29.5
Estimated Diameter [m]	2.1-9.5	2.2-10
OCC	3	1
Next Optical Opportunity [yyyy-mm (visual mag.)]	none	2028-06 (23.9)
Next Arecibo Radar Opportunity [yyyy-mm]	none	none
Next Arecibo Radar Opportunity [yyyy-mm]	none	none

Table 4: NEO properties and next observation opportunities according to NHATS§

† http://ssd.jpl.nasa.gov/sbdb.cgi?sstr=2008%20JL24

‡ http://ssd.jpl.nasa.gov/sbdb.cgi?sstr=2006%20RH120

§ http://neo.jpl.nasa.gov/nhats/

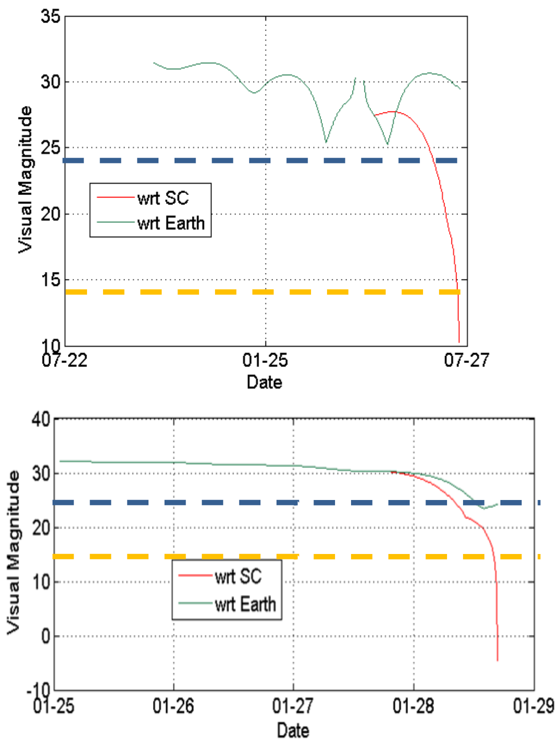

Figure 1: Visual magnitude of 2008 JL24 (top) and 2006 RH120 (bottom) from Earth and from a SC on a preliminary transfer trajectory

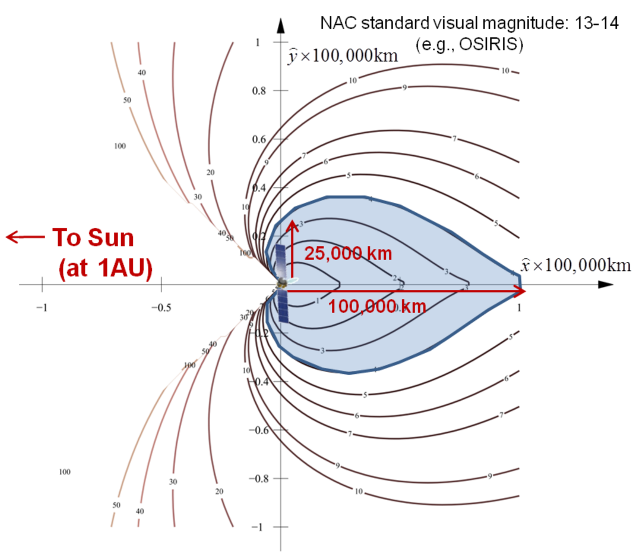

Figure 2: Observability diagram of a faint object from a vantage point at 1 AU

Finally, Figure 2 shows the region around the spacecraft where an asteroid of 4 meters diameter will be visible by a standard narrow angle camera at 1 AU distance from the Sun (approximately that of the spacecraft during the transfer for these two particular asteroids). In the figure the spacecraft is in the origin of coordinates, the Sun direction is towards the negative x-axis, and the blue curve encloses the region where an asteroid 4 meters in diameter would be seen from the spacecraft. The area where the asteroid can be seen lies mostly away from the Sun as the Sun is illuminating the asteroid. It can be thus understood that not only will the asteroid be visible during the last days of approach, when at very close distances, but also the approach needs to ensure a certain geometrical configuration with respect to the Sun and the asteroid.

II.I. Orbit Determination Quality

Despite the fact that the Orbit Condition Code of 2008 JL24 and 2006 RH120 is initially considered acceptable for both objects, a preliminary GNC analysis shows that the error in position for objects 2008 JL24 is too large for a feasible rendezvous. This is due to the combination of the level of uncertainty on the object ephemeris and the timespan since the last observation campaign. The last observation of the object occurred during 2008, and no future observation campaigns will be possible until the rendezvous of the spacecraft with the asteroid in 2027. As shown then in Figure 3, this represents a build-up of uncertainty in position due to runoff drift that is equivalent to a 3-sigma error in position of about 250,000 km from the centre of the ellipsoid of uncertainty. As indicated by Figure 2, detection of the asteroid by the spacecraft may then not be straightforward and the risk of completely missing the asteroid may as a consequence become very high. This however could be avoided, if by the launch time, Earth based telescope technology has improved sufficiently to allow detection of objects with visual magnitude between 25 and 26, or if spacecraft narrow cameras have also increased significantly their limiting visual magnitude. The knowledge of the ephemeris of 2006 RH120 is however much more accurate, which allows a reliable rendezvous even without further observation campaigns. Moreover, 2006 RH120 will be visible from Earth during the approach of the spacecraft to the asteroid, strengthening then the case for this target as baseline choice.

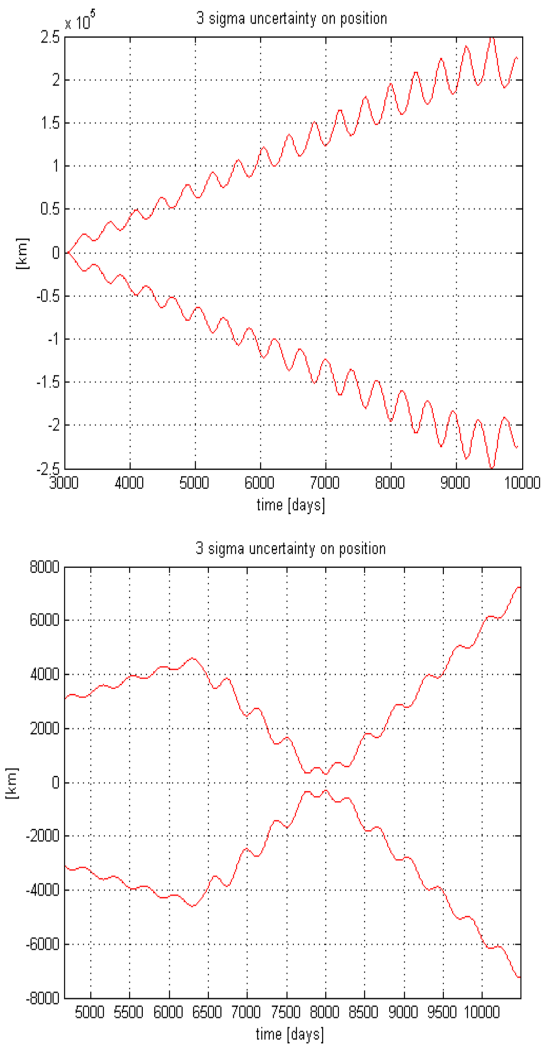

Figure 3: Uncertainty in asteroid position for 2008 JL24 (top) and 2006 RH120 (bottom) as a function of time with the date of arrival at 10479 MJD2000.

III. GNC STRATEGY AND ANALYSES

The GNC design for the LightTouch^2 mission should derive naturally from previous experience in flown and conceptual missions to small bodies (NEAR, Dawn, Rosetta). Particularly relevant, given the small size of the asteroid, and the type of operations involved are JAXA's Hayabusa mission[12] and ESA's Don Quijote / Marco Polo concepts[13].

For such missions, which rely heavily on optical navigation, the combined analysis and design of the approach and operational strategy with the GNC system (algorithms, hardware) is critical. This section places focus on the GNC strategy, particularly emphasis being given to the phases between detection of the asteroid to transition to close operational state. The GNC Strategy and Operational Timeline are presented in section III.I.

The operational phase, where ablation of the asteroid is performed for up to 2 years, from a 50 m distance, with fully autonomous GNC, in purposely left out of this paper, as it has additional particularities exclusive to the type of mission and the type of deflection selected. During this phase the problem is quite different as the spacecraft is subject to the small but not negligible plume and the asteroid is constantly changing its state of motion. Even though the forces to be counteracted are small, they are always present. The issue of the life-time of GNC components becomes relevant as the number of RCS actuations rises to the tenths of thousands, the same order of magnitude of their operational limits.

Part of the GNC analysis follows the guidelines for a GNC design for small NEO missions identified by Gil-Fernandez et al.[14] Typically design and analysis is divided into a Far Approach phase with poor Line-of-Sight (LOS)-only observability and large, usually ground-commanded manoeuvres, a Close Approach phase with the asteroid resolved in the FOV of the VBS, and either a descent or orbital operational phase.

In the LightTouch^2 concept, some critical points have very important differences with respect to the typical NEO-encounter mission, while at the same time putting it closer to the challenges faced in Rendez-Vous / Formation Flying missions to non-collaborative targets (like orbital debris). Examples of GNC designs for relative motion are ATV, Prisma[15] and Proba-3[16] where the Relative Motion Formation Flying and Rendez-Vous GNC, particularly the VBS-only relative navigation experiments, developed by GMV, are extremely relevant and applicable to LightTouch^2; as well as Mars Sample Return studies[17].

The main challenges from LightTouch^2 in terms of GNC design when compared to typical NEO missions are:

- **Small Gravity.** The gravity field of the asteroid, for approach and rendez-vous operations is almost *negligible* in our case. With regard to GNC, it can be considered a small perturbation in the dynamics with respect to the 40 μN Solar Radiation Pressure (SRP).
- **Low Visual Magnitude.** The absolute visual magnitude of Hayabusa's Itokawa is 19.2. The 160-m-wide 2002AT4, 21-absolute magnitude target of Don Quijote could be detected from a distance 2500000 km. 2006 RH120 worst-case magnitude (3σ) is 31. The Narrow Angle Camera (NAC) from Rosetta would only detect it at 40 000 km from the most favourable illumination angle. Additionally, its ephemeris knowledge is of the same order of magnitude as this distance of detectability. To cover the uncertainty region (3σ) in position of

5000 km from the detectability distance, scanning manoeuvres need to be performed, with implications in the early encounter trajectory.

Because many of these challenges are very familiar to those of Formation Flying / Rendez-Vous / Orbital Debris Removal missions, the following section addresses them taking on the expertise from GMV's NEO studies (CHILON, Don Quijote, Marco Polo[14]) as well as Formation Flying (MSR, Proba-3 [16]).

III.I. GNC Strategy and Mission Timeline

With reference to Figure 4 and Figure 5, which report the mission profile with respect to the Earth and the Sun from launch till well into the operational phase, the mission will be conceptually divided in seven phases characterized by different operational modes. The results and discussions are focused on phases 4 to 7.

The mission phases are:

1. **Launch** (GTO and escape)
2. **Commissioning**: Immediately after separation, the spacecraft will autonomously de-tumble, deploy its solar arrays and acquire a coarse three-axis stabilised Sun-pointing attitude. After launch, a tracking campaign will be performed in order to verify the interplanetary transfer trajectory and, if required, implement correction manoeuvre TMC-1, 7 days after departure, to correct injection errors. Before putting the spacecraft into hibernation mode, all its functions will be checked and the payload will be commissioned.
3. **Earth to Asteroid Cruise/Interplanetary**: During the cruising phase the spacecraft will be in hibernation mode and no ground support will be required. The spacecraft will be resumed for 2 weeks to allow the spacecraft to perform the single DSM, 79 days before arrival. After the DSM, a tracking campaign determines the spacecraft's orbit. TCM-2, 7 days after DSM is possibly performed. The transfer lasts for 296 days, and the spacecraft arrives at the asteroid approximately 90 days before its perihelion.
4. **Matching/Early Encounter/Arrival phase**: described in detail in Section III.II.
5. **Far-Approach (11 days):** described in detail in Section III.III.
6. **Close-approach (11 days):** described in detail in Section III.IV.
7. **Transition to the Close operative phase (26 days)** described in detail in Section III.V.
8. **Operational Phase.** Start of the deflection by ablation process

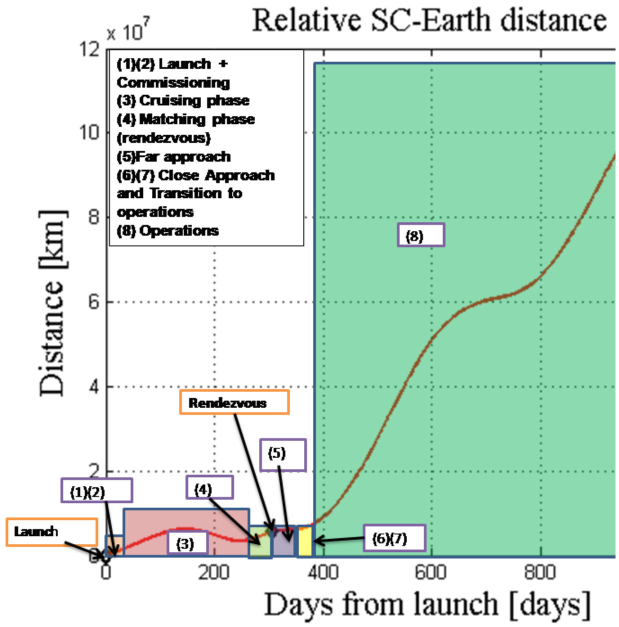

Figure 4: Mission phases with respect to the Earth distance

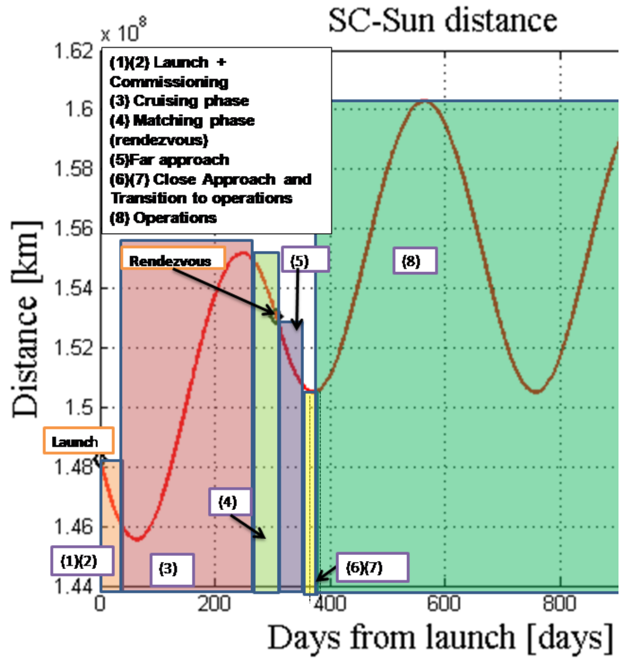

Figure 5: Mission phases with respect to the Sun distance

III.II. Early Encounter

The relative visual magnitude of a celestial object depends on its phase angle (optics-target-Sun), distance to Sun and distance from camera to target. Figure 6 shows the area from where a camera of 13.5 can detect an asteroid of a certain absolute magnitude. Highlighted in blue is the area in space from where a target with an absolute magnitude of 31 can be detected. The Early Encounter trajectory, overlapped with the plot, arrives at the phase angle of 0º at 30 000 km, being able, at this point to detect the worst-case-faint asteroid. The whole trajectory lies in the area of detection of the nominal magnitude asteroid. After entering the worst case 3σ area of the asteroid, in remains within it because as the phase angle becomes closer to 90º, the range decreases.

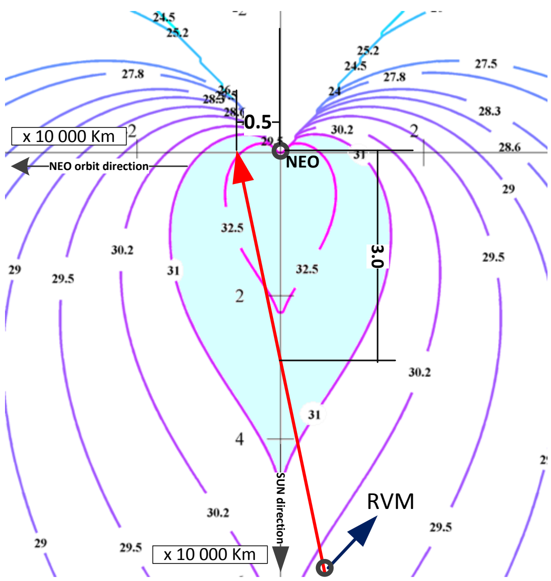

Figure 6: Detectable Area

Detection shall be attempted from the start of the Early Encounter phase, and is assured, at most, at its middle point, at 30 000 km, 0 degree phase angle to the NEO. From this point onwards TCM can be programmed to take into account the improvement on relative precision due to optical LOS navigation.

In order to minimize or exclude a scanning manoeuvre, detection shall be performed as soon as possible, as illustrated in Figure 7.

At 60 000 km of distance to the asteroid, where the Rendez-Vous Manoeuvre RVM is programmed, and where asteroid can be nominally detected, the NAC's FOV of 2.95 deg covers an area of 3000 km. To cover the 3σ, or 5000 km of ephemeris uncertainty of the asteroid, a small scanning manoeuvre (4 pictures) would be necessary.

At 30 000 km of distance, where detection of even the faintest (3σ) asteroid is possible, the NAC's FOV covers an area of 1540 km , about the 1σ value of ephemeris uncertainty. In the combined worst case for ephemeris uncertainty and faint asteroid, the scanning manoeuvre would have to cover a 9.5 deg FOV (50 pictures would be necessary).

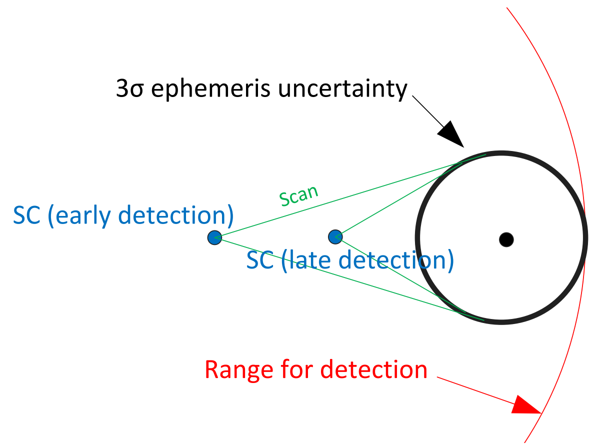

Figure 7: Angular search area depending on detecting distance

After all considerations the resulting trajectory is shown in Figure 8.The Radiometric-based RVM aims at a point in the perpendicular plane to the sun direction, 5000 km (the initial ephemeris uncertainty) distance from the asteroid in its orbital direction. The Early Encounter lasts for 2 weeks. During the scanning phase, batches of 10 long-exposure (2.5 sec) images per hour are collected every 10 hours. After target acquisition has been confirmed (which should occur right after RVM but at most occurs after 7 days), 1 image per hour is collected. Two TCM are programmed:

- EE-TCM-1: performed 10 days after RVM. At this point LOS measurements to the asteroid have been obtained from an angle amplitude of 25 deg. (nominally, worst-case is 15 deg). The nominal distance is 17 000 km, and the relative position accuracy has been improved to <500 km.
- EE-TCM-2: 12 days after RVM, LOS measurements have been taken from an amplitude of angles of 40 degrees (nominally, worst-case is 30 degrees). The nominal distance is 8 600 km and the relative position accuracy has been improved to <200 km 3σ (4% of the initial). Illustrative example in Figure 9

The Far Approach Preparation Manoeuvre (FAPM) is executed with the main engine 14 days after RVM, when the phase angle is 90 degrees. It reduces the relative velocity to leave the spacecraft in the same orbit of the asteroid, 5 000 km ahead. The relative position | velocity accuracy shall be better than 10 km | 10 mm/s (3σ) at this point

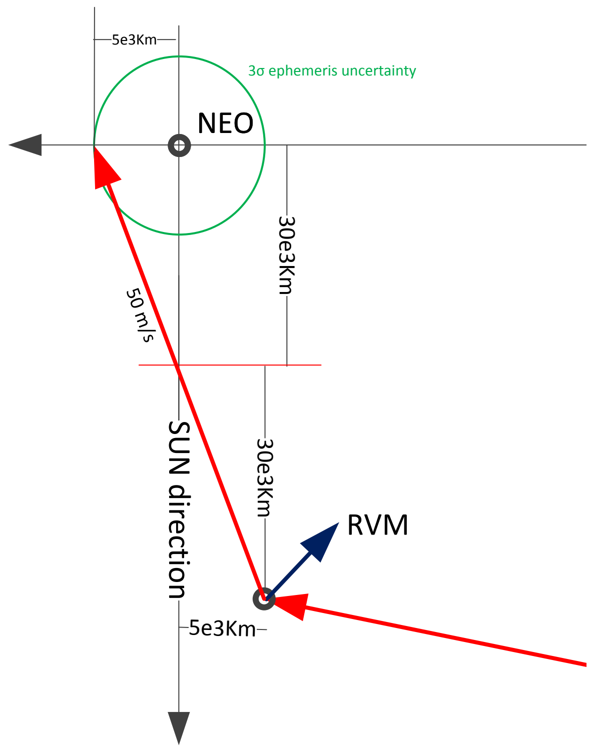

Figure 8. Early Encounter Trajectory

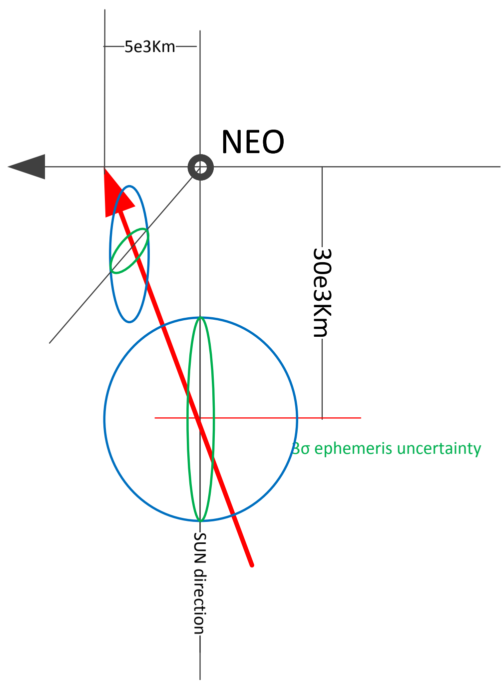

Figure 9: Schematic of the proposed optical navigation: initial knowledge (blue) improves as LOS measurements are processed (green)

III.III. Far Approach

The far approach phase aims at arriving at a relative range and relative accuracy that will allow the start of the autonomous operations of close approach. The objective is to lower the range to the asteroid and collect LOS measurements from different angles to improve the relative navigation accuracy. At start of Far Approach the asteroid still spans less than 1 pixel in the FOV. The differential gravity acceleration of ~1µm/s^2 dominates the dynamics earlier until <500 km where it becomes lower than the SRP (~0.07 µm/s^2).

The design of the far approach trajectory was designed as a dogleg to observe the asteroid from a phase angle from 90 degree to 0 (final). After one day of cleanup of the FAPM with RCS and preparation, the Far Approach Start Manoeuvre (FASM) is commanded from ground and executed.

This phase is split in two approximately 5 day segments. For almost the entire first segment of the Far Approach, the asteroid lies within a single pixel of varying brightness. Two NAC images per day are relayed to the ground. Notice, however, that due to the rotation of the asteroid and the fact that it is observed from different phase angles, this assessment is still coarse. At the second segment, the asteroid already spans more than 25 pixels in the FOV. At this point, as in the close approach phase (see next section), the LOS precision is affected by the offset between CoB and CoM.

At the end of the far approach phase, the spacecraft lies in the Sun-asteroid direction at 10 km range. The asteroid spans in an area of at least 8x8 (64 pixels) in the NAC and is already visible in the WAC. A coarse characterization of its size has been performed and calibration of all the sensors is achieved.

The relative navigation provides an overall accuracy 3σ of 1 km, 1 mm/s.

III.IV. Close Approach

This phase main objective is to safely and quickly deliver the spacecraft to within range of the ranging sensor for the proximity operations. The 38 µN SRP would cause the spacecraft to move 1 km and 12 mm/s in 2 days towards the asteroid, so it is essential to have autonomy in the GNC for the approach.

The design of an approach profile for LOS navigation presents roughly the same challenges, and again, a series of dog-leg manoeuvres are a robust option. As the range to the asteroid decreases so should the magnitude of the manoeuvres. The smallest considered size for the asteroid is 2 m of diameter, which will span 8×8 pixels in the NAC at the 10 km start and 266×266 at its 300-m range end.

Figure 10 shows the way points and approach velocities for each of the 2-day segments. Differential-corrective guidance (fixed-time-of-arrival) including the model of solar radiation pressure for relative motion is employed to take the spacecraft through the 90 degree amplitude dog-legs. To further assist the observability in the range direction at each way point (including the intermediate WP1, WP3 and WP5), a breaking to zero followed by a new impulsive manoeuvre is performed - a knowledge of 10% of the value of an transversal impulsive Δv, and LOS rate measurements, would, with no other contributions, lead to a knowledge of 10% in range (e.g., 100 m at 1 km).

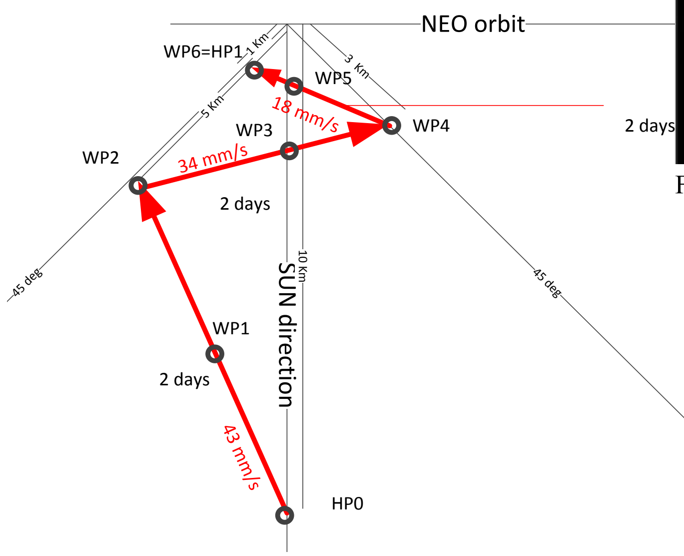

Figure 10: Close Approach way points of Dog-Leg Autonomous Aproach Segment

While the major source of perturbation is the Solar Radiation pressure, the most important source of measurement error is the fact that the CoM doesn't correspond to the measured brightness centroid (CoB). This is particularly relevant in the velocity estimation, as the maximum rotation rate of the asteroid is expected to be 21 rev/hour – if a drift of 0.1 m in CoB-CoM offset is caused by one rotation, then an unfiltered estimate from LOS rate would provide an apparent lateral velocity of 3 mm/s. Notice that the effect of drift of CoB is only significant when in large phase angle (close to WP2, 4 and 6). The effect is illustrated in Figure 11.

When ground issues the command, an impulsive manoeuvre of 38 mm/s puts the spacecraft in a slow trajectory towards the close approach final point, which should be reached within 6 hours of ground-supervised autonomous operation. The knowledge accuracy shall be <3 m, <0.3 mm/s (3σ).

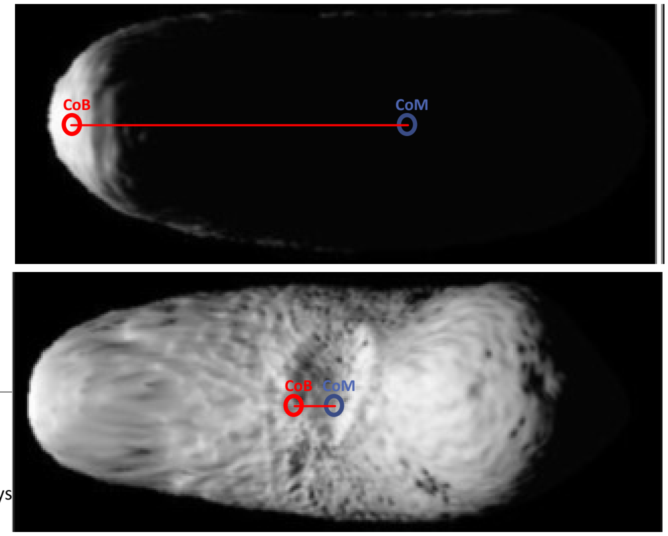

Figure 11: Asteroid observed from 60 deg phase angle, still geometry except for rotational state

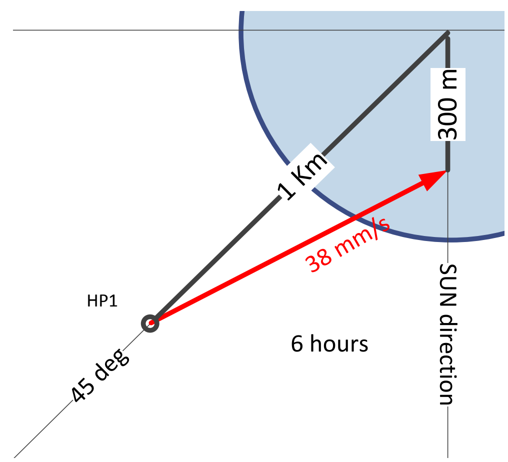

Figure 12: Close Approach Final Segment

III.V. Transition to Operations

During this phase, the asteroid kinematics and shape model are built. Up to the acquisition of the final relative position the phase lasts 26 days.

At the beginning of it, the full metrology has been acquired. The rangefinder provides 10 cm 1σ accuracy measurements to the surface. Centroiding IP algorithms provide the LOS to the CoB and best estimate of the CoM offset for both cameras.

The Feature Extraction Integrated Circuit shall be functional and able to accurately extract, identify and track features (corners - points of maximum contrast in any direction) in the NAC frame (example in Figure 13).

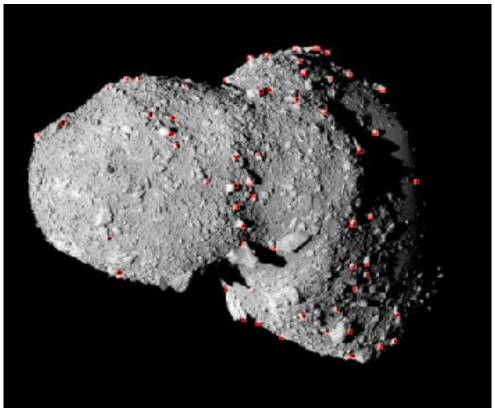

Figure 13: Harris corner detection in a 300 × 300 pixel frame (20 deg phase angle)

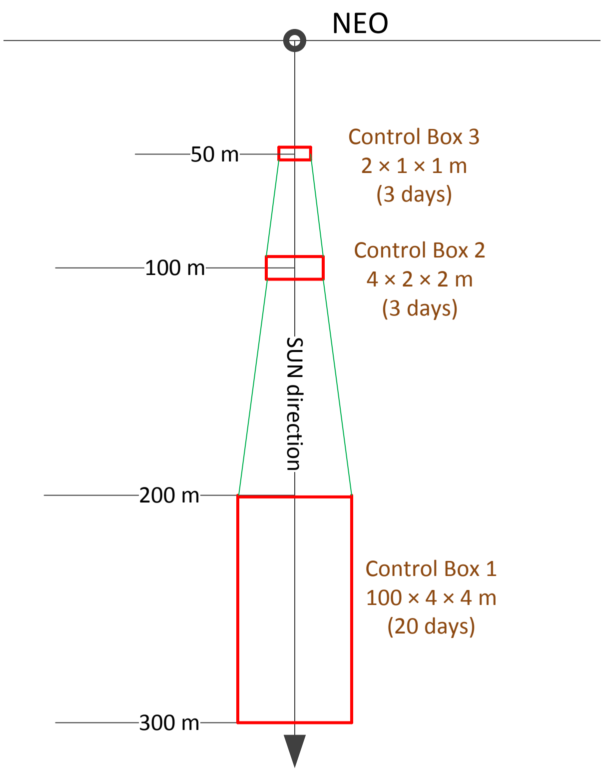

Figure 14: Transition to operation phases

IV. CONCLUSIONS

One of the main issues concerning the deflection of a small or vey faint object is the challenge of its detectability, and the design of a robust approach trajectory given the poor orbit determination quality associated to such small objects. In the frame of the ESA's SysNova challenges, the Light-Touch[2] team proposed the use of laser ablation as a technology demonstrator to deflect a small asteroid of 2-4 m. Among the various challenges that were analyzed over the course of an intensive two month study, one of the mission drivers was the approach and GNC design for rendez-vous prior to an operational phase of deflection, given the faintness and the poor orbit determination quality of the object.

This paper presents the proposed final approach concepts and GNC strategies, from initial scan and detection of the target object to the final rendez-vous position 50 meters from the asteroid.

The strategy presented is applied to a particular asteroid (2006 RH120) but it would be however valid for any small asteroid of similar size, or larger asteroids with low brightness or an interception at a larger distance from the Sun. It can also be scaled up (or down) to any particular target body.

The GNC strategy is also not limited to a laser ablation deflection system, but it is completely appropriate to any mission that requires a proximity phase around asteroids. It would not be however the selected strategy for an impulsive high velocity encounter, such as the one required by a kinetic impactor. Nonetheless, possibly this would not be the appropriate deflection technique for such small objects. In the GNC field there are many synergies to be exploited with other asteroid missions such as asteroid characterisation, orbiters, landers, sample return, and asteroid capture. A similar GNC system for detection and approach phases can be applied in all cases.

Concerning the reduced census of small bodies, and the poor orbit quality of most of them, which currently limits the applicability of any type of GNC strategy, an extensive campaign of observations and follow-ups of small bodies would be highly recommendable.

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