Spacecraft Mission Design for the Destruction of Hazardous Near-Earth Objects (NEOs) via Distributed-Energy Explosives

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Earth has been struck and will be struck again by asteroids and comets whose orbits bring them into close proximity with Earth's orbit, collectively termed Near-Earth Objects (NEOs), and such collisions can be catastrophic. One possible means of eliminating the threat posed by a NEO on a collision course with Earth is to deliver and emplace explosive charges into blast holes drilled into the NEO by a human and/or robotic crew. Preliminary design work has been completed regarding the proper fashion in which to distribute these charges throughout the NEO to ensure that their detonation breaks the NEO into fragments no larger than 30 – 50 m in mean diameter so that any fragment that should still collide with Earth will burn up in the atmosphere and not harm Earth's surface. This paper examines the requirements for a spacecraft mission to deliver this distributed-energy blasting system to a given NEO by considering four example target NEOs drawn from the currently known NEO population. A preliminary mission outline for completing the NEO blasting operation is presented that includes basic rendezvous trajectories and deliverable payload mass results for each target NEO, a survey of NEO proximity operations methods and considerations, and a discussion of the issues associated with supporting a human crew for such a mission. This study has concluded that current and near-term launch and propulsion technology is insufficient for support of a distributed-energy blasting mission unless the overall blasting system mass can be dramatically reduced or launch technology improves significantly. NEO proximity operations are deemed feasible for the blasting mission with continued development. Sustaining a human crew for the duration of multi-year NEO blasting mission will also require advances in technology such that crew health and sustenance can be ensured in the remote space environment for an extended duration. All of these required enabling technologies for a blasting mission are of general interest in terms of the overall advancement of crewed and un-crewed solar system exploration.

I. Introduction

EARTH has been struck and will be struck again by asteroids and comets whose orbits bring them into close proximity with Earth's orbit, collectively termed Near-Earth Objects (NEOs). These collisions can be

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catastrophic when the impacting NEOs are massive enough, generally 1 km or more in mean diameter. This study examines distributed-energy blasting of an incoming NEO as one potential strategy for fragmenting or deflecting the NEO, thereby eliminating it as a threat to Earth.

Methods are being developed to perform distributed-energy blasting on a NEO such that the largest remaining fragment is small enough, no more than 30 – 50 m in size[1] to burn up in the atmosphere should one or more fragments still collide with Earth[2]. This strategy requires rendezvous with the NEO followed by proximity and surface operations to drill all required blast holes and properly position all the blast charges prior to detonation. Given the complexity of these operations, a combination of human and robotic crew members may be required. Note that drilling into a rubble pile NEO will be more complex than drilling into more solid NEOs in terms of anchoring the drilling equipment.

The feasibility of this strategy from a spacecraft mission design viewpoint is evaluated in this study by characterizing how much payload mass can be delivered efficiently to each of four sample target NEOs using current or near-term technology. Additionally, the subsequent mission operations required to carry out the blasting process are outlined, with a focus on the spacecraft proximity operations trajectories about the NEO. The issues associated with ensuring the health and sustenance of a human crew for a multi-year NEO blasting mission are also discussed. Finally, recommendations are presented regarding space technology development paths that would make distributed-energy blasting missions more tractable.

II. Target NEO Selections

Four target NEOs have been selected for examination in this study. These NEOs primarily were chosen for their mineability and size classifications, and it is also helpful that science missions have successfully flown to two of the four targets, these being the Near-Earth Asteroids (NEAs) Eros and Itokawa. The Stardust mission (2004) performed a flyby of comet 81P/Wild-2 and collected particle samples from the coma but did not engage in extended operations in the vicinity of the comet. Asteroid 1986 DA has not yet been visited by a spacecraft.

In practice, a characterization mission must be flown to any given target NEO prior to the deployment of the distributed-energy blasting mission so that the proper set of explosive charges may be chosen, drill hole locations and depths computed, and support equipment selected.

In this section we present the orbital characteristics of each target NEO and summarize their physical characteristics in the context of distributed-energy blasting.

A. Orbital Characteristics

The heliocentric Keplerian orbital elements for each of the four target NEOs are presented in Table 1. The orbits are reasonably characteristic of the range of NEO orbits found in nature, with inclinations between ~ 1.6 and 10.8°, semi-major axes between ~1.3 and 3.4 AU, and eccentricities between 0.22 and 0.58. Rendezvous is feasible with all of the NEOs, and the critical question of how much payload mass can be delivered via efficient rendezvous is examined in a subsequent section, which includes simulation plots of each NEO's orbit for reference.

Table 1. Heliocentric Keplerian orbital elements for target NEOs at epoch 2454000.5 JD[*]

	Asteroid Itokawa	Asteroid Eros	Comet 81P/Wild-2	Asteroid 1986 DA
a	1.3239271241608 AU	1.45814310173926 AU	3.45053662470409 AU	2.80928103722431 AU
e	0.28008278025999	0.222725171917015	0.538267561189038	0.586387346386578
i	1.62222623973754°	10.8288322885544°	3.23860607789994°	4.3097178493379°
Ω	69.0954733111702°	304.385917264693°	136.133375034149°	64.7887036244007°
ω	162.76618539854°	178.650047241258°	41.8388967791372°	127.1956757338°
M	193.30712326056°	352.085019984876°	157.337135868471°	119.176015891677°

[*] http://neo.jpl.nasa.gov/orbits/

B. Physical Characteristics

NEO orbital characteristics were not the dominant factors considered in target NEO selection. Rather, NEOs were chosen that have been visited previously by scientific characterization missions so that meaningful distributed-energy blasting operations could be designed for them in Ref. 2. Table 2 summarizes the important physical characteristics for each of the target NEOs.

Table 2. Target NEO physical characteristics relevant to distributed-energy blasting design from Ref. 2.

NEO	Fragmentability	Size Classifcation	Constituents	Physical Size, km	Bulk Density, g/cm^3
81P/Wild-2	Group 0	Class 3	comet (mostly ices)	$1.65 \times 2.00 \times 2.75$	1.5
Itokawa	Group 1	Class 2	friable rock (rubble pile)	$0.535 \times 0.294 \times 0.209$	1.9
Eros	Group 2	Class 3	hard rock	$13 \times 13 \times 33$	2.67
1986 DA	Group 3a	Class 3	metal-rock mix	2.3 (diameter)	5

The fragmentability and size classifications are defined specifically in the context of distributed-energy blasting and are discussed in detail in Ref. 2. Briefly, fragmentability depends on the structure and composition of the NEO and characterizes the ease with which it is broken-up, which decreases with increasing group number. Size classification is based upon how many blasts are required, which affects mission duration and the number of teams required for blasting operations. Clearly, larger NEOs will require more blasts and hence a larger number of teams operating over a longer period of time. Note that none of the target NEOs is or ever will be a threat to Earth.

III. Distributed Energy Blasting for NEO Fragmentation and Deflection

The preliminary designs for distributed-energy blasting systems have been completed for each target NEO in Ref. 2 and the results are summarized here in Table 3 for comparison to mission design results presented in a subsequent section herein.

Table 3. Distributed-energy blasting design values for each target NEO from Ref. 2.

NEO	General Approach	# Blasts	Explosives Mass, metric tonnes	Equipment Mass, metric tonnes	Drilling, km	# Teams	Time Needed, yrs
Itokawa	destruction	6	11.0	22	6.6	1	0.5
81P/Wild-2	phased destruction	10	4.75×10^3	402	2522	20	4.0
1986 DA	Deflection	1-3	2.24×10^8	202	346	10	2.0
Eros	splitting & deflection	17	3.82×10^6	10000	1.36×10^5	500	20.4

Asteroid Itokawa is clearly the most tractable fragmentation target, because it is a relatively small and strengthless, low-density rubble pile object. 81P/Wild-2 is the next most tractable target for fragmentation but the distributed-energy blasting system requirements are still one to several orders of magnitude higher than those for Itokawa. Asteroids 1986 DA and Eros would be candidates for testing deflection mechanisms rather than targets for fragmentation. For Eros, this is due to its large size whereas for 1986 DA, it is because of its (assumed) metallic composition. The optimal orientation for the resultant impulse vector for deflection is beyond the scope of this study but is treated in detail in other research[3].

Note that the drilling length values in Table 3 are the sums of the lengths of the array of drill shafts drilled into a NEO, and this sum can be considerably larger than the physical dimensions of the NEO.

The details of the drilling and explosives emplacement operations are presented in Ref. 2 and are not repeated here, apart from stating that an array of blast holes will be drilled into the NEO at various depths and explosive packages placed within these holes. Note that the problems associated with providing sufficient normal force for drilling into a rubble pile are immense.

It is assumed that, in general, an independent scientific characterization mission is sent to any target NEO prior to the design of a distributed-energy blasting system being sent to the NEO. It is clear from Table 3 that the mode of operation, duration of operation, and mass of material required for each of the four target NEOs discussed here vary dramatically and thus any arbitrary NEO will also have a unique set of requirements.

It may be possible to generate the components for ammonium nitrate/fuel oil (ANFO) type explosives in-situ when dealing with comets, as described in Ref. 2, which would significantly decrease the required mass of explosives to be delivered to the NEO. This in-situ manufacturing process is currently estimated in Ref. 2 to be doable concurrently with blast hole drilling.

The number of years required in Table 3 is based on the overall system operating (blast hole drilling and explosive emplacement) continuously 50% of the time. The composition of the "teams" has not yet been fully defined beyond including at least one human. Additionally, the equipment mass is only an estimate and could vary in practice by as much as + 200% or - 50%. This equipment mass estimate also does not include standard spacecraft equipment, crew life support, or robotic systems for explosives emplacement.

IV. Blasting Mission Outline

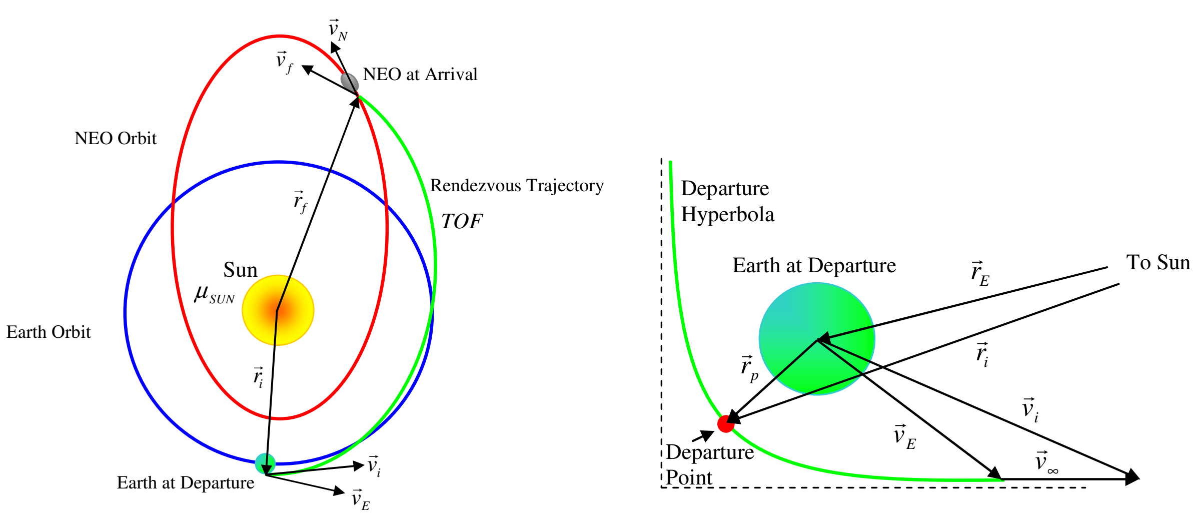
The NEO blasting mission begins once the requisite spacecraft components are prepared for launch from Earth. The spacecraft will launch at the appropriate time and rendezvous with the target NEO.

NEO proximity operations begin after the spacecraft has arrived on orbit with the NEO followed by NEO surface operations in which the human crew, robots, or some combination thereof drill the blast holes and emplace the distributed-energy blast charges. Next, the charges are detonated in a controlled sequence to fragment or deflect the NEO. An observation spacecraft on orbit with the NEO will observe the post-detonation state of the NEO to provide data for mission evaluation.

We survey these issues and present a general outline that captures the important steps in the mission, discuss the challenges and potential solutions, and provide some simulation and design numbers intended to provide some first-order sizing for selected aspects of the overall design problem.

A. NEO Rendezvous Trajectory Design

The NEO rendezvous trajectories presented herein are conic section ballistic arcs computed via a Lambert targeting algorithm, the derivation of which is found in the literature[4]. Two-body dynamics are assumed, with the Sun as the central body. The orbital geometry for rendezvous is presented in Fig. 1a and the Earth departure geometry is shown in Fig. 1b.



(a) **(b)**

Figure 1. (a) Geometry for Lambert targeting between the Earth and a NEO and (b) Earth departure geometry.

The functional form of the Lambert targeting algorithm is given in Eq. (1). The TOF and initial and final heliocentric position vectors are selected a priori, and the gravitational parameter of the Sun is provided as known input.

$$\left(\vec{v}_i, \vec{v}_f\right) = lambert\left(\vec{r}_i, \vec{r}_f, TOF, \mu_{SUN}\right) \tag{1}$$

The outputs of the algorithm are the required initial velocity on the rendezvous trajectory arc and the final velocity on the rendezvous arc at the time of arrival, after the TOF has elapsed. The total change in energy, and hence required fuel, to complete the rendezvous can now be computed. Two phases are examined: departure and arrival.

The departure geometry is shown in Fig. 1b. The energy required for departure is characterized by the quantity denoted as C_3, given by Eq. (2).

$$C_3 = v_\infty^2 = \left\|\vec{v}_i - \vec{v}_E\right\|^2 \tag{2}$$

The available launch mass for a particular launch vehicle is typically specified as a function of the C_3 required by a given rendezvous trajectory. Note that the initial velocity in Eq. (2) is computed via the Lambert algorithm as shown in Eq. (1) and the velocity of the Earth at the time of departure, obtained from an ephemeris. Subsequent sections will show the dependence of launch mass on C_3 for the launch vehicle chosen for this study.

Figure 2 depicts the geometry at the time of spacecraft arrival on orbit with the NEO, which marks the completion of the orbital rendezvous phase of the mission. The final velocity of the spacecraft on the rendezvous trajectory is provided by the Lambert algorithm and the position and velocity of the NEO are obtained from an ephemeris. In order to complete the rendezvous, the spacecraft must use its rendezvous thruster to perform a maneuver that matches its velocity to the required velocity for rendezvous, which is equal to the orbital velocity on the NEO's heliocentric orbit at the arrival point slightly behind the NEO along its orbit, as shown in Fig. 2.

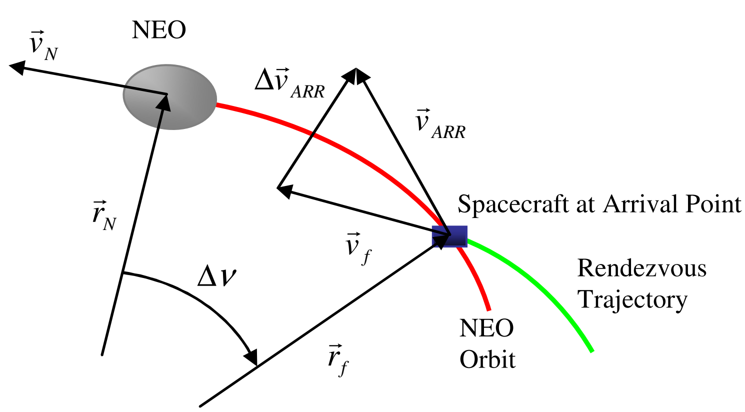


Figure 2. Geometry at NEO arrival.

The final position vector at the arrival point is determined by applying a small change to the NEO's true anomaly at the time of arrival to yield a position on the NEO's orbit slightly behind the NEO, as shown in Eq. (3). Note that the spacecraft may also arrive ahead of the NEO if that is deemed more advantageous for the mission.

$$\vec{r}_f = \vec{r}_N\left(\nu\left(t_{ARR}\right) - \Delta\nu\right) \tag{3}$$

Similarly, the required velocity at the time of arrival is equal to the velocity on the NEO's orbit at the point of arrival, as shown in Eq. (4).

$$\vec{v}_{ARR} = \vec{v}_N\left(\nu(t_{ARR}) - \Delta\nu\right) \tag{4}$$

The final velocity of the spacecraft along the rendezvous trajectory arc is provided by the Lambert algorithm as shown in Eq. (1), allowing the arrival maneuver to be computed via Eq. (5). The magnitude of this maneuver is a key factor in the payload mass calculations.

$$\Delta v_{ARR} = \left\| \vec{v}_{ARR} - \vec{v}_f \right\| \tag{5}$$

Once the orbital rendezvous is complete, the spacecraft will have consumed all of its arrival fuel and will jettison the arrival thruster and associated tankage to reduce its mass and improve its inertia tensor, making subsequent proximity operations and attitude maneuvers, respectively, more efficient. The proximity operations maneuvers will bring the spacecraft and its payload into close proximity with the NEO so that surface operations can commence in which the blast holes are drilled and the distributed-energy explosives emplaced for detonation.

The launch vehicle must contain in its payload fairing all of the mass required by the spacecraft. This total launch mass is the sum of many important spacecraft systems and components, but for this study we initially focus on three: fuel mass for arrival maneuver, the dry mass of the arrival thruster, and the deliverable payload mass, which includes distributing-energy blasting equipment, crew, and crew equipment, including the habitat spacecraft. This logical categorization of mass is depicted in Fig. 3.

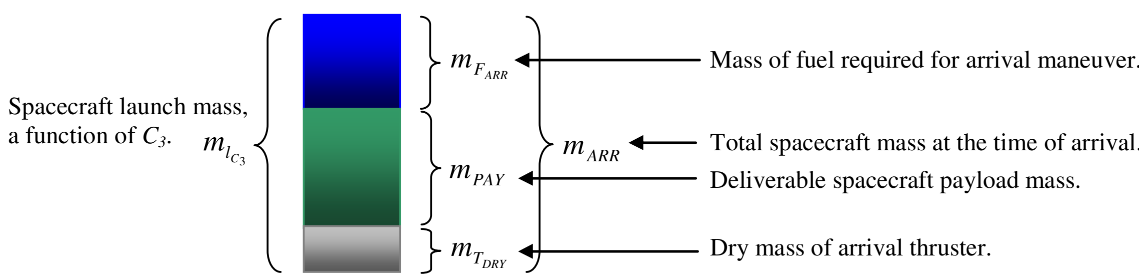


Figure 3. Logical spacecraft mass categorization.

The delivered payload mass is the true quantity of interest as it includes, among other things, the spacecraft structure, thrusters, sensors, instruments, power generators, communications hardware, and the payload of distributed-energy blasting equipment. Additionally, this deliverable payload mass must account for any robots or humans as well as life support and habitation for the humans, along with thrusters and fuel to return the human crew to Earth. Note that the additional mass for human crew return can be eliminated by a fully robotic mission. A further constraint is that the entire launch payload must fit in the payload fairing of the launch vehicle. While we cannot examine this factor at the current stage of the design process, it may turn out that the number of required launches will be driven by the total volume rather than total mass of the equipment.

The objective is to compute the delivered payload mass as a function of the rendezvous trajectory parameters and the launch vehicle and arrival thruster capabilities. We begin with a form of the rocket equation, presented in Eqs. (6). Note that I_{SP} is a measure of the efficiency of the arrival thruster and is in units of seconds. The parameter g is the acceleration of gravity at Earth's surface, 9.80665 m/s^2.

$$\begin{aligned} m_F &= m_{DRY}\left(e^{\frac{\Delta v}{g I_{sp}}} - 1\right) \\ m_{TOT} &= m_F + m_{DRY} \end{aligned} \tag{6}$$

Equations (6) can be written in terms of the mass quantities specified in Fig. 3 and the arrival maneuver magnitude given in Eq. (5), as shown in Eqs. (7).

$$
\begin{aligned}
m_{F_{ARR}} &= \left(m_{PAY} + m_{T_{DRY}}\right)\left(e^{\frac{\Delta v_{ARR}}{I_{sp}}} - 1\right) \\
m_{l_{C_3}} &= m_{F_{ARR}} + m_{PAY} + m_{T_{DRY}}
\end{aligned}
\qquad (7)
$$

Rearranging Eqs. (7) and solving for the deliverable payload mass yields Eq. (8).

$$
m_{PAY} = \left(\frac{m_{l_{C_3}}}{e^{\frac{\Delta v_{ARR}}{g I_{sp}}}}\right) - m_{T_{DRY}} \qquad (8)
$$

Equation (8) specifies the deliverable payload mass as a function of the rendezvous trajectory parameters, the launch vehicle capability, and the arrival thruster fuel efficiency. The most efficient trajectories maximize Eq. (8), allowing the maximum mass to be delivered to a given NEO for subsequent on-orbit operations. The launch vehicle performance profile utilized in this study is shown in Fig. 4, which depicts launch payload mass as function of C_3 for the Boeing Delta-IV Heavy, one of the most powerful launch vehicles currently available. The arrival thruster used is the Pratt & Whitney RL-10, a LOX/LH thruster featuring one of the highest specific impulses available in a contemporary upper stage engine, 451 seconds, and strong interplanetary mission heritage*.

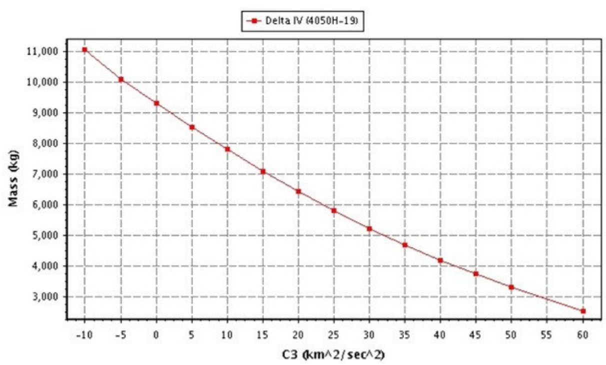


Figure 4. Launch payload mass performance for the Boeing Delta-IV Heavy†.

The NEO initial conditions in Table 1 were utilized, along with Earth ephemerides, in a Lambert targeting trajectory scanning software tool written for this analysis to compute and characterize trajectories to each target over a range of launch and arrival times beginning in 2008 and extending 30 years into the future. The trajectories were characterized according to Eq. (8) in order to identify the trajectory for each NEO that delivers the maximum amount of mass given the launch vehicle and arrival thruster performance. This maximized delivered payload mass was then compared to the required explosives and equipment mass totals from Table 3 for each NEO to compute a first-order estimate of the number of launches required, assuming them to be mass limited and not payload fairing size limited. These results are all summarized in Table 4.

It is clear from the data in Table 4 that significant advancements in launch vehicle capability are required to accommodate the payload masses called for by the current distributing-energy blasting system designs. The one

* http://www.pratt-whitney.com

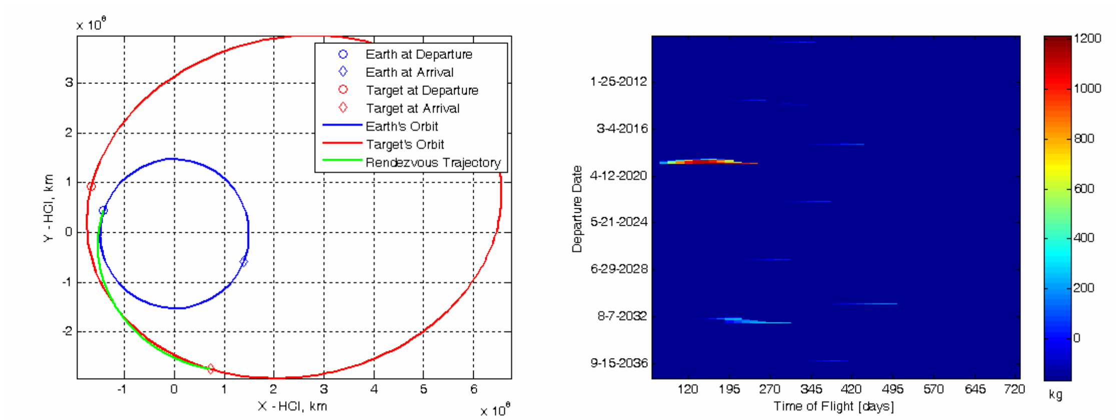
† http://elvperf.ksc.nasa.gov/elvMap/

exception is asteroid Itokawa, which can be accommodated in 6 launches, which is tractable. Thousands to tens of millions of launches are required for the other three NEOs, and such launch operations are clearly not feasible.

Table 4. Maximum delivered payload mass trajectory results and number of required launches for blasting.

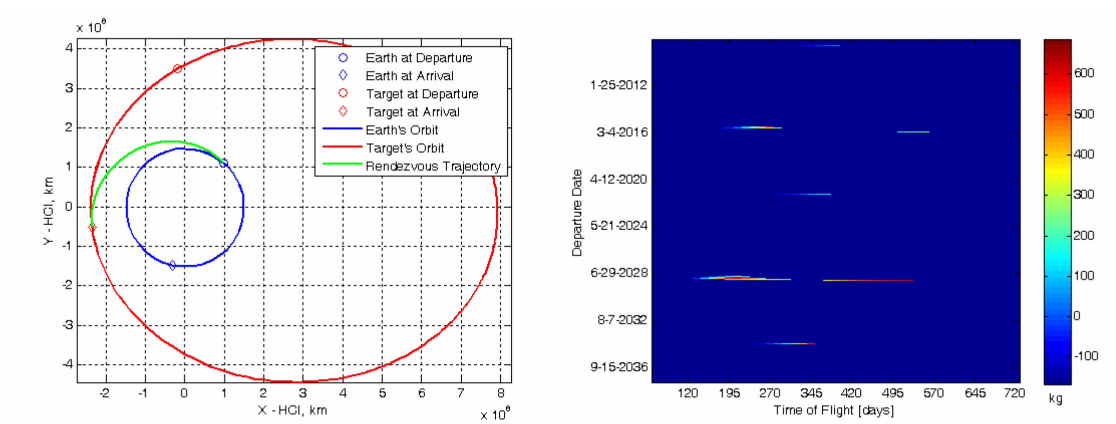
Destination NEO	Departure Date	Flight Time	m_{PAY} [kg]	Number of Launches
Asteroid 1986 DA	March 4, 2019	6 months	1215.42	1.843×10^8
Comet 81P/Wild 2	November 11, 2028	7 months	686.22	7.508×10^3
Asteroid Eros	February 8, 2035	8.5 months	2839.75	1.349×10^6
Asteroid Itokawa	May 18, 2036	6 months	5981.94	6

For reference, Figs. 5a thru 5a show each NEO orbit along with Earth's orbit and the maximum delivered payload mass rendezvous trajectory. Figures 5b thru 5b show how the delivered payload mass varies as a function of launch date and TOF for each NEO rendezvous scenario; the dark blue areas in the plots represent unreachable zones.



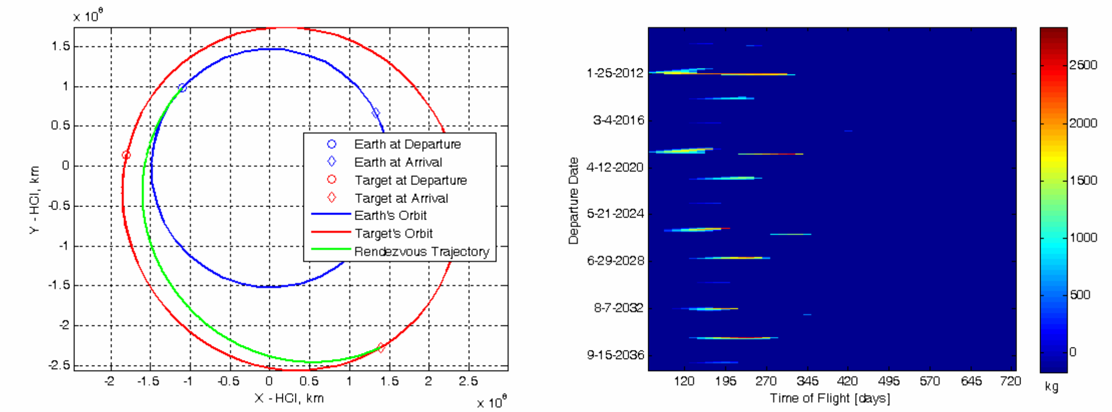
(a) **(b)**

Figure 5. (a) Maximum Payload Mass Rendezvous with Asteroid 1986 DA and (b) Maximum Payload Mass as a Function of Departure Date and Time of Flight



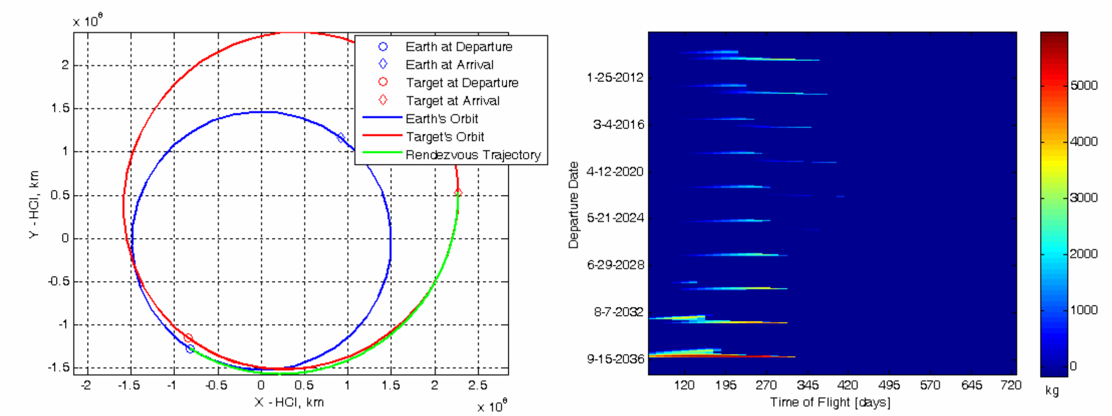
(a) **(b)**

Figure 6. (a) Maximum Payload Mass Rendezvous with Comet 81P/Wild 2 and (b) Maximum Payload Mass as a Function of Departure Date and Time of Flight



(a) (b)

Figure 7. (a) Maximum Payload Mass Rendezvous with Asteroid Eros and (b) Maximum Payload Mass as a Function of Departure Date and Time of Flight



(a) (b)

Figure 8. (a) Maximum Payload Mass Rendezvous with Asteroid Itokawa and (b) Maximum Payload Mass as a Function of Departure Date and Time of Flight

B. NEO Proximity Operations

Proximity operations around a NEO are a direct extension of well known proximity operations between spacecraft operating in Earth orbit. The techniques are readily extended to the case where the central body is the Sun, the reference orbit is the NEO's orbit, and the target object about which the spacecraft maneuver is the NEO. The two primary challenges arise in either harnessing or overcoming the NEO's own gravitational field and computing proximity operations maneuvers in the presence of the NEO's orbital eccentricity; traditional proximity operations equations are derived only for circular reference orbits and the dynamics do not include inter-spacecraft mutual gravitation. Note that there is significant heritage to build upon, such as the NEAR-Shoemaker mission of 2001, which operated in close proximity to the asteroid Eros for an extended period and the more recent Haybusa/MUSES-C mission to asteroid Itokawa, which also operated in close proximity to the asteroid. Furthermore, the aforementioned proficiency with proximity operations in Earth orbit ensures that NEO proximity operations for the distributed-energy blasting mission are tractable though rigorous analysis and design is still required.

NEO proximity operations begin once the final arrival maneuver is completed and the spacecraft is on orbit with the NEO, trailing (or leading it) by some nominal distance. The initial proximity operations maneuvers will bring the spacecraft within a few kilometers of the NEO, at which point final approach maneuvers will begin. For a multi-year operation it is necessary to place the crew habitat (which possibly also serves as the crew return vehicle) in a parking posture (hovering or orbiting) near the NEO that can be maintained with minimal fuel. The crew habitat might also be anchored to the NEO's surface to conserve fuel; further trade studies are required to determine whether mass is saved by including habitat anchoring equipment rather than habitat station-keeping fuel. Note that the spin/tumble state of a NEO will complicate communications and lighting. One possible strategy is to have the crew spacecraft station-keep relative to the NEO and let the NEO spin/tumble in front of the spacecraft to achieve NEO surface coverage from the spacecraft.

Subsequent to that, the crew must deploy to the NEO's surface and begin surface operations, possibly using environment suits equipped with small thrusters or surface tethers or both. We also recommend placing at least one supporting spacecraft, termed the NEO orbiter, in a close orbit about the NEO to provide the crew with NEO surface observations to aid in navigating to the correct locations for blast hole drilling. The NEO orbiter may also relay communications signals if line of sight between communication points is ever lost. These considerations, along with fuel efficiency and optimal solar panel pointing, will influence the trajectory design for the NEO orbiter.

The design of proximity operations around the NEO for any purpose is performed in one or both of two regimes: NEO-captured orbits that harness the NEO's own gravity and NEO-independent trajectories for which the spacecraft guidance, navigation, and control (GNC) system treats the NEO's gravity as yet one more perturbation to be rejected, either implicitly or explicitly. The spacecraft GNC system will have to fight solar gravity, planetary gravity, solar radiation pressure, and thermal re-radiation regardless. Additionally, in the case where the NEO's gravity is utilized, the fact that the NEO's gravitational field is severely non-spherical (owing to a severely non-spherical and non-homogenous NEO mass distribution) will complicate matters. Both of these regimes are surveyed in the sections that follow. Note that specific proximity operations design is not possible at this stage of analysis since specific drilling and explosive emplacement operations have not yet been defined.

1. NEO-captured Orbit Considerations

Analysis of NEO captured orbits begins with the concepts of the Sphere of Influence (SOI) and Sphere of Activity [*](SOA) centered at the NEO's center of mass. Both of these concepts are related to defining a volume of space around the NEO where its own gravity has the ability to dominate the motion of an object that is very small in comparison to the NEO.

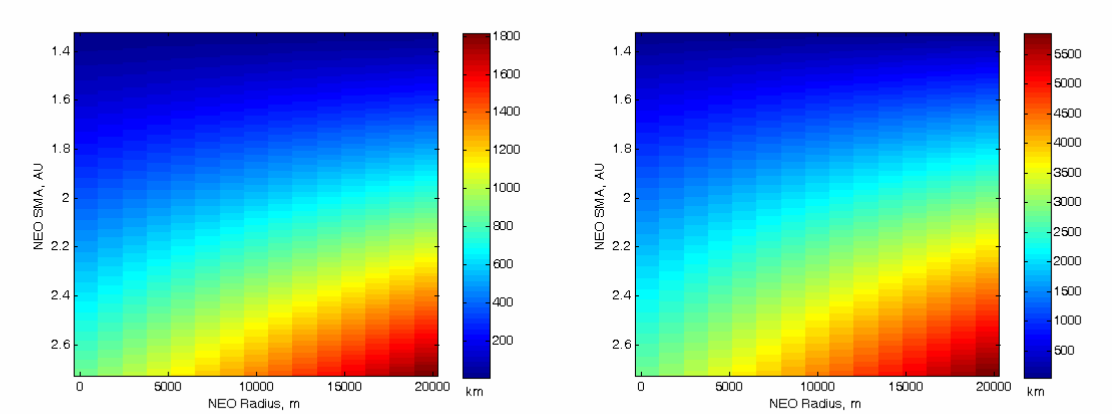
In this study we assume that the NEOs are spherical with homogeneous mass distributions and that the primary gravitational competitor to the NEO is the Sun. Further studies will have to refine these assumptions, but for now they readily provide initial sizing information. Equation (9) specifies the radius of the SOI in terms of the NEO's mass, heliocentric orbit semi-major axis, and the mass of the Sun[5]. Equation (10) specifies the NEO's SOA radius as a function of the same parameters as the SOI, but also includes the NEO's orbital eccentricity[6]. The difference between the SOI and the SOA is mostly operational; the SOI is intended to characterize the region about a planet within which the patched conic approximation is valid and the SOA is intended to characterize a three-body system in which one body is relatively tiny, e.g., a spacecraft near a NEO but also experiencing solar gravity, in terms of the volume in space around the second-largest body (the NEO) for which the tiny body can be in a captured orbit about the second-largest body.

$$r_{SOI} = a_{NEO}\left(\frac{m_{NEO}}{m_{SUN}}\right)^{\frac{2}{5}} \tag{9}$$

$$r_{SOA} \approx a_{NEO}\left(1-e_{NEO}\right)\left(\frac{m_{NEO}}{3m_{SUN}}\right)^{\frac{1}{3}} \tag{10}$$

To characterize the altitudes of both the SOI and SOA, a NEO orbital eccentricity was chosen that is the average of the eccentricities presented for the four target NEOs in Table 1, which is 0.407, and the semi-major axis was varied between the minimum and maximum values in Table 1. The NEO radii were varied between the range of NEO sizes presented in Table 2 for the target NEOs. This produces a parameter space that is representative of the NEOs discussed herein. The SOI results are shown in Fig. 9a and the SOA results are shown in Fig. 9b.

[*] The "Sphere of Activity" sometimes goes by other names in the literature, e.g., the "Hill's Sphere" or the "Roche Sphere."



(a) **(b)**

Figure 9. (a) Sphere of Influence altitude and (b) Sphere of Activity altitude for NEOs of varying radii and heliocentric orbit semi-major axis length.

In Figs. 9a and 9b is clear that the SOI radii are smaller than the SOA radii by approximately a factor of three and hence the SOI is treated as the more conservative estimate of the volume of space around a NEO in which a spacecraft can find stable NEO-dominated orbits.

Next, the surface gravity, surface escape velocity, orbital velocity in a circular NEO-captured orbit, orbital period in this NEO-captured orbit, SOI radius, and SOA radius were computed for all four target NEOs and the results are presented in Table 5. For these calculations each NEO was modeled as a homogeneous sphere with the largest ellipsoidal semi-axis length being used for the NEOs that have known elliptical dimensions in Table 2.

Table 5. NEO gravitational field analysis results.

NEO	Mass, metric tonnes	Surface Gravity Acceleration, m/s^2	Surface Escape Velocity, m/s	Circular Orbit Velocity at Twice NEO Radius, m/s	Circular Orbit Period at Twice NEO Radius, hrs	NEO SOI Radius, NEO radii	NEO SOA Radius, NEO, radii
Itokawa	3.270×10^{7}	0.000030	0.0040	0.0020	14.62	9.03	93.98
81P/Wild-2	7.127×10^{9}	0.000252	0.0263	0.0132	11.54	39.47	183.92
1986 DA	3.185×10^{10}	0.001607	0.0608	0.0304	4.18	69.92	264.16
Eros	7.797×10^{12}	0.001911	0.2511	0.1256	14.51	22.83	112.34

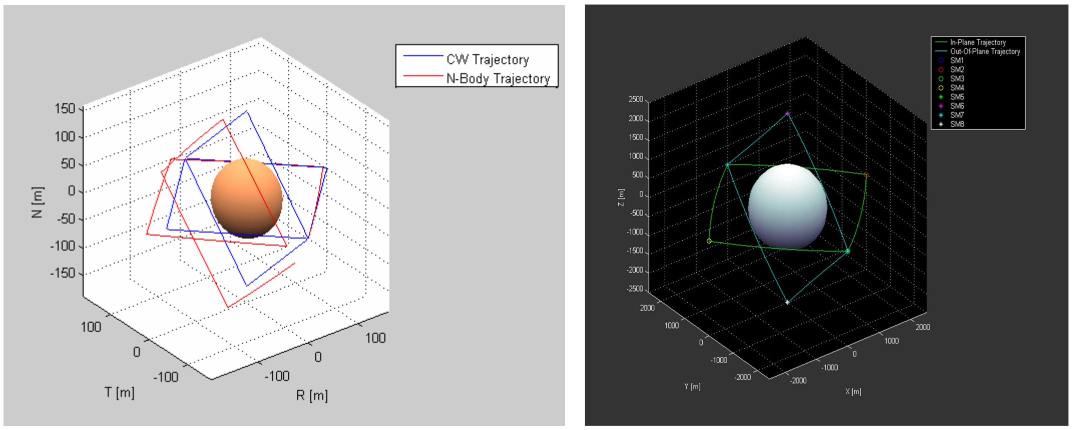
The surface gravitational acceleration and escape velocity are crucial parameters for planning NEO surface operations because they characterize the effort that must be expended to keep the crew on the NEO surface during drilling operations. These values are very small and highlight the challenges in providing the necessary reaction forces to operate the drilling equipment on the NEO.

The NEO SOI and SOA radii, expressed in terms of NEO radii for each NEO, provide a measure of assurance that captured NEO orbits are possible for all four NEOs though it is a bit tenuous for Itokawa, the least massive NEO. Note that the stability of captured orbits in the presence of the full dynamics model has not yet been evaluated, and this will drive the amount of fuel required to maintain NEO-captured orbits for the duration of the blasting mission.

Examining the simple case of circular orbits centered on the NEO, assuming two-body dynamics with the NEO as the central body, indicate very small orbital velocities and orbit periods on the order of tens of hours for orbit radii twice the NEO radii. This indicates that orbits can constructed that complete full revolutions around the NEO quickly enough or slowly enough to be useful, depending on what is needed.

2. NEO-independent Orbit Considerations

Trade studies may show that in many cases it is desirable to design relative motion about a NEO that treats the NEOs' gravity as a perturbation. This is feasible because the NEO's gravity is weak enough for a spacecraft to maneuver independently of it, even near the NEO. Consider Figs. 10a and 10b from two previous investigations, which show the trajectories followed by a spacecraft circumnavigating a NEO by flying through a series of waypoints that form a regular octahedron around the NEO for the purpose of viewing the entire surface of the NEO with sensors.



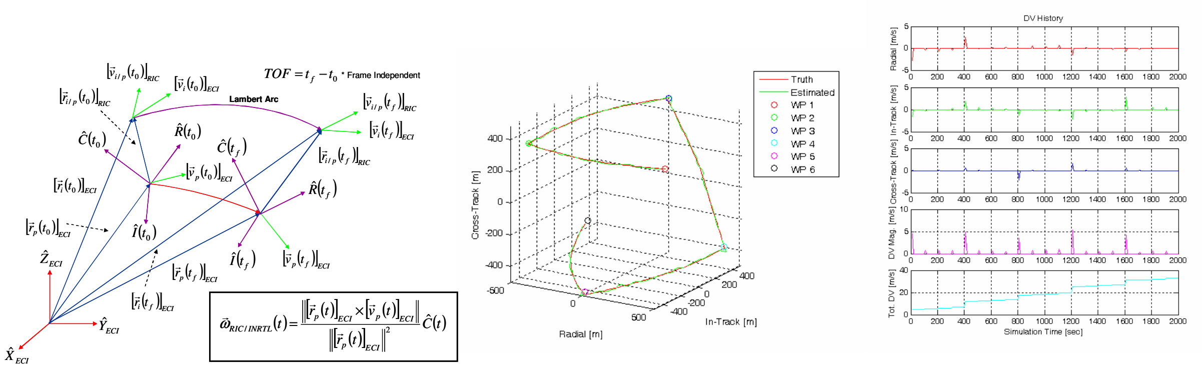
(a) **(b)**

Figure 10. Waypoint-based relative motion trajectories about a NEO (a) showing both linearized dynamics motion and non-linear dynamics motion including NEO gravity[7] and (b) showing only linearized motion and waypoints[8].

The magnitudes of the velocity change maneuvers and the flight times per trajectory segment in Figs. 10a and 10b are of the same order as those presented in Table 5 for NEO-captured orbits. Figure 10a shows the linearized trajectory computed using standard CW targeting along with the non-linear motion resulting from propagating the spacecraft's motion using a full n-body gravitational model that includes the NEO's own gravity acting upon the spacecraft. It is clear that the non-linear motion deviates from the linear model, but not catastrophically. As long as the spacecraft's navigation sensor measurements are of sufficient quality and the navigation filter in the spacecraft's flight software is capable enough, the spacecraft can control to follow the targeted trajectories as tightly as is required. The issues at this point are how much fuel is required for the duration of the mission and how long the spacecraft can continuously maneuver before its hardware begins to fail or its fuel is exhausted. Further trade studies are required to address these issues.

Regarding the issues of computing spacecraft maneuvers for proximity operations in the presence of non-linear dynamics and navigation uncertainty, we present Figs. 11a, 11b, and 11c, which are the result of unrelated previous work performed by the authors for spacecraft proximity operations in Earth orbit; the same principles apply around a NEO. Figure 11a presents all the relevant geometry for an algorithm to compute spacecraft proximity operations maneuvers using Lambert targeting, the same type of targeting used to compute the previously discussed interplanetary NEO rendezvous trajectories, instead of CW targeting. The advantage gained in doing so is that Lambert targeting is a non-linear method that includes two-body orbital mechanics whereas CW targeting is a linearized dynamics method that is necessarily less accurate. The advantage of using CW targeting is that it is somewhat less computationally intensive. Further trade studies are required to assess which approach best satisfies the requirements for proximity operations around a NEO.

Figure 11b shows the relative motion trajectory centered on a target spacecraft that results from applying control based upon estimated spacecraft states generated by filtering noisy measurements, which is exactly representative of what any spacecraft faces during a mission. The result is clearly that the spacecraft is able to control well enough to tightly follow the desired trajectory and arrive at all the scheduled waypoints. Figure 11c shows the control history and fuel consumption over time.



(a) (b) (c)

Figure 11. (a) Vector geometry for relative motion guidance using Lambert targeting, (b) relative motion achieved using Lambert relative guidance and applied control with navigation error in simulation, and (c) associated control history and fuel consumption in terms of Δv expenditure.

To bring the NEO proximity operations concepts together and prepare for a discussion of surface operations, we present Fig. 12., which shows a NEO with relevant reference frames, an example blast hole drilling location on the surface, and an example surface feature that might be used for navigation by the human or robotic crew. Figure 12 also shows a support spacecraft orbiting the NEO on a NEO-centered orbit that is, in general, the product of forced and natural motion, where the applied control is based on the estimated spacecraft state provided by the onboard navigation system. The reference frames shown in Fig. 12 are the standard Radial, In-Track, Cross-Track (RIC) relative motion frame and the NEO's body-fixed frame (NEO-BOD).

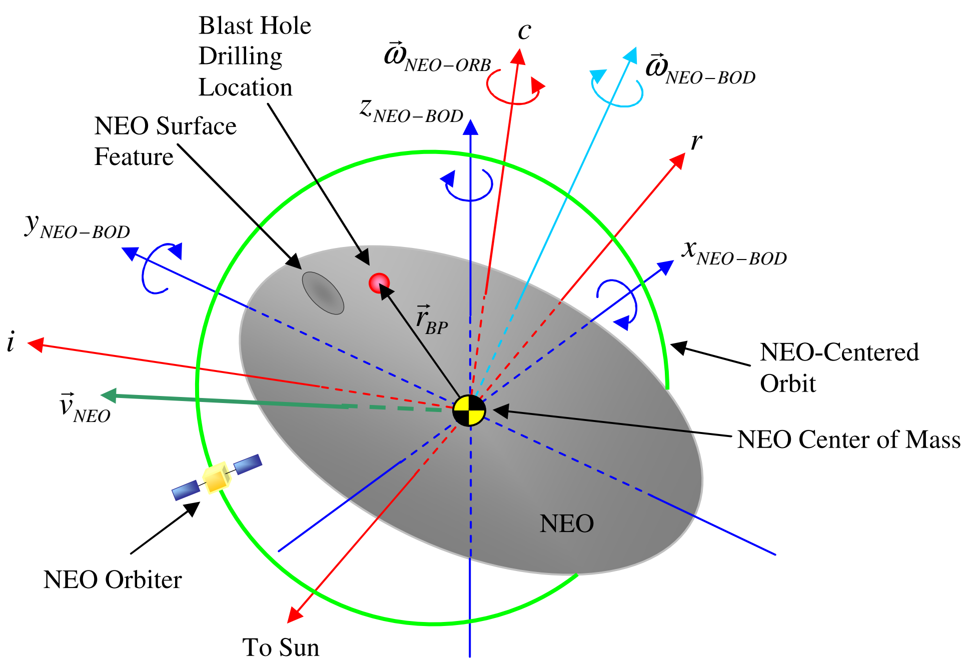


Figure 12. Reference frames and NEO-centered support spacecraft orbit required for proximity and surface operations.

3. General NEO Proximity Operations Considerations and Summary

Smooth and continuous natural motions about a NEO that result from the linearized equations of relative motion proceed with a period equal to that of the NEO's heliocentric orbit. This means that a spacecraft orbiting a NEO on such a trajectory will take around a year to make it all the way around once since most NEO orbits have a semi-major axis around 1 AU. By contrast, a captured orbit about the NEO that makes use of the NEO's gravity can have a much shorter period, on the order of hours, as shown previously. We have also presented another option, which is to use the equations of relative motion to construct a set of trajectories relative to the NEO that proceed through a series of waypoints relative to the NEO. In this fashion a complete circumnavigation of the NEO can be accomplished in a matter of hours or days instead of a year or more. All these possibilities must be analyzed for stability and resultant fuel requirements in order to assess feasibility and synthesize the best means of NEO circumnavigation for the purposes of constructing parking orbits and placing support spacecraft on the NEO-centered trajectories they need to be on to do their jobs.

Key to the assessment of guidance and control feasibility for NEO proximity operations trajectory realization is assessment of our ability to accurately navigate on orbit with the NEO. Both the absolute (Heliocentric Inertial, HCI) state and the state of spacecraft relative to the NEO, e.g., in the NEO's RIC frame, are important. These states must be able to be determined by the spacecraft to sufficient accuracy in order for operations to proceed. This essentially requires that the spacecraft's absolute and relative navigation measurements are consistently of sufficient quality to yield a serviceable certainty of a correct navigation solution when processed by onboard navigation filters. Further trade studies are required to characterize how accurately we can navigate in proximity to a NEO with respect to navigation accuracy requirements for the mission, which themselves need to be derived in detail in future work.

Understanding and accounting for the NEO's spin state is critical since the ultimate goal is to deliver drilling equipment and explosive charges to very specific points on the NEO's surface, which will be rotating of its own accord beneath any spacecraft in proximity to the NEO, provided that the spacecraft are not exerting control authority in order to remain fixed above a point on the NEO's surface. De-spinning a NEO is currently beyond our technological capabilities due to the tremendous mass and size and hence tremendous angular momentum of a rotating NEO.

One final note is that it is possible that attaining the level of launch and propulsion technology required to deliver a tremendous mass of blasting material to the NEO in the first place implies having the technology to also de-spin the NEO, but this cannot be assessed at this time. Interestingly, this further implies that we might also then have the technology to deal with a NEO using far more powerful methods than chemical or nuclear explosives, but we currently do not have enough information to assess this possibility.

C. NEO Surface Operations

NEO surface operations primarily consist of multiple human and robot crews traversing the NEO's surface and drilling blast holes at the required locations. Figure 12 shows an example blast hole drilling location at which a shaft will be drilled. The position of a blast hole location is specified by a vector naturally coordinated in a reference frame fixed to the NEO body, which is generally rotating. Meanwhile, a support spacecraft may be orbiting the NEO, along with the crew habitat. The support spacecraft may be providing telemetry to the crew to aid the crew in navigating successfully to the blast hole collar locations.

One possible method for aiding surface navigation is landmark tracking on the part of the supporting NEO Orbiter. Recognizable surface features, predominantly impact craters and pieces of rubble, are plentiful on all observed NEOs and their locations are fixed in the NEO's body-fixed frame. Optical landmark tracking measurements have been successfully used previously for navigation in close proximity to the Moon during lunar missions. Additionally, terrain recognition algorithms employed by terrestrial cruise missiles may have application here.

Other currently unsolved surface operation challenges include the anchoring of drilling equipment to the NEO to generate the required reaction forces for drilling. It is conceivable that thrusters might also be attached to the drilling apparatus armature to aid reaction force generation and to drive drill motion. Further design cycles and trade studies are required to address these issues.

One final issue mentioned for consideration is the need to precisely determine the NEO's spin state and center of mass location from observations on orbit. It is useful that previous studies have already developed algorithms for performing these determinations on tumbling spacecraft by processing optical observations to determine spin state and center of mass location[9].

D. Crew Life Support Issues

Throughout the entire mission, from Earth launch to proximity and surface operations and drilling and explosives emplacement operations, the crew must be kept alive and healthy. This will require a crew habitat and return vehicle that will keep the crew warm and provide an adequate air supply. Sufficient water and food supplies must be carried along, and methods to reclaim and recycle water or grow food will minimize the associated mass. Finally, the crew must be protected from the harsh radiation present in interplanetary space. All of the required equipment will contribute to the overall equipment mass required for the mission and further trade studies are required to characterize how much mass is required to support a human crew of a given size.

Given that NEO blasting missions are likely to be multi-year missions, as indicated in Table 3, psychological impacts on the crew must be accounted for and extensive training and conditioning for the crew will be required. Crew injuries are possible and on-site medical care must be available. Such considerations will help define crew member roles. Adequate measures must be taken to ensure that the crew's physical bodies do not atrophy to the point of uselessness in the microgravity environment. Long term microgravity health studies and design of countermeasures to the adverse affects of microgravity are required, and some progress along these lines has been made by NASA in the International Space Station (ISS) program.

The crew must also have adequate environment suits that permit sufficient mobility and dexterity for drilling and explosive emplacement operations while still providing adequate thermal and radiation shielding as well as sufficient atmospheric pressure. The suits will also have to be robust in the presence of abrasive NEO surface material and drilling debris.

Finally, crew scheduling and equipment availability must be accounted for. In Table 3, the time to complete the blasting operations is computed with the assumption of fully productive activity 50% of the time. This accounts for downtime for equipment maintenance and repair, and an additional discount for working with unfamiliar systems in an unfamiliar and hostile environment. Further trade studies are required to address these issues.

E. Terminal Mission Operations

Once all the blast holes are drilled and all the explosives are in place, the crew will return to their habitat vehicle and move to a safe distance from the NEO, which must be determined from the given mission parameters. At this point the explosives are detonated in sequence, hopefully producing the desired fragmentation or deflection of the NEO. As mentioned previously, there may be several drill-emplace-detonate cycles before the destruction of the NEO is complete, and the crew will have to retreat to a safe location prior to detonation for each iteration. The determination of a "safe distance" or "safe stand-off location" for the spacecraft and crew during blasting has not been determined. Once destruction or deflection is complete, the crew spacecraft will then embark upon an Earth return trajectory and the NEO Orbiter may stay behind to continue observing the post-detonation evolution of the NEO's trajectory or the trajectories of the NEO's fragments. The telemetry gathered will be studied on Earth in order to characterize mission success and apply all that is learned to subsequent NEO blasting missions in order to improve performance and efficiency.

V. Conclusion

We have discussed a conceptual mission design outline for deploying a distributed-energy fragmentation mission to a NEO using four example target NEOs to size parameters relative to the mission. Given the effective energy density of the overall distributed-energy blasting methodology, which includes the mass of explosive material, deployment equipment, crew life support, and spacecraft mass, the required launch mass even for the smallest NEO considered is daunting. Launch masses for moderately sized to large NEOs are beyond current or near-term propulsion technology, requiring an extremely extensive and time-consuming campaign of launches and subsequent operations for rendezvous and system deployment.

Furthermore, given the fact that an actual hazardous NEO will need to be rendezvoused with and destroyed or deflected wthin a specific timeframe, we will probably not have the luxury of waiting for the most optimal launch window and taking large amounts of time to perform a gradual rendezvous, especially one involving planetary flybys for gravity assist to conserve fuel. Rather, a reliable means of eliminating a threatening NEO must be agile enough to launch quickly and rendezvous quickly.

Bringing distributed-energy blasting up to a sufficient readiness level will require an initial campaign of on-orbit testing to refine the process and become proficient with rapid and reliable deployment, even in adverse circumstances. The ability to deploy missions of such magnitude implies improvements in space propulsion technology that may even allow NEO fragments containing useful material and of safe size to be returned to Lunar orbit or Earth-Moon Lagrange points for subsequent resource utilization and study.

The primary advance in space propulsion technology required is the development of ultra-high specific impulse thrusters that also offer high thrust magnitudes, enabling a high-mass payload to perform rendezvous with a given

NEO quickly. Launch technology must be improved in the same way, though alternative launch strategies that do not rely upon conventional exhausting thrusters (e.g., a space elevator) but can deliver high-mass payloads to Earth orbit may be employed if available. It is also possible to build bases on the Moon from which spacecraft can be launched on NEO rendezvous trajectories with less energy.

In the meantime, other strategies have been conceived of that are theoretically capable of eliminating hazardous NEOs by means of deflecting them using ultra high energy density systems, such as nuclear explosives deployed in standoff or surface burst modalities as described in Ref. 3. Future research into distributed-energy blasting will investigate using the distributed-energy technique to impart an impulse to a NEO with a specific orientation and magnitude, where the orientation and magnitude are achieved through proper placement of the charges and design of the detonation sequence. The algorithms for achieving this impulse vector will also account for arbitrary NEO shape, surface topology, composition, physical structure, and other relevant factors. Additionally, these algorithms will make use of research conducted regarding choosing the optimal orientation of the applied impulse vector, detailed in Ref. 3.

NEO proximity operations have been surveyed and found to be feasible based on first-order analyses. Key trade studies have been identified that will yield robust algorithms and systems for satisfactory GNC around a NEO.

The issue of sending a human crew to perform NEO drilling and explosives emplacement duties or oversee robots performing those duties have been surveyed and the key challenges identified. Heritage is building in this area from our experience in the near-Earth environment but this must be extended to interplanetary missions in order to make a multi-year crewed mission to a NEO feasible in terms of crew survivability.

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