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Performance and Derived Requirements of a Gravity Tractor serving as a Precursor to a Kinetic Impactor within the NEOShield Study Framework

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Abstract

Independent studies and competitions over the last decade have provided a wealth of methods for deflecting near-Earth Objects (NEO)s on Earth close approaches or from direct impacting trajectories. This paper provides an in-depth analysis of the deflection achieved by a gravity tractor acting on a “most likely PHA” recently studied through the NEOShield study. Topics investigated include the choice of propulsion system, scalability to NEOs in the range between 50 m to 200 m in diameter for spacecraft between 1000 kg and 12 000 kg, and discussion of mission scenarios and related operations. As a gravity tractor/kinetic impactor concept is also being investigated within the NEOShield study, we look at the measurements’ and operations’ requirements imposed on the gravity tractor serving as a precursor to an impactor spacecraft. We present a case study for a small spacecraft at the NEOs of interest for the NEOShield, and discuss the performance, trades and challenges involved in performing close proximity operations in such low gravity environments.

1. Introduction

Among asteroid impact mitigation techniques, using a spacecraft mass to deflect a small body is a long time favorite due to its simplicity and its independence from the small body physical properties. This conclusion comes out of the recent reports from NASA [1] and the National Research Council (NRC) [2], which have reviewed the different mission concepts considered for asteroid impact mitigation.

The concept of a gravity tractor is not new. Lu and Love [3] were the first to discuss the principles of a gravity tractor, presenting a 20-ton nuclear-electric powered concept in *Nature*. At the NASA workshop on NEOs in 2006, Schweickart et al. [4] discussed the concept for a 1000 kg spacecraft over 20 years. Then, the dynamics and control of a gravity tractor were further discussed by Wie [5] using a halo orbit to accommodate multiple tractoring spacecraft, and by Fahnestock for large spacecraft [6,9].

In 2008, JPL released a technical report on the feasibility of a proposed 1000-kg gravity tractor to avoid a gravitational keyhole [7]. The study assesses the improvement in the orbit determination of a NEO+gravity tractor over ground-based observations, indicating with precision the required deflection (if any) to prevent a keyhole entry. It is shown that existing radio tracking capabilities could provide sufficient knowledge on time scales of a week. Simulations were carried to demonstrate a proposed hovering control law for the spacecraft to stay up to six months at the asteroid. Combined with a kinetic impactor, the study also discusses the gravity tractor ability to determine the asteroid’s new trajectory after a kinetic impact, and to perform any necessary trim maneuvers.

As part of the NEOShield study, we investigate the feasibility and applicability of the gravity tractor for small NEOs with diameters between 50 m and 200 m. We also discuss related operations involved in having precursor spacecraft to either a larger tractor or a kinetic impactor, and give a case study. Other topics related to the gravity tractor have still been relatively unexplored. For instance, the deflection of binary asteroid systems and the influence of the Yarkovsky effect combined tractoring have yet to be fully studied (see [8,9,10,11] for previous work). We also include short discussions on those topics in the last section.

2. NEAs of Interest

The focus of the NEOShield study is on near-Earth asteroids with diameter between 50 m and 200 m. We also investigate the particular case of 2011 AG5, which was thought to be a Potentially Hazardous Asteroid until very recently. For the generic cases, a density value of 1.5 ± 0.5 g/cm^3 was chosen, which includes about 80% density values that have been estimated to date for NEOs [14]. For consistency with other work done on 2011 AG5, the publish mass of 4×10^9 kg is kept for the analyses [15]. Assuming a density value at the upper limit of

2.0 g/cm^3, AG5's diameter is 156 m. The NEA characteristics are listed in Table 2.

Table 1. Characteristics of NEAs of Interests.

NEAs	Diameter (m)	Density (g/cm^3)	Mass (kg)	Surface grav. (cm/s^2)	Vel escape (cm/s)	Hill's sphere (km)
Lower limit NEA	50	1.5 ± 0.5	$9.82 \pm 3.27 \times 10^7$	0.7 – 1.4	1.9 – 2.6	3.3 – 4.2
Upper limit NEA	200	1.5 ± 0.5	$6.28 \pm 2.09 \times 10^9$	2.8 – 5.6	7.5 – 10.6	13.3 – 16.8
2011 AG5	156	2	4×10^9	5.5	8.8	13.1

3. Fundamentals and Assumptions

To maximize deflection a gravity tractor should be placed such that the NEO is accelerated either along or against its instantaneous velocity vector [5]. Assuming a circular orbit, the resulting deflection ΔX and change in speed ΔV caused by an acceleration a_{NEO} along the velocity vector can be expressed analytically as a function of the lead time t_T and thrusting time t_A:

$$\Delta X = \frac{3}{2} a_{NEO}\, t_A \,(2t_T - t_A) \qquad (1)$$

$$\Delta V = 3\, a_{NEO}\, t_A$$

For a given standoff distance d, the gravity tractor must point its thrusters at a minimum canting angle β to avoid plume impingement of the NEO. This is usually represented as shown in Figure 1 [3]. Since it is desirable to minimize cosine losses, β is chosen such that the edge of exhaust plume is tangential to the NEO:

$$\frac{r}{d} = \sin(\beta - \varphi) \qquad (2)$$

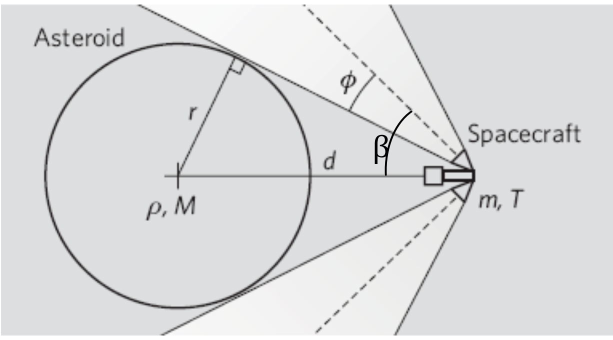

Figure 1. Geometry of the gravity tractor and near-Earth object [3].

To maintain a fixed standoff distance, the spacecraft must exert thrust to mitigate the gravitational force between itself and the NEO:

$$F_G = T \qquad \text{where} \qquad F_G = \frac{GMm}{d^2} \qquad \text{and} \qquad T = \dot{m} \,.\, I_{sp} \,.\, g_0 \,.\, \cos(\beta)$$

which gives the relation:

$$\dot{m} \,.\, I_{sp} \,.\, g_0 \,.\, \cos(\beta) = \frac{GMm}{r^2} \sin^2(\beta - \varphi) \qquad (3)$$

The NEO's acceleration due to the presence of the gravity tractor is given by:

$$a_{NEO} = \frac{Gm}{d^2} \qquad \text{since} \qquad F_G = M a_{NEO}$$

And the thrusting time is given by:

$$t_A = \frac{m_i}{\dot{m}}.$$

There exists an optimal standoff distance $d_{optimal}$ that maximizes the deflection ΔX, calculated through

$$\frac{d\Delta X}{d\beta} = 0$$

for the optimal thruster canting angle β and finding $d_{optimal}$ through equation (2).

As the mitigation concept feasibility study is shared among few partners (Astrium, University of Surrey, SETI CSC), the common assumptions were:

- Launcher considered: Delta-V Heavy (D IV H) and Falcon Heavy (FH)
- Hyperbolic insertion: C3 < 6 km^2/s^2
- Generic transfer Delta-V of spacecraft to asteroid: ~ 3 km/s
- Transfer time (of spacecraft to asteroid): 2 years
- The above gives a maximum delivered mass to asteroid (assuming low-thrust, Isp 4300 s):
    - 11600 kg (FH, 858 kg propellant used during transfer)
    - 9000 kg (D IV H, 666 kg propellant used during transfer)
- Due to study of 2011 AG5, Earth impact is still assumed to be in 2040
- A gravity tractor is limited to a lifetime of 15-20 yrs
- Launching year limit: 2039

3. Capability of a gravity tractor as a function of the NEO

Figure 2 and 3 show the deflection capability of a gravity tractor as a function of the target body diameter for bounding values of typical asteroid densities. The NEO diameter has a strong influence on the b-plane deflection capability of a gravity tractor. For example, a 1000 kg gravity tractor that can deflect a 50 m asteroid by 35,000 km after 25 years will be able to displace a 200 m object by 750 m over the same time period. Figure 3 shows deflection comparison for larger gravity tractor, up to 13500 kg. If the mission is limited to 15 years, a 50 m NEO would be deflected 16000 km while the 200 m NEO would be deflected by 425 m (Figure 4 and 5).

From these results, we conclude that for the asteroids of interest, the gravity tractor could be used as a deflection method against direct impact for the very small NEOs (50 m diameter), while a keyhole deflection or trajectory fine tuning strategy would be more appropriate and realistic for the 200 m case. As the NEO increases in size, this mitigation concept becomes more applicable to keyhole deflection.

The advantage a gravity tractor over alternate impact mitigation techniques is that its performance is largely independent of the composition and rotation rate of the NEO. As long as the gravity tractor maintains a fixed standoff distance it will exert a steady gravitational force regardless of the NEO's porosity, fragmentation and rotation.

The irregularity and rotation of an asteroid could however affect the gravity tractor's ability to maintain a fixed standoff distance due to resonance and other periodic effects. Yeomans et al. (2008) have characterized the translational station keeping requirements of a gravity tractor operating in proximity of an aspherical asteroid [7].

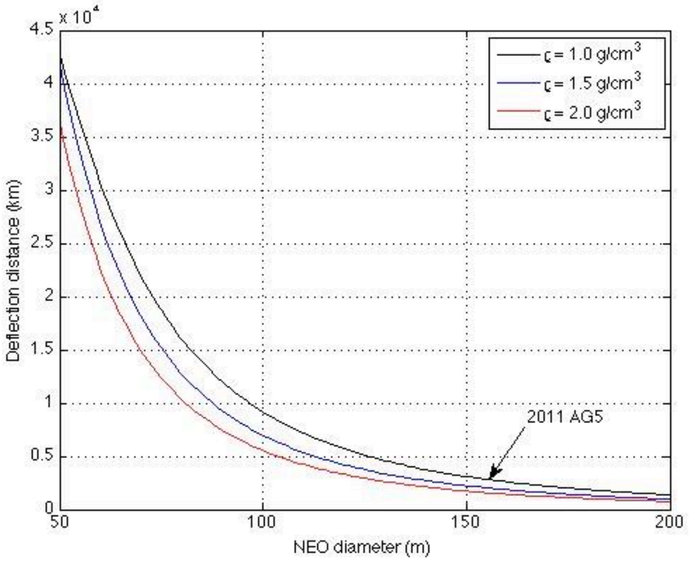

Figure 2: B-plane deflection as a function of NEO diameter with lead time t_T = 25 yrs for densities between 1 and 2 g/cm^3 assuming a spherical shape. The gravity tractor is assumed to have m = 1000 kg, φ = 20°, dry mass fraction 0.8 and I_{sp} = 3100 s.

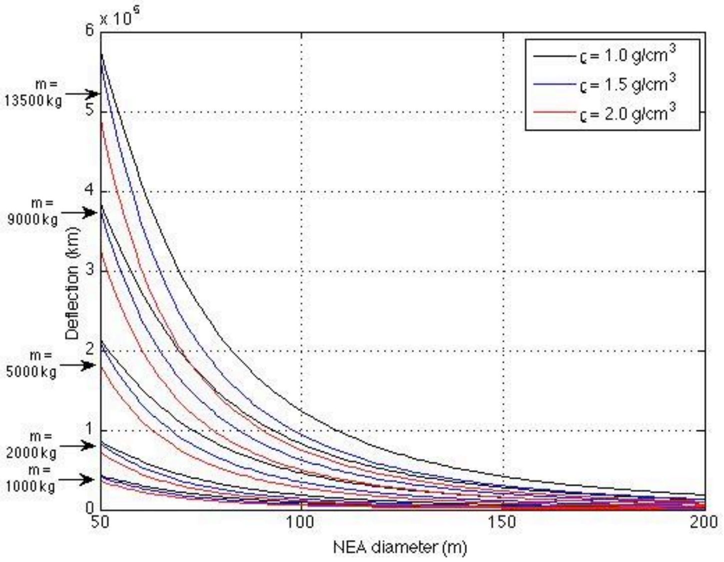

Figure 3. B-plane deflection as a function of NEO diameter with lead time = 25 yrs for densities between 1 and 2 g/cm^3. We show results for gravity tractor between 1000 kg and 13500 kg.

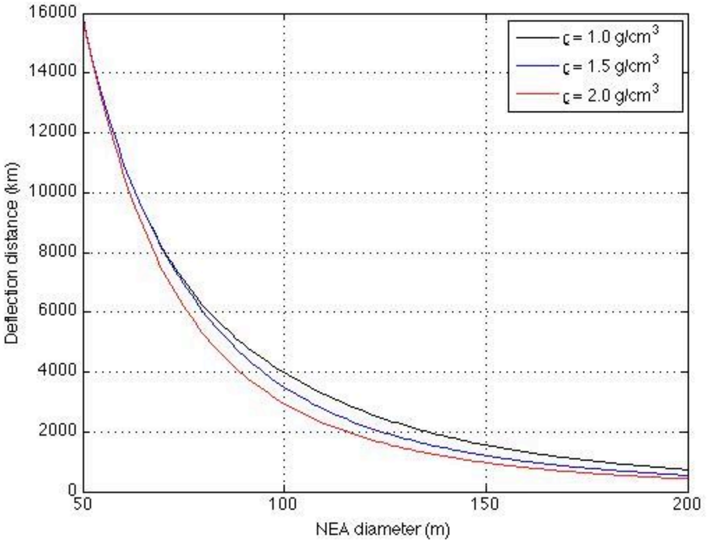

Figure 4. B-plane deflection as a function of NEO diameter with lead time = 15 yrs for densities between 1 and 2 g/cm^3, for gravity tractor of 1000 kg.

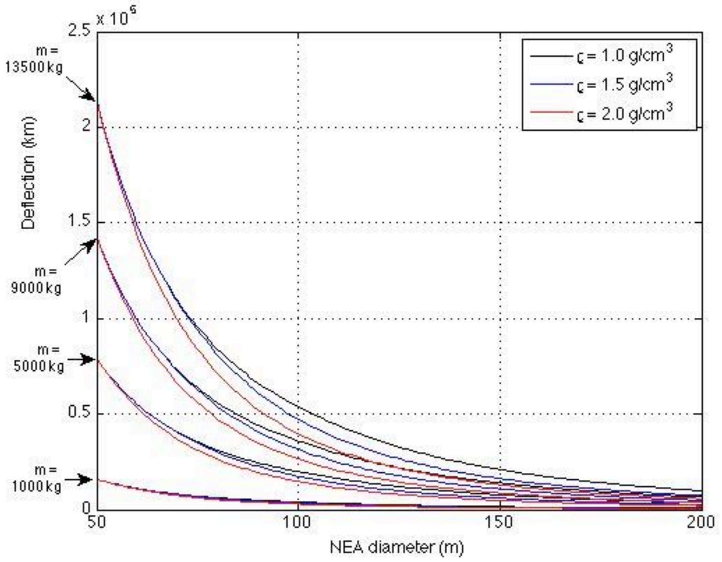

Figure 5. B-plane deflection as a function of NEO diameter with lead time = 15 yrs for densities between 1 and 2 g/cm^3. We show results for gravity tractor between 1000 kg and 13500 kg.

4. Mission Scenarios and Related Operations

4.1. Mission Scenarios for a Gravity Tractor

From previous deliverables of the NEOShield study, the following mission scenarios are applicable.

- Single Gravity tractor: A single gravity tractor is launched, using the Delta-IV and Falcon-Heavy vehicles. Assuming a hyperbolic escape with an associated C3 of 6 km^2/s^2, the allowable spacecraft wet masses are 9000 kg and 12000 kg, respectively.

- Use of a Precursor: In this scenario, we include either the use of a small spacecraft/gravity tractor as a precursor to a larger gravity tractor, or to a kinetic impactor. The spacecraft would then need to acquire a number of measurements to feed in the design of the follow-on spacecraft. See a case study discussion next.

- Multiple Gravity Tractors: Work by Foster et al. has quantified the effectiveness of multiple gravity tractors. See work done by the Surrey partner for follow-on development.

4.2 Proximity Operations: from Approach to Tractoring

Before tractoring activities, and if the gravity tractor or a spacecraft is to be used as a precursor to another impactor or larger gravity tractor, the proximity operations need to be designed to gather specific measurements while minimizing risks. Typically, over 2-3 months, the spacecraft will gradually approach the target, refined data products as it does. There are usually three major phases: the approach, the survey and characterization phase, and close range operations which could be combined with the tractoring phase. These are summarized in Figure 6. The total Delta-V associated with the preliminary operations are typically less than 20 m/s for the small NEOs considered.

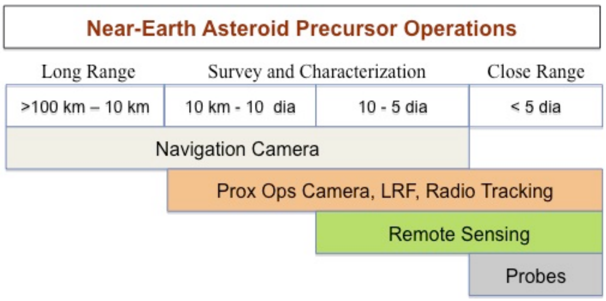

Figure 6. Overview of precursor operations.

Approach

After target detection, the images and spacecraft radio tracking are used to precisely identify the asteroid location. As the spacecraft gets closer to the target, the spin pole orientation and spin period are determined while added features and morphologic details are used to create preliminary shape models, derive volume estimates, and simulate the dynamics more accurately. For these small NEAs, the navigation cameras can provide a high-resolution remote sensing (< meter scale) from a safe distance. Stereo imagery is used to calculate altitudes, reconstruct shape models and build topographic maps. Direct measurements from laser rangers do not rely on illumination, providing quick and reliable altitude data.

Survey and Characterization

As the spacecraft approaches within 10 km, measurements and operations can be performed using orbit, hovering, or hyperbolic flyby. High-resolution camera and UV-Vis spectrometers provide interesting solutions for debris assessment and terminator imaging, and can be used from a few kilometers out. Slow flybys provide fail-safe trajectories, as the spacecraft is always directed on a non-impacting course with the NEA. However, hovering is necessary for any surface activities planned on the surface and especially for tractoring.

Close approach to the NEA requires knowledge of the mass and gravity field. For such small bodies, measurement of the spacecraft trajectory velocity change becomes difficult due to the low gravity and the limitations of current tracking assets. Figure 7 and 8 show the mass resolution that can be obtained from close flybys at a 50 m and a 200 m diameter NEO, respectively. These estimates are obtained by defining a minimum change in velocity detectable with current radio tracking techniques, and reworking the vis-viva equation [16]. The mass calculated through this resulting expression is then translated into mass resolution for the particular cases of 50 m and 200 m NEOs. In the figures, the curves indicate mass resolutions in percentage using the average NEA mass and the calculated mass accuracy. The curves show the required flyby conditions for resolutions between 10% and 50%. Note that the flyby distance is measured from the center of the NEA. For a 50 m NEA, it is difficult to obtain a resolution higher than 30% under safe conditions; from a flyby velocity of 20 cm/s, the spacecraft would need to come within 25 m altitude. Slowing down to 10 cm/s, this same flyby distance lowers to a resolution of 20% at best. At the 200 m NEA, these same flyby speeds can yield 10% resolution for close approach distances less than 1000m.

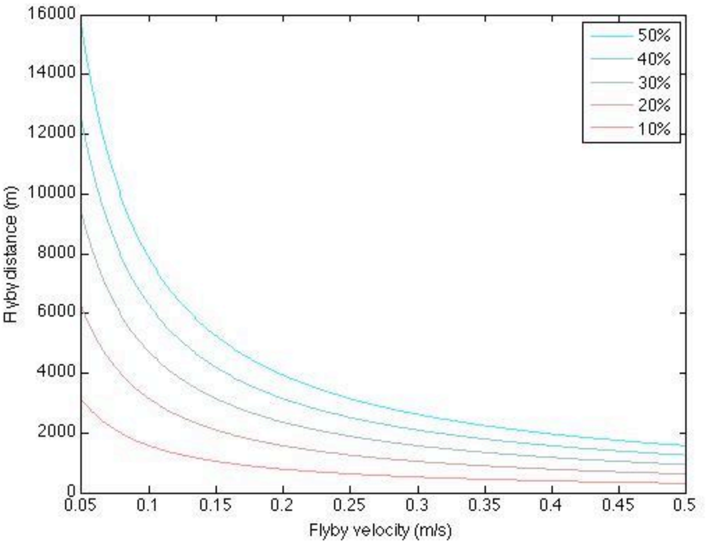

Figure 7. Mass resolution and associated flyby distance and velocity constraints for a 50 m NEA.

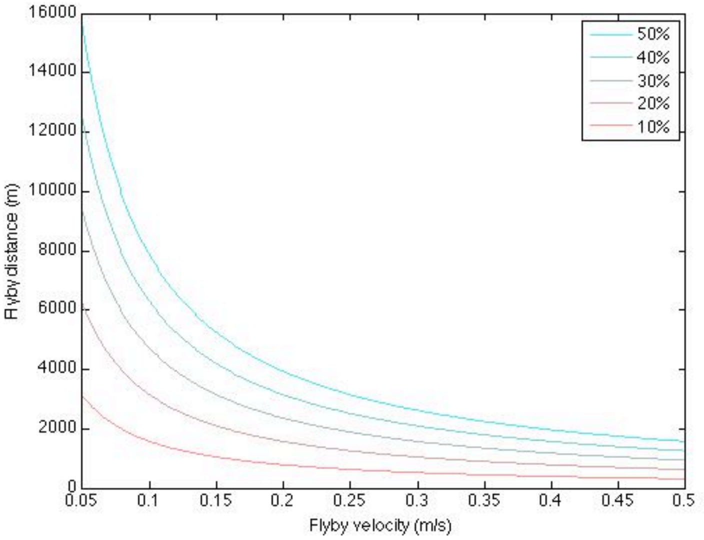

Figure 8. Mass resolution and associated flyby distance and velocity constraints for a 200 m NEA.

If more refined measurements are required, surface probes offer a relatively inexpensive solution. If the probe is tracked efficiently, and assuming similar geometry and Doppler accuracy, mass measurements can be improved to a few percent accuracy due to the proximity from the NEA compared to using solely spacecraft tracking.

For further surface characterization, using a mid-infrared camera allows features identification and correlation over multiple wavelengths. As dust processes on small bodies resemble those of the Moon, a UV-Vis spectrometer like the one on LADEE is well suited for mapping dust movement. Then, NIR measurements are well suited to reveal the mineral compositions from spectral properties, or reveal hidden features due to the topography or low albedo (at wavelengths >~3 microns).

Elemental composition instruments may be necessary to refine a kinetic impactor design. The difficulty of using these instruments is due to integration times; the orbit approach may be of short duration, limiting instruments' sensitivities. The XGRS on NEAR returned its most useful data during the final two weeks of the mission as the spacecraft was sitting on Eros surface. However, the use of elemental composition instruments can particularly be enhanced during tractoring.

Close Range

Close range operations, within 5 radii from the NEA, require high fidelity models and surface maps. Dust mobility and surface mechanical parameters can be inferred from high-resolution images, down to centimeter scale over visual and infrared spectrum. Comparing temporal images will shed light on dynamical phenomena, while the presence of boulders, craters, and slopes will indicate strength, porosity, and surface stability. In addition, composition and thermal variations obtained from IR data can reveal hidden objects and variations in density.

To gather high-resolution measurements, most efficient methods are to image the surface (stereo), obtain spectrophotometry (grain size, micro texture), and use impact probes. Note that probe deployment is sensitive to small errors that can easily lead to a miss or rebound and escape.

As derived in section 3.3, tractoring is effective within this altitude.

4.3. Surface Operations

In this low gravity environment, any drilling, scooping, digging, or grabbing instruments may be a challenge. The spacecraft onboard attitude control system is of prime importance, as it needs to maintain spacecraft stability from any motion. Anchoring devices need to include sufficient margin for a range of surface mechanical properties since NEA densities are still very much unknown.

Once surface stability is achieved, chemical and elemental composition can be obtained using neutron, x-ray, gamma-ray, and Raman spectrometers. Integration times may necessitate relatively long still position. Other small sensors on the spacecraft legs or other free surfaces can quickly return data from the surface.

Small surface probes such as CubeSats, NanoSats, and impact probes provide ideal low cost solutions for measuring mechanical and electrical properties. However, the probe is not guaranteed to remain where it is deployed. Given the relatively small dimensions of these probes, their lifetime is also generally limited to several hours. The impact of the probe itself can indicate surface strength and compressibility, while revealing fresh subsurface material.

5. Small Spacecraft Case Study

5.1 Spacecraft Architecture

We looked at a 1000 kg spacecraft to be used as a precursor to larger missions, acting as a small gravity tractor and kinetic impactor precursor. The mission goal is to at least return the information essential to determine the asteroid mass accurately to scale a larger gravity tractor from high precision trajectory analysis, and returning intrinsic surface properties to design an appropriate kinetic impactor. The baseline mission design takes advantage of the ESPA ring to rideshare launch with another mission, and can launch as early as 2016. Follow-up work will include more accurate trajectory analysis depending on NEOShield target selection.

The architecture derives from LCROSS and LADEE at NASA Ames Research Center [19] to enable interplanetary missions from a cheap rideshare or dedicated launch. The propulsion system baseline uses Busek Hall Effect Thrusters and a rebuild of the DAWN Xenon tank. On arrival at the target, a small monoprop system is used for maneuvering. The design study also used Draper's Rendezvous & Proximity Operations (RPO) components.

The baseline payload contains the following instruments. A long range visible camera is used to acquire images of the target at rendezvous while a short range visible and mid-IR cameras support the proximity operations by correlating surface features in multiple wavelengths. A UV-Visible Spectrometer looks for the dust or debris field surrounding the target. Thumpers provide ground truth from impacting the surface, carrying small probes and a 'Crashcam' to capture surface details pre- and post impact.

5.2. GNC Solutions

Some hovering control laws were assessed in Yeomans et al [7] to evaluate the tracking capability of a gravity tractor. Fahnestock and Broschart, and Fahnestock and Scheeres investigated control laws for a gravity tractor, at single and binary asteroid system respectively [9,6]. McInnes [16] investigated a spacecraft flying in a halo orbit, which was then studied by Wie [5] for multiple gravity tractors. The use of multiple gravity tractors was further explored in [18].

We investigated GNC solutions for this small spacecraft, applicable for this study [19].

Angles-Only-Navigation

The potential for angles-only navigation has been recognized in applications ranging from target tracking, orbit determination, interplanetary navigation, formation flying for unmanned aerial vehicles, and orbital rendezvous. At large distances, the long range camera will see the asteroid at sub-pixel level. As the spacecraft approaches, the target asteroid subtends a larger angle in the camera field of view. Common algorithms are used to determine the asteroid center. In this mode of operation, strategic maneuvers are used to determine the relative range that is typically considered unobservable.

As the spacecraft gets closer, it is necessary to alter the image processing strategy from measuring a centroid to detecting and identifying feature points or landmarks upon the asteroid.

Terrain Relative Navigation

The essential elements of Terrain Relative Navigation are composed of the following components, shown in Figure 9 [19]:

- **Image Processing to** extract point features that are likely to be recognizable in successive images (for instance, see [22]). These features are added to a feature database, which contains information about each known feature.

- **Feature Matching to** match features extracted from a new image against features recorded in a database. It combines feature 3D locations and surface normals from the database with the expected position and orientation of the asteroid relative to the camera to predict which features should be visible to the camera and at what image coordinates.

- **Pose Estimation** to solve for the position and orientation of the camera relative to 3D features [23].

- **Filtering to** combine with pose estimates over time, and estimate the asteroid’s pose, rotational velocity, center of rotation offset, and ranges.

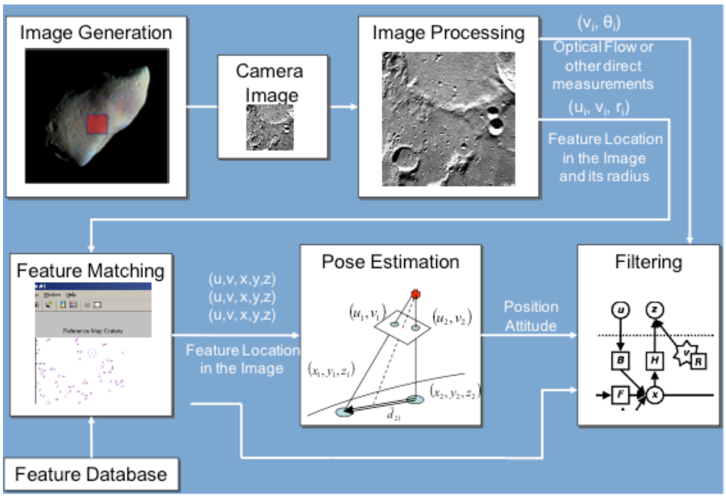

Figure 9. Terrain relative navigation process [19].

Guidance and Control

A number of guidance and trajectory control methods can be used for asteroid rendezvous and proximity operations. Lambert guidance can be used to arrive at a location from which autonomous operations may begin, and can be used from ground commands or onboard depending on the spacecraft level of autonomy desired.

Within approximately 100 km of the target asteroid when the onboard camera is able to acquire and track the target asteroid in real-time, proportional navigation can be used to correct and keep the spacecraft on an rendezvous course with the target asteroid. A terminal burn at a lo altitude can insert the spacecraft into a 1 km station-keeping hold location. During proximity operations, guidance laws based on linearized equations of motion around the target asteroid’s elliptical orbit can be used.

6. Additional Scenarios

6.1. Gravity Tractor at a Binary System

A spacecraft has about 1/6 chance of rendezvous with an unidentified binary system. There are still basic questions to be answered on the effectiveness of deflecting a binary system and on the influence of the binary system parameters. The same principles apply when looking at deflecting a binary system with a gravity tractor. However, the difference relies in that the deflection is performed through the binary center of mass, as opposed to deflecting components only. Note that the interaction between the components, or the system dynamic, add perturbations and complexity to the operations.

Tackling a binary system with a satellite sharing more than 10% of the total mass would be a challenge from a control scheme and proximity operations point of view. We find that even though a large deflection can be delivered to the moon due to its smaller mass, relatively little deflection is delivered to the binary center of mass compared to tractoring the primary. The deflection increases as the system reduce in size [24].

We also find that separating the components of a small binary system, or bringing them closer to each other, has little deflection effect compared to pulling along the system’s barycenter through the primary ([24], also see [20,21] for stability analysis). However, these options may be advantageous for very small systems (~50 m diameter). In both cases, tractoring times easily reach ten years.

6.2. Gravity Tractors and the Yarkovsky Effect

The idea of mitigating a hazardous NEO taking advantage of a nongravitational perturbation on its orbit, the Yarkovsky effect, was first publicly presented by Spitale, 2002. The author investigated the possibility to alter the Yarkovsky effect changing the surface thermal conductivity and the albedo of the NEO [25]. We explored whether a gravity tractor can significantly deflect a NEO, indirectly via the Yarkovsky effect, by perturbing the asteroid’s spin axis.

Possible consequences due to a modified radiation effect was found to be minimal. We obtain a 1.57 degrees precession of the obliquity axis when considering an Apophis-sized asteroid as in Table 3, for a 1000 kg gravity tractor thrusting for 3 years at a standoff distance of 1.5 times the asteroid's radius. This precession determines a total displacement due to the change in the Yarkovsky effect of ~34 km over a period of 50 years. The same gravity tractor, in nominal configuration as a NEO, could impart a deflection of ~666 km in the same time frame. Note the Yarkovsky effect is not equally applicable to all hazardous NEO since it is strongly influenced by an object's physical parameters (size, shape, thermal properties, spin axis initial orientation, etc).

7. Conclusions

This work undertaken as part of the NEOShield study has addressed several questions specific to the gravity tractor concept. We looked at gravity tractor performance for asteroids with diameter between 50 m and 200 m. A 1000 kg gravity tractor that can deflect a 50 m asteroid by 35,000 km after 25 years will be able to displace a 200 m object by 750 m over the same time period. If the mission is limited to 15 years, a 50 m NEO would be deflected 16000 km while the 200 m NEO would be deflected by 425 m

We propose a conceptual study of a small spacecraft acting as a precursor to a larger gravity tractor or a kinetic impactor. Such a mission could use proven electric thruster technologies to deflect an easily accessible NEO. We discussed proximity operations for approach and characterization scenarios, including related instruments and GNC solutions.

As a reminder of the gravity tractor concept, we present a summary of findings below:

- There exists an optimal standoff distance separating a gravity tractor from its target NEO to maximize the deflection it can deliver for a given propulsion system and lead time.

- The required gravity tractor mass scales linearly with the target deflection distance and is roughly inversely proportional to the square of the lead time.

- An electric propulsion system provides an order of magnitude improvement in deflection distance than a similarly-sized chemical system due to the high specific impulse and low-thrust nature of gravity tractor operations. The use of nuclear electric systems or improvements in large-scale solar arrays will significantly improve a gravity tractor's deflection capability.

- Deflection distance is very sensitive to the size of a NEO. A doubling in size will incur almost a tenfold penalty in deflection for an object of equal density. We restate from previous studies that the functionality of a gravity tractor is however largely independent of a NEO's rotation, composition or irregularity, but may be affected when considering the complexity of proximity operations.

- The best strategy for deflecting a multi-body asteroid system is to tractor the primary component along the barycenter's instantaneous velocity vector. If the secondary component's mass is negligible relative to the primary, the performance penalty incurred by the satellite will be minimal. Larger moons will noticeably degrade the performance of a gravity tractor.

- The tractoring strategy of separating the components of a binary system is less efficient than pulling along the system's barycenter.

- The deflection caused by multiple gravity tractors is the sum of deflections caused by each gravity tractor if it were acting alone. The use of more than one gravity tractor will be necessary to achieve greater deflections that what a single launch vehicle can deliver and can assure mission success through redundancy and international collaboration.

- While it is possible for a gravity tractor to indirectly deflect a NEO via the Yarkovsky effect by perturbing the asteroid's spin axis, we find that it provides two orders of magnitude less deflection on an Apophis-sized asteroid than a gravity tractor operating in the classical pull mode.

- Among the existing conclusions and recommendations for planetary defense actions and international collaboration, additional attention needs to be taken for nation responsibility for gravity tractor implementation as the impact risk corridor becomes a slow moving agent potentially adding to current political issues.

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