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Planetary defense mission concepts for disrupting/pulverizing hazardous asteroids with short warning time

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ABSTRACT

This paper presents an overview of space mission concepts for disrupting or pulverizing hazardous asteroids, especially with warning time shorter than approximately 10 years. An innovative mission concept, referred to as a nuclear hypervelocity asteroid intercept vehicle (HAIV) system, employs both a kinetic-energy impactor and nuclear explosive devices. A new mission concept of exploiting a multiple kinetic-energy impactor vehicle (MKIV) system that doesn't employ nuclear explosives is proposed in this paper, especially for asteroids smaller than approximately 150 m in diameter. The multiple shock wave interaction effect on disrupting or pulverizing a small asteroid is discussed using hydrodynamic simulation results. A multi-target terminal guidance problem and a planetary defense mission design employing a heavy-lift launch vehicle are also briefly discussed in support of the new non-nuclear MKIV mission concept. The nuclear HAIV and non-nuclear MKIV systems complement to each other to effectively mitigate the various asteroid impact threats with short warning time.

KEYWORDS

planetary defense
kinetic-energy impactor (KEI)
asteroid disruption
terminal intercept guidance
heavy-lift launch vehicles (HLLV)

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1 Introduction

Despite the lack of a known immediate impact threat from an asteroid or comet, historical scientific evidence suggests that the potential for a major catastrophe created by an asteroid or comet impacting Earth is very real. Humankind must be prepared to deal with such an event that could otherwise cause a regional or global catastrophe. There is now growing national and international interest in developing a global plan to protect the Earth from a catastrophic impact by a hazardous near-Earth object (NEO). This growing interest was recently spurred by the Chelyabinsk meteorite impact event that occurred in Russia on February 15, 2013 and a near miss by asteroid 367943 Duende (2012 DA14), approximately 40 m in size, on the same day.

A variety of NEO deflection/disruption technologies, including kinetic impactors, gravity tractors, and nuclear explosions, have been investigated by planetary defense researchers during the past two decades [1–7]. Kinetic impactors and nuclear explosions are the most practically viable technologies for asteroid deflection or disruption, as concluded in the 2010 NRC report [6].

A so-called "kinetic impactor" mainly utilizes its translational momentum to cause an instantaneous ΔV of the center-of-mass of a target body as a result of its hypervelocity collision with the target body. In fact, such a kinetic impactor is a technically viable option for deflecting a small hazardous asteroid that can be detected with sufficient mission lead time ($>$ 10 years). However, it is probable that the kinetic impactor will cause unintentional fragmentation of a target asteroid because its hypervelocity kinetic energy can be too excessive compared to the gravitational binding energy, as well as the energy required for disruption, of the target asteroid. The term "kinetic impactor" should be distinguished from the term "kinetic-energy impactor (KEI)" that utilizes its hypervelocity kinetic energy for deliberately disrupting or pulverizing a target body.

All of the non-nuclear techniques, which are intended mainly for deflection missions, will require mission lead time much longer than 10 years, even for a small NEO ($\ll 150\,\text{m}$). When the time-to-impact with the Earth

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exceeds a decade, the velocity perturbation needed to alter the orbit of a target asteroid sufficiently to deflect it away from Earth impact is relatively small (approximately 1–2 cm/s). Thus, most non-nuclear options as well as a nuclear standoff explosion can be employed for deflection missions, if any hazardous asteroid can be detected with sufficiently long warning time. However, due to various uncertainties and constraints in asteroid detection and tracking, the warning time or mission lead time can be very short.

An 18-m-diameter meteor exploded with the energy of 30 Hiroshima nuclear bombs 30 km above the city of Chelyabinsk, Russia, on February 15, 2013, with no warning at all. Asteroid 367943 Duende (2012 DA14), which had a near miss of the Earth on the same day as the Chelyabinsk event, was initially discovered on February 23, 2012. That is, we would have had only one year of warning time if the 40-m DA14 was going to collide with Earth. Another recent example is asteroid 2014 RC, which had a close encounter with Earth on September 7, 2014. This 20-m asteroid was initially discovered on August 31, 2014 by the Catalina Sky Survey near Tucson, Arizona, USA, and independently detected the next night by the Pan-STARRS 1 telescope, located on the summit of Haleakala on Maui, Hawaii, USA. We would have had only one week of warning time if 2014 RC was going to collide with Earth.

If an asteroid or comet on an Earth-impacting course is detected with a short warning time (< 10 years), the challenge becomes how to mitigate its threat in a timely and reliable manner. For a small asteroid impacting in a sufficiently unpopulated region, mitigation may simply involve evacuation [6]. However, for larger asteroids, or asteroids impacting sufficiently developed regions, the threat may be mitigated by either disrupting the asteroid (i.e., destroying or fragmenting with substantial orbital dispersion), or by altering its trajectory such that it will either avoid impacting the predicted impact location, or miss the Earth entirely. When the time-to-impact with Earth is short, the velocity change required to deflect an asteroid becomes extremely large. Thus, for the most probable mission scenarios, in which the warning time is shorter than 10 years, the use of high-energy nuclear explosives in space may become inevitable [6]. To date, however, there is no consensus on how to reliably and safely mitigate the impact threat of hazardous NEOs with short warning time.

A scenario in which a small Earth-impacting NEO is discovered with short warning time is nowadays considered the most probable scenario because smaller NEOs greatly outnumber larger NEOs, and smaller NEOs are more difficult to detect. Most direct intercept missions with short warning time will result in arrival closing velocities of 10–30 km/s with respect to the target asteroid. A rendezvous mission to a target asteroid that requires such an extremely large arrival ΔV of 10–30 km/s is not feasible. When the warning time is short, disruption (for dispersive pulverization or vaporization) is likely to become the only feasible strategy, as was concluded in the 2010 NRC report [6]. Despite the various uncertainties and concerns about the nuclear disruption approach, nuclear disruption can become an effective strategy if most fragments disperse at speeds in excess of the escape velocity of the asteroid so that a very small fraction of fragments impacts the Earth. Because nuclear energy densities are nearly a million times higher than those possible with chemical bonds, a nuclear explosive device is the most mass-efficient means of storing energy with today's technology. However, in this paper, we propose a new non-nuclear approach as an option that can be employed to disrupt or pulverize asteroids smaller than approximately 150 m in diameter.

This paper will present a brief overview of an HAIV (hypervelocity asteroid intercept vehicle) mission concept of blending a kinetic-energy impactor and a nuclear subsurface explosion, followed by the description of a new non-nuclear MKIV (multiple kinetic-energy impactor vehicle) mission concept for disrupting or pulverizing small asteroids. Hydrodynamic code simulation results for examining the multiple internal shock wave interaction effect on disrupting or pulverizing a small asteroid will be discussed. The 2D hydrodynamic code model is comprised of a reference 5000-kg MKIV system consisting of a 1000-kg carrier vehicle, four 1000-kg KEIs, and a 2D circular 100-m solid object with a nominal density of 2000 kg/m^3. A new multi-impact terminal guidance problem and a planetary defense mission design employing a heavy-lift launch vehicle will also be briefly discussed. It is emphasized that the nuclear HAIV and non-nuclear

MKIV systems complement to each other to effectively mitigate the various asteroid impact threats with short warning time.

2 HAIV mission concept

NASA Innovative Advanced Concept (NIAC) Phase 1 & 2 studies, titled "An Innovative Solution to NASA's Near-Earth Object (NEO) Impact Threat Mitigation Grand Challenge and Flight Validation Mission Architecture Development", have been conducted at the Asteroid Deflection Research Center (ADRC) of Iowa State University in 2011–2014. The study objective was to develop an innovative, yet practically implementable mitigation strategy for the most probable impact threat of an asteroid or comet with short warning time (< 10 years). The NIAC study has resulted in an HAIV (hypervelocity asteroid intercept vehicle) mission concept employing both a kinetic-energy impactor and nuclear explosive devices (NEDs), as illustrated in Fig. 1.

The HAIV mission concept is intended to optimally reduce the severity and catastrophic damage of an NEO impact event, especially when we don't have sufficient warning time for non-destructive deflection of a hazardous NEO. Detailed technical descriptions of the HAIV system, planetary defense mission design, and terminal guidance control technologies can be found in Refs. [8–29]. The NIAC study results can also be found in the final technical report, which can be downloaded from the ADRC website (www.adrc.iastate.edu).

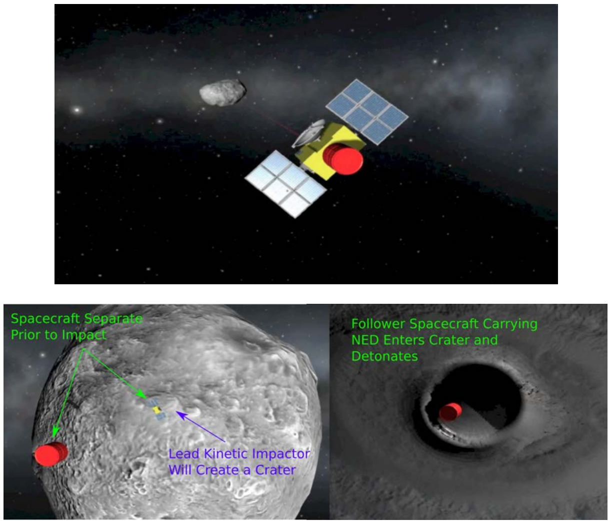


Fig. 1 A notional depiction of the HAIV mission concept [8, 9, 14, 15]. Reproduced with permission from Ref. [8], © IAA 2012.

Most direct intercept missions with short warning time will result in closing arrival velocities of 10–30 km/s (relative to a target asteroid). A rendezvous mission to a target asteroid, requiring such an extremely large arrival ΔV of 10–30 km/s, is not practically feasible. A nuclear subsurface explosion, even with shallow burial to a depth of 3–5 m, can deliver a large amount of energy into the target asteroid, so that there is a likelihood of totally disrupting the target asteroid. Such subsurface nuclear explosions are known to be at least 20 times more effective than a nuclear contact burst [30]. However, state-of-the-art nuclear subsurface penetrator technology limits the impact velocity to less than about 300 m/s because higher impact velocities prematurely destroy the fusing mechanisms/electronics of nuclear explosive devices [30].

The HAIV system concept overcomes such practical constraints on the penetrated subsurface nuclear explosion. It will enable a nuclear disruption mission with intercept velocities as high as 30 km/s. The HAIV is a two-body space vehicle consisting of a fore body (leader) and an aft body (follower), as illustrated in Fig. 1. The leader spacecraft creates a kinetic-impact crater in which the follower spacecraft carrying nuclear explosive devices (NEDs) makes a robust and effective explosion below the surface of the target asteroid body. Surface contact burst or standoff explosion missions will not require such a two-body vehicle configuration. However, for a precision standoff explosion at an optimal height of burst, accurate timing of the nuclear explosive detonation will be required during the terminal guidance phase of hypervelocity intercept missions.

As illustrated in Fig. 2, the terminal guidance phase may begin 2 h prior to the final intercept collision. The nuclear fuzing system may be activated, arming the NED payload, much earlier in the terminal phase operations timeline. Instruments located on the leader spacecraft detect the target NEO, and a terminal guidance subsystem on-board the HAIV becomes active. Measurements continue through visual/IR cameras located on the leader spacecraft and an intercept impact location is identified on the target asteroid body. The high-resolution visual/IR cameras provide successive images of the NEO to the terminal guidance system for a few trajectory correction maneuvers. Separation must occur between the leader spacecraft and the follower spacecraft before the leading kinetic-energy impactor

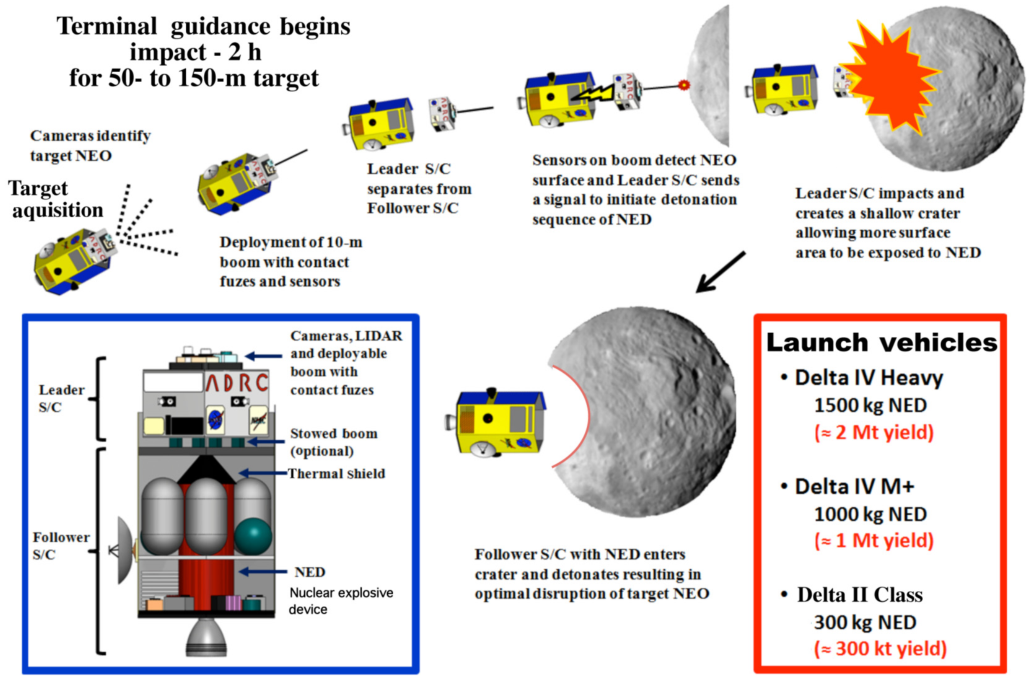


Fig. 2 A reference HAIV flight system and its terminal guidance operational concept [9]. Reproduced with permission from Ref. [9], © IAA 2013.

collides with the target. A variety of existing launch vehicles, such as Delta II class, Atlas V, Delta IV, and Delta IV Heavy, can be used for the HAIV mission carrying a variety of NED payloads of mass ranging from 300 (with approximately 300-kt yield) to 1500 kg (with approximately 2-Mt yield).

Because the hypervelocity kinetic impact and nuclear subsurface explosion simulations rely heavily on energy transmission through shocks, the early research work conducted for the HAIV mission concept study [11, 12] used adaptive smoothed particle hydrodynamics (ASPH) to mitigate some of the computational and fidelity issues that arise in more complex, high-fidelity hydrocode simulations. The propagation of the nuclear explosive shock can be seen for an illustrative benchmark test case shown in Fig. 3. The shock propagation process dissipates some energy due to interactions with the rebounding shock front. In the center area of deeper regolith, the seeding process naturally results in a much more porous material, absorbing energy from the shock. Upon reaching the second core at the far side, some large chunks escape the disruption process in some cases (even with lower material strengths). An improved ASPH code, implemented on a modern low-cost GPU desktop computer, has been developed for the HAIV mission study [11, 12].

3 Experimental HAIV flight demonstration mission

This section briefly describes a flight demonstration mission design conducted for an experimental HAIV system in Refs. [14, 17]. It is emphasized that such an experimental HAIV demonstration mission design is directly applicable to an MKIV system to be presented in the next section.

3.1 NEO science missions

Between 1986 and 2011, a total of eleven science spacecrafts have performed flybys of six comets and seven asteroids, and rendezvoused with two asteroids [14]. Although there has been no space mission for directly demonstrating or validating planetary defense technologies, space agencies such as NASA, ESA, and JAXA have had several successful missions that demonstrate technology and mission capabilities that are somewhat relevant to planetary defense. Some of the most notable missions to NEOs are the Hayabusa mission by JAXA, and the NEAR-Shoemaker and Deep Impact missions by NASA.

In early December of 2014, Japan's JAXA launched

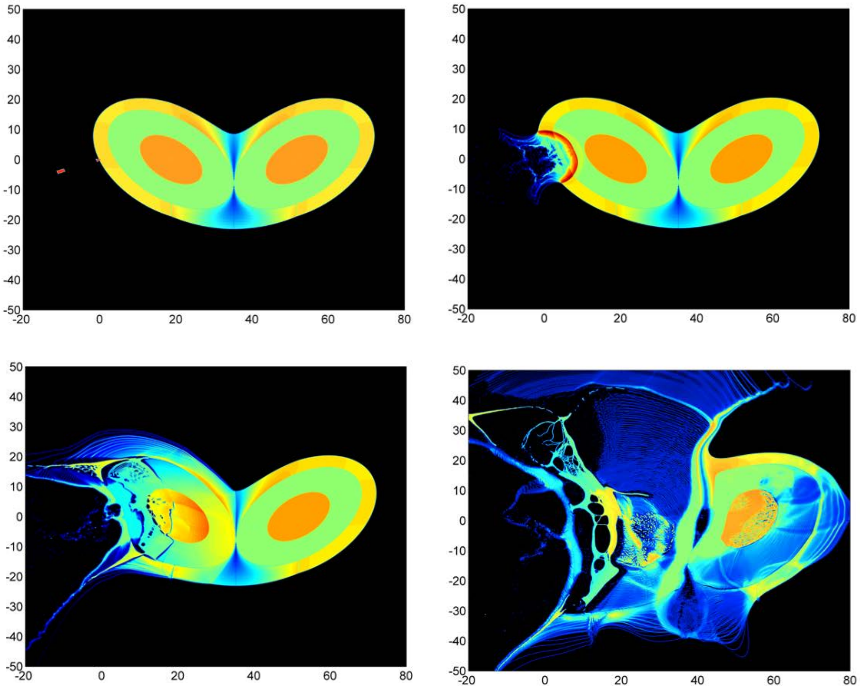


Fig. 3 A 70-m asymmetric 2D model disrupted by a 10-km/s kinetic impact and a subsequent 70-kt nuclear subsurface explosion of the HAIV system [11, 12]. Reproduced with permission from Ref. [11], © IAA 2012.

an asteroid sample return mission known as Hayabusa 2 with the goal of returning samples from the NEA 162173 (1999 JU3). On September 8, 2016, NASA launched the OSIRIS-REx mission to rendezvous with asteroid 101955 Bennu (1999 RQ36) and return samples of the asteroid material to Earth in 2023. This mission will utilize large deep space maneuvers, an Earth gravity assist, rendezvous and proximity operations maneuvers, and an asteroid departure maneuver.

3.2 Experimental HAIV mission design

The overall configuration/system design of an experimental HAIV system is illustrated in Fig. 4. This reference HAIV system consists of the leading impactor portion of the vehicle, the trailing follower portion of the vehicle (carrying the dummy mass proxy for the NED), and the 10-m AstroMast extendable boom that provides the necessary separation between the impactor and follower during NEO impact. This optional configuration employing a deployable boom ensures that the two parts of the vehicle remain collinear during impact. The length of the boom is customized for the particular mission scenario at hand such that the boom length provides an appropriate delay time between when the impactor creates the crater on the NEO and when the follower arrives in the crater and detonates the NED. The appropriate delay time is of course dependent on the terminal approach profile, which is chiefly dominated by the HAIV velocity relative to the NEO at impact.

For launch vehicles, the United Launch Alliance (ULA) Atlas V 400/500 Evolved Expendable Launch Vehicle (EELV) Series, the SpaceX Falcon 9, and the Boeing Delta IV series were studied in Ref. [14]. The Atlas V 401 with a 4-m fairing was finally selected as the primary launch vehicle for an HAIV flight demonstration mission study.

Asteroid 2006 CL9 was chosen as a reference target of the conceptual flight validation mission design. The physical and orbit properties of 2006 CL9 are presented in Table 1. The orbital elements of 2006 CL9 listed in this table are heliocentric ecliptic J2000 orbital elements at epoch JD 2456400.5 (2013-04-18.0) TDB (JPL Orbit ID 26).

An important consideration in target selection was how well the orbit of the NEO is known. If there is too much uncertainty in our knowledge of the NEO's orbit it may not be possible to guide the HAIV to a precision intercept with the NEO. The quality of NEO orbit knowledge is usually expressed by the orbit condition code (OCC), which is an integer scale describing the amount of along-track uncertainty in the NEO orbit knowledge. The size, shape, and orientation of NEO orbits are generally easier to estimate than the position

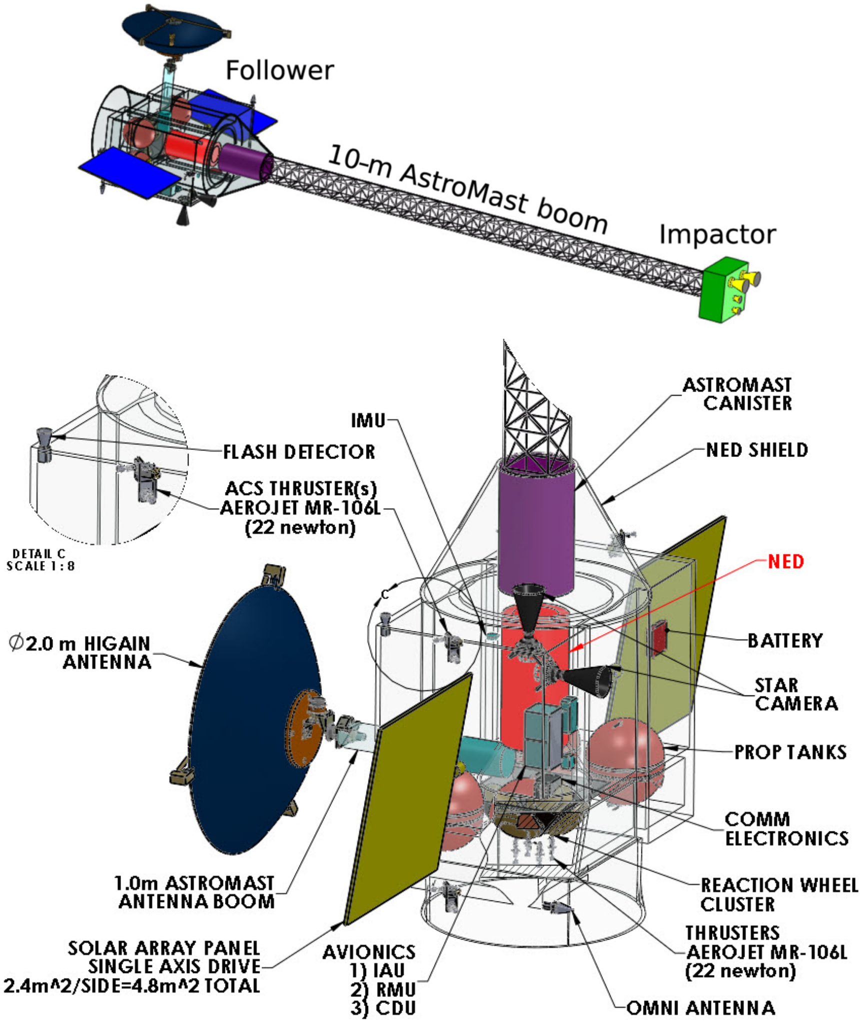


Fig. 4 An experimental HAIV flight system [14]. Reproduced with permission from Ref. [14], © IAA 2014.

Table 1 Physical and orbital properties of a reference target (asteroid 2006 CL9) [14]

Parameter	Value
Absolute magnitude H	22.73
Estimated diameter ($w/p = 0.13$)	104 m
Estimated diameter ($w/p = 0.25$)	75 m
Rotation period	$0.145 \pm 30\%$ h
Semi-major axis a	1.34616 AU
Eccentricity e	0.23675
Inclination i	2.93551 deg
Longitude of ascending node Ω	139.313 deg
Argument of perihelion ω	9.94912 deg
Mean anomaly at epoch M_0	209.664 deg
OCC	5
Earth MOID	0.03978 AU

of the NEO along its orbital path, and the location of the NEO on its orbit is therefore usually the least well known aspect of the NEO's orbit. The OCC scale ranges from 0 (very well known orbit) to 9 (very poor orbit knowledge), and NEOs with OCC > 5 are generally considered "lost" for the purposes of locating them in the sky during future observing opportunities [14].

Note that two estimated diameter values for 2006 CL9 are presented in Table 1 based on the parameter p, which is the geometric albedo of the NEO (a measure of how optically reflective its surface is). The albedos of NEOs vary widely and are very difficult to ascertain from ground-based observations. This leads to significant uncertainty in the physical size of most known NEOs. The problem can be summarized as: small shiny objects can have the same brightness in the sky as large dull objects. The intrinsic brightness of the NEOs, expressed by the absolute magnitude H, is much better constrained (because it is directly observed) than albedo [14].

A reference mission trajectory selected for 2006 CL9 is summarized in Table 2. The reference trajectory design

Table 2 Notional flight validation mission selected for 2006 CL9 [14]

Parameter	Value
Earth departure date	2019-08-02
Earth departure C_3	11.99 $\mathrm{km}^2/\mathrm{s}^2$
Flight time to intercept	121.41 days
NEO relative velocity at intercept	11.5 km/s
Approach phase angle	3.04 deg
Max. distance from Earth	0.36 AU
Max. distance from Sun	1.28 AU

is based on patched conics with Lambert targeting applied to high-fidelity ephemerides for the Earth and NEO, and, therefore, no deterministic ΔV is required on the part of the spacecraft in this initial trajectory design.

A reference orbital trajectory of an experimental HAIV mission to asteroid 2006 CL9 is shown in Fig. 5, which is similar to the Deep Impact mission trajectory due to the fact that both missions are intended to directly intercept and impact the target object. For the Atlas V 401, the dispersion on the Earth departure C_3 is 0.15 $\mathrm{km}^2/\mathrm{s}^2$, which leads to a ΔV for launch dispersion correction of approximately 26 m/s, including maneuver execution errors. The declination of the launch asymptote (DLA) and right ascension of the launch asymptote (RLA) are $-12.0°$ and 52.4°, respectively. The time of injection into the outbound Earth departure hyperbola is 2019-08-02, 08:47:26.443 UTC. The flight time to NEO intercept is 121.41 days, which leads to a time of intercept of 2019-12-01, 18:37:50.443 UTC. The velocity relative to the target at intercept is 11.5 km/s and the approach phase angle is 3 deg. The maximum distance from the Earth is 0.36 AU and the maximum distance from the Sun is 1.28 AU. This particular trajectory design was assumed to be the middle of the launch window. The total post-launch ΔV budget for the mission is 37.1 m/s.

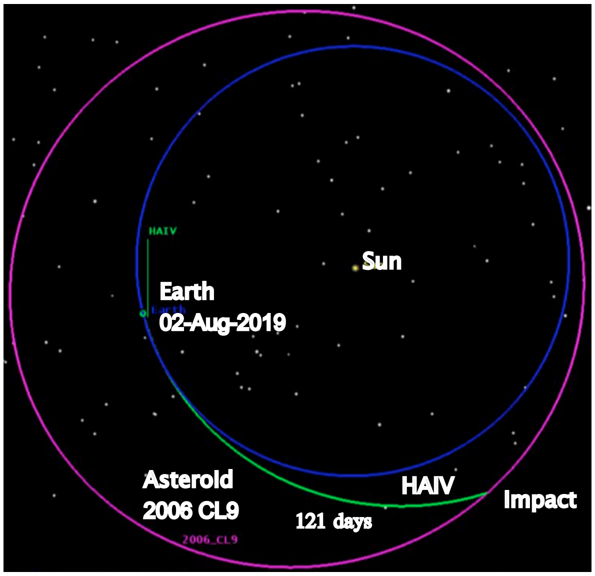


Fig. 5 An experimental HAIV mission trajectory for a target asteroid (2006 CL9) [14, 17]. Reproduced with permission from Ref. [14], © IAA 2014.

4 New MKIV mission concept

As discussed in Ref. [31], a hypervelocity kinetic-energy impactor (KEI) with an impact speed larger than approximately 5 km/s has a "mass-multiplication efficiency" of approximately 10^5–10^7. That is, a unit mass of optimally configured KEI can pulverize 10^5–10^7 times its own mass of a target asteroid. For example, a 1000-kg hypervelocity KEI may be able to pulverize and disperse an asteroid with a mass of 10^8–10^{10} kg. In Ref. [31], the specific energy (per unit asteroid mass) required for dispersive pulverization of asteroids of 30 m–10 km in diameters is stated as approximately 100–10,000 J/kg and the specific energy for vaporizing them is stated as approximately 1×10^6–3×10^6 J/kg.

A 1000-kg KEI with an impact speed of 10 km/s has a kinetic energy of 5×10^{10} J, and it can cause a center-of-mass ΔV of at least 1 cm/s for a 100-m (diameter) spherical asteroid with a uniform density of 2000 $\mathrm{kg/m}^3$ via an ideal linear momentum transfer. Note that a 100-m (diameter) spherical asteroid with a uniform density of 2000 $\mathrm{kg/m}^3$ has a mass of 10^9 kg and that its gravitational binding energy is approximately 8×10^5 J, which is relatively small compared to the kinetic energy (5×10^{10} J) of a 1000-kg hypervelocity KEI with an impact speed of 10 km/s.

In Ref. [31], dispersive pulverization of an asteroid into meter-scale fragments by exploiting the hypervelocity kinetic energy was proposed as an option for mitigating the impact threat of small asteroids, especially with short warning time. However, fragmenting a solid object into pieces of pre-specified maximum scale (e.g., 1-m fragments) requires the imposition of a fracture-level stress field having the same periodicity. In order to maximize the fragmentation benefits of large-scale crack propagation, the simultaneous imposition of such stress field over a large fraction of the object was considered in Ref. [31]. As a result, various innovative ways (e.g., a massive 3D penetration projectile lattice, multiple large spinning nets, etc.) of effectively distributing the hypervelocity kinetic-impact energy to dispersively pulverize a small asteroid were proposed in Ref. [31]. However, a deployment of such large complex structures in space will require advanced space technologies that will not be readily available in the near future.

In this paper, expanding upon the fundamental "mass-multiplication efficiency" property of the hypervelocity KEI as described in Ref. [31], we present a new non-nuclear MKIV mission concept [32] for dispersively disrupting small asteroids detected with short warning time ($<$ 10 years). The MKIV system proposed for asteroid disruption (without employing nuclear explosives) consists of a carrier vehicle (CV) with on-board visual/IR seekers and a number of KEIs attached to the CV, each equipped with its own divert and attitude control thrusters. The MKIV mission concept is basically similar to the concept of an MKV (multiple kill vehicle) system developed by Lockheed Martin [33] as part of the Ballistic Missile Defense System of the United States. Two different deployment schemes of the MKV system have been developed. The MKV-L by Lockheed Martin consists of a CV and attached KEIs, while the MKV-R by Raytheon consists of identical multiple KEIs without a CV [33, 34]. The MKV was once envisioned in the early 2000s and is being re-developed as an MOKV (multi-object kill vehicle) since 2015.

As illustrated in Fig. 6, near a target asteroid, the CV of an MKIV system will dispense several KEIs and guide them to hit near-simultaneously different locations widely distributed across the target surface area and to cause shock waves to more effectively propagate across the wider surface area. Figure 6(b) also illustrates a variant of the baseline MKIV concept, which attempts to exploit a potential effectiveness of the 3D penetration projectile lattice concept [31].

The proposed MKIV system with its total mass in the range of 5000–15,000 kg can be launched from a single large booster such as Delta IV Heavy, Falcon Heavy, or the SLS. The MKIV system will complement a less heavier HAIV system carrying NEDs, which was originally conceived for disrupting larger asteroids ($>$ 150 m). The MKIV concept can also be extended to a nuclear multi-HAIV system for much larger asteroids ($>$ 500 m). Note that it may be impractical to design a single massive ($>$ 5000 kg), yet highly agile, kinetic-energy impactor with a precision terminal intercept maneuvering capability.

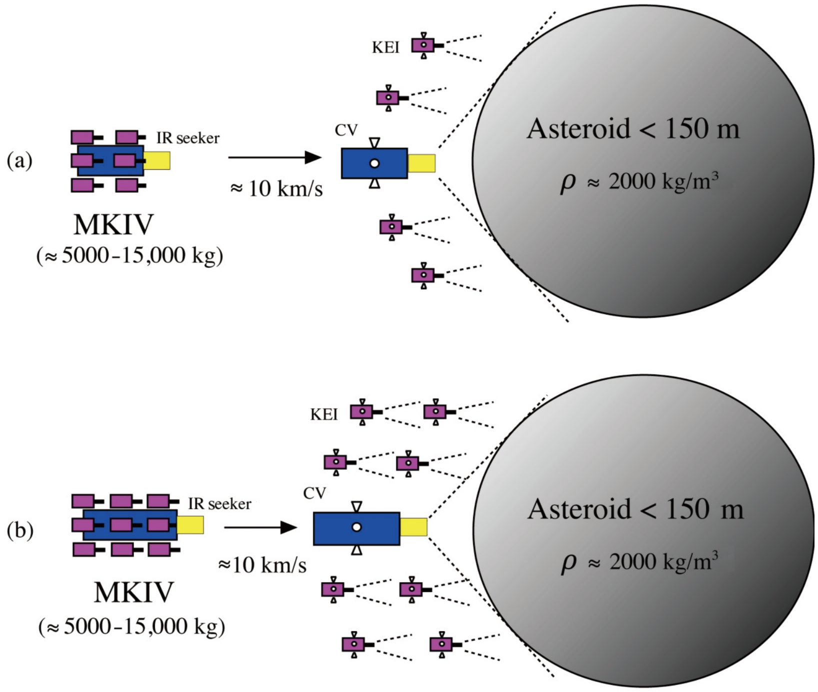


Fig. 6 Conceptual 2D illustration of a non-nuclear MKIV mission concept for dispersive disruption or pulverization of a small asteroid [32]. Reproduced with permission from Ref. [32], © AAS 2015.

5 Hydrocode simulation of multiple kinetic-energy impacts

Simulation results of multiple kinetic-energy impacts obtained using an in-house GPU-accelerated hydrocode are briefly discussed in this section. Modeling and simulation of hypervelocity kinetic-energy impacts and nuclear explosions for deflecting or disrupting asteroids is a complex physical/computational problem, as extensively investigated in Refs. [10–12,35–43]. A simple 2D simulation model is developed in Refs. [40–43] for multiple kinetic-energy impacts. It is comprised of a reference 5000-kg MKIV system, consisting of a 1000-kg CV and four 1000-kg KEIs, and a 2D circular 100-m object with a nominal density of 2000 kg/m^3. The main objective of conducting a hydrocode simulation study in Refs. [40–43] was to determine whether an asteroid can be dispersively pulverized by the proposed MKIV system more effectively than by a single massive KEI of the same total mass as the MKIV system.

5.1 Hydrocode simulation cases

An ideal 2D hydrocode simulation model for a single KEI is illustrated in Fig. 7. The target body is modeled as a 2D circular 100-m-diameter solid body with a nominal uniform density of 2000 kg/m^3, while the KEI is modeled as a 1 m × 1 m box. No porosity effects are considered for the target asteroid. The asteroid body is modeled as granite, while the KEI is modeled as aluminum.

Two distinct mission scenarios for multiple kinetic-energy impactors are illustrated in Fig. 8. For multiple KEIs in parallel, shown in Fig. 8(a), all KEIs are assumed to hit simultaneously at time $t = 0$, and the kinetic energy transferred to the target body is monitored in simulations. The multiple KEIs arranged in series, as illustrated in Fig. 8(b), is slightly more challenging for hydrocode simulations. Each KEI is spaced 10 m apart, and at time $t = 0$, the lead KEI hits the target. It is assumed that each KEI is completely destroyed in these simulations before the following KEI hits the bottom of the crater. All KEIs again are assumed as 1 m ×1 m boxes.

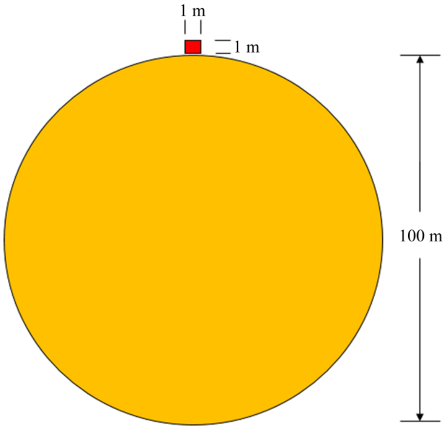
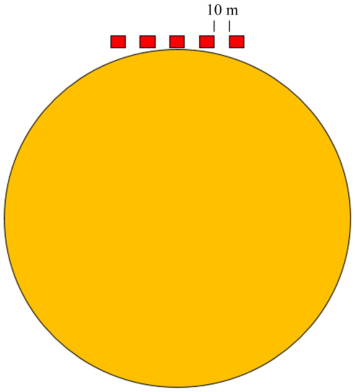
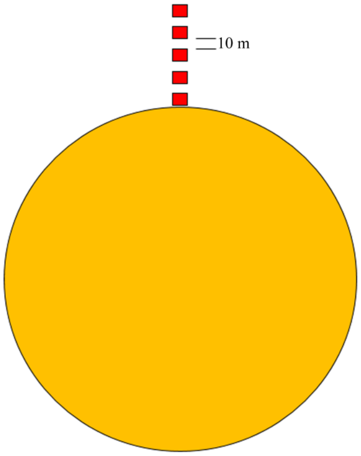


Fig. 7 An ideal 2D hydrocode simulation model with a single kinetic-energy impactor [40, 41]. Reproduced with permission from Ref. [40], © IAA 2015.



(a) Multiple KEIs in parallel



(b) Multiple KEIs in series

Fig. 8 2D illustration of two distinct mission engagement scenarios of multiple KEIs [40, 41]. Reproduced with permission from Ref. [40], © IAA 2015.

Several simulation test cases are considered in Refs. [40, 41]. For Case 1, the size of the single KEI is not varied, while its mass is varied from 162, 600, and up to 1000 kg. The depth of the generated crater is monitored at several elapsed time. For Case 2, the KEI mass is held at 1000 kg, but the shape is varied from a square box to a rectangular box. Again, the crater depth is monitored at several time. Case 3 explores a single massive 5000-kg KEI, while Cases 4 and 5 consider the multiple impact scenarios in parallel and series, respectfully. In this section, we briefly discuss only Cases 3, 4, and 5 as follows.

5.2 Case 3

This case considers a single massive KEI with a mass of 5000 kg traveling at 10 km/s. The simulation results showing the density contours are shown at three different elapsed time in Fig. 9. The single massive KEI generates a substantially deep crater, roughly 5 m in depth at 3 ms of simulation time. The shock wave produced in the asteroid body is significantly stronger than Case 1 with a 1000-kg KEI.

5.3 Case 4

In this test case, a parallel deployment of multiple KEIs with the CV impactor is considered. At $t = 0$, it is assumed that all impactors strike the target. All impactors have the same initial kinetic energy, traveling downward at 10 km/s. It is important to note that the CV impactor in the middle hits perpendicular to the target body, while the remaining four KEIs are slightly off from perpendicular, as can be noticed in Fig. 10.

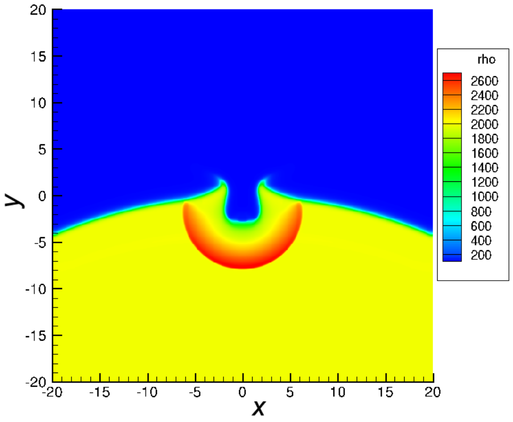
5.4 Case 5

Rather than placing multiple KEIs in parallel, an array of multiple KEIs in series is considered for Case 5. At $t = 0$, the lead CV impactor makes contact with the target. Each impactor is traveling downward at 10 km/s, meaning that after an impactor hits, a follower impactor will make contact roughly 0.1 ms after.

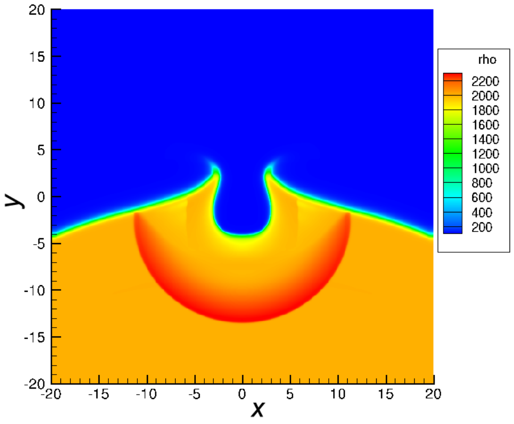
Results for five different elapsed time are shown in Fig. 11. Each subfigure illustrates the density contours 1 ms after the impact. For example, Fig. 11(c) is 1 ms after the third impactor has struck the target, or total time of 3 ms. A benefit of this approach is the increased depth of the crater, which at 5 ms is roughly 10 m. Hence, one possible solution to effect a deeper subsurface explosion is to employ multiple KEIs in series, as was also previously suggested in Ref. [31].

5.5 Summary

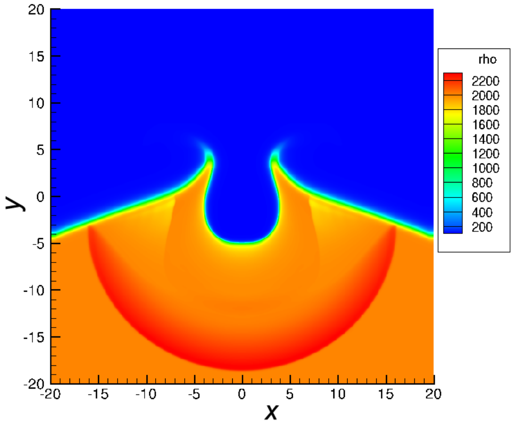
The effectiveness of multiple kinetic-energy impact approaches is briefly discussed herein using the simulation results presented in this section.



(a) Elapsed time = 1.0 ms



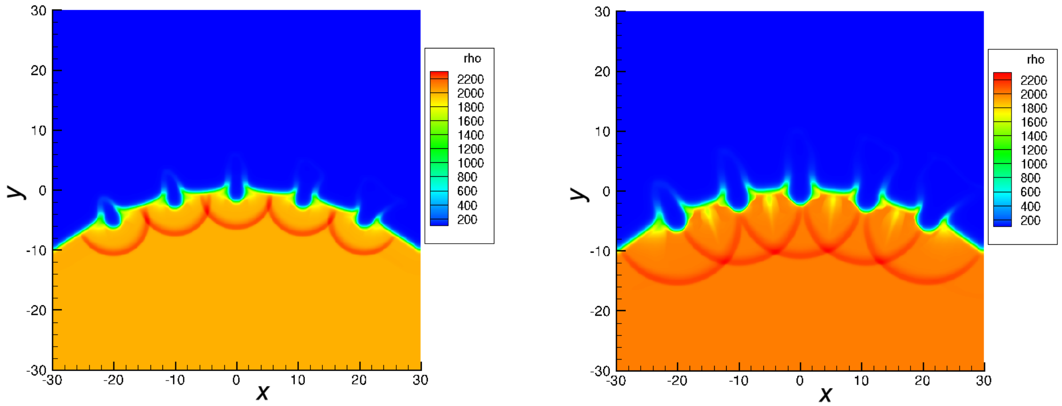
(b) Elapsed time = 2.0 ms



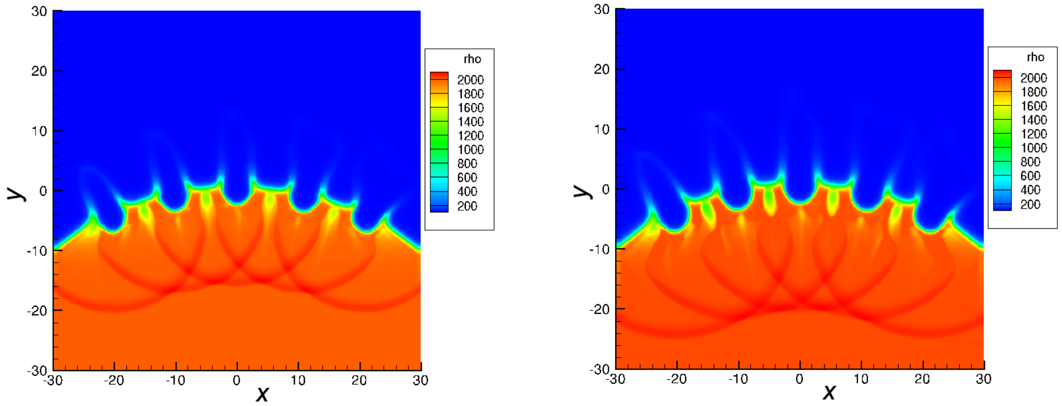
(c) Elapsed time = 3.0 ms

Fig. 9 Case 3 for a single massive 5000-kg KEI [40, 41]. Reproduced with permission from Ref. [40], © IAA 2015.

Lightweight impactors, with density much less than the target body, produce relatively small craters (approximately 1–2 m in depth) in a short elapsed time. The multiple impactors in parallel have the capability to inflict high damage in a wider area, which may cause a more effective disruption for soft or porous



(a) Elapsed time = 1.0 ms (b) Elapsed time = 2.0 ms



(c) Elapsed time = 4.0 ms (d) Elapsed time = 8.0 ms

Fig. 10 Case 4 for parallel KEIs [40, 41]. Reproduced with permission from Ref. [40], © IAA 2015.

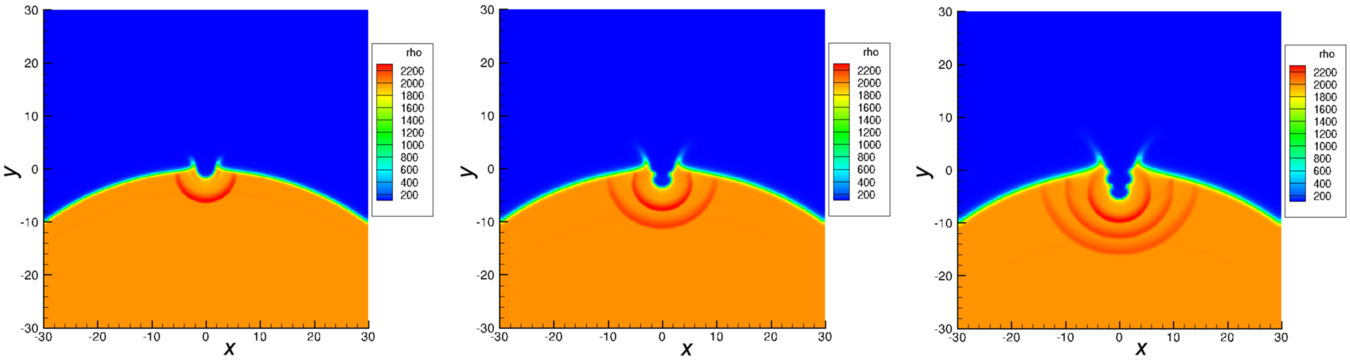
targets. A serial array of multiple impactors is shown to be very effective for deep penetration (Fig. 11). The depth of the crater is significantly increased, allowing more energy to be coupled from a nuclear subsurface detonation for the HAIV mission. In Refs. [40–43], only a 2D circular target with constant density was considered. Future work must include more realistic 3D asteroid bodies. Additionally, the density of the targets should be varied, including porosity, to further investigate the effectiveness of a non-nuclear MKIV system as well as the HAIV concept. A new equation of state (EOS) is desired, as the current one used in Refs. [40–43] does not hold for the high temperatures and pressures associated with the problem.

6 MKIV terminal guidance

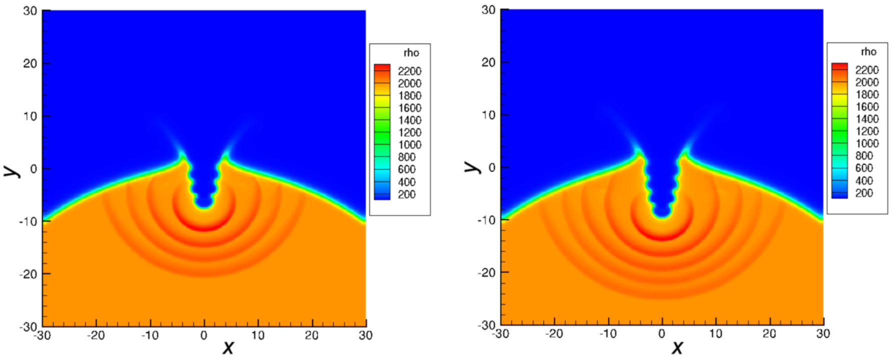
Detailed descriptions of hypervelocity terminal guidance technologies applied to intercepting asteroids can be found in Refs. [20–29]. In this section, we briefly describe a multi-impact terminal guidance algorithm that is required for the proposed MKIV system [29].

A multi-impact terminal guidance algorithm for guiding several KEIs to hit near-simultaneously different locations widely distributed across the target surface area was simulated by acquiring the target asteroid at 2 h before intercept. Once the target is detected by the CV's on-board visual/IR cameras, an image-array algorithm determines impact locations for the remaining KEIs. A depiction of image separation and impact location determination can be seen in Fig. 12. The terminal guidance algorithm determines the amount of vertical channels that are needed, which is based on the maximum vertical and horizontal pixel illumination of the asteroid on the image plane array. Then, area allocation is divided amongst the impacting KEIs. When an allocated array area is met, the centroid of the area is determined.

This centroid is the location of impact on the target body. Similarly, the other remaining KEIs undergo the



(a) Elapsed time = 1.0 ms (b) Elapsed time = 2.0 ms (c) Elapsed time = 3.0 ms



(d) Elapsed time = 4.0 ms (e) Elapsed time = 5.0 ms

Fig. 11 Case 5 for serial KEIs [40, 41]. Reproduced with permission from Ref. [40], © IAA 2015.

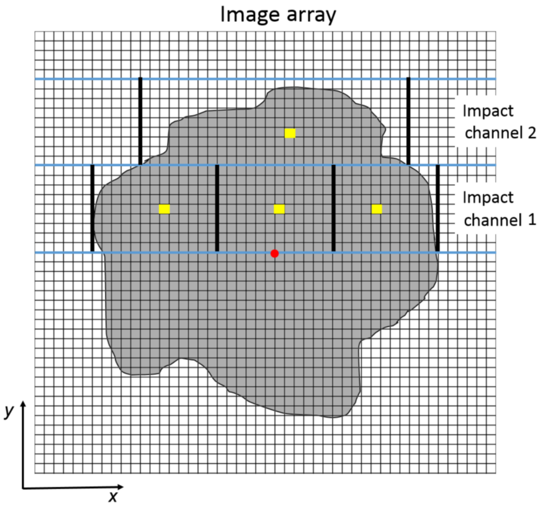


Fig. 12 Conceptual illustration of a multi-impact terminal guidance image processing algorithm for a reference MKIV system consisting of a CV and four KEIs [29]. Reproduced with permission from Ref. [29], © AAS 2016.

centroid process (chunk centroiding). However, these impact locations are calculated for both, the upper and lower image or the left and right image. The selection of the image plane processing is determined by the asteroid orientation on the image array. Once each impact location is determined for the KEIs and CV, this information is communicated to KEIs and appropriate control accelerations are commanded.

Each KEI and CV use the same hybrid guidance scheme described in Refs. [27–29]. This scheme uses a combination of kinematic impulse (KI) and pulsed proportional navigation (PPN) to ensure intercept success. However, the closed-loop PPN guidance is very sensitive to line-of-sight (LOS) rate of the target. There are instances where the impact locations on the image plane array change due to shadowing, asteroid orientation change, or other factors. These factors may cause an event called “pixel jump”. When the pixel jump is large, the first-order rate estimation causes a drastic jump in the estimated LOS rate. To remedy this situation, a sliding-window-averaging filter may be applied to the LOS data, which reduces the sharp changes in the LOS rate. At 60 s before the final impact, the commanded control acceleration is reduced to near zero to avoid large LOS rates caused by the asteroid illuminating more pixels on the image-plane array.

Simulations were ran, using a scaled 216 Kleopatra asteroid model. This asteroid is scaled down to a 100-m diameter and is chosen due to its dog-bone-like shape. A shape such as this will require a multi-impact terminal guidance algorithm to select impact locations on each lobe. Figure 13 depicts the preliminary results for the desired impact locations determined by the proposed algorithm and simulated impact locations on the asteroid. As can be seen in this figure, the image used is of a visual camera and not an infrared camera. A visual camera is simulated to show difficulties in selecting an appropriate impact location. The bottom image shows that all impacts, by CV and KEIs, intercept the asteroid. However, all did not hit their intended location although all did hit the target asteroid. A further detailed study for the multi-impact terminal guidance using visual/IR cameras is needed [29].

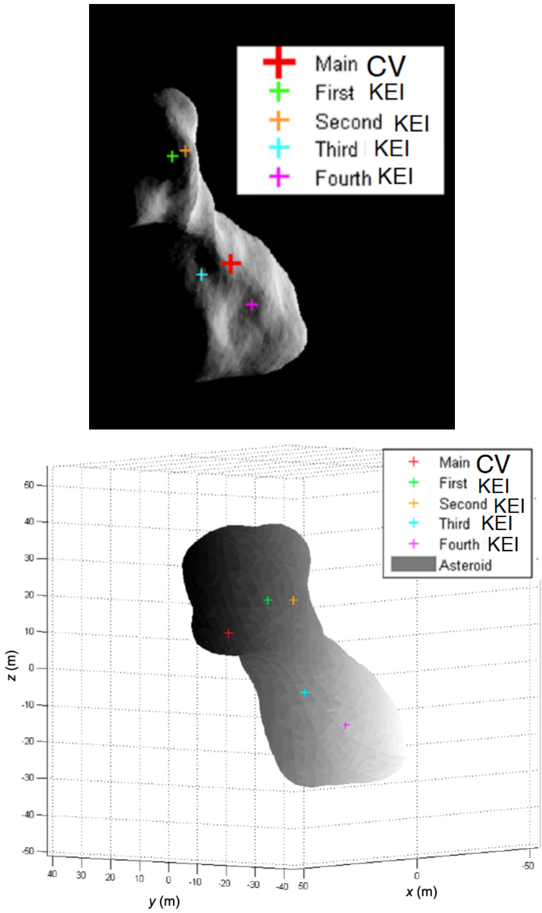


Fig. 13 Asteroid images with commanded and simulated impact locations [29]. Reproduced with permission from Ref. [29], © AAS 2016.

7 Heavy-lift launch vehicle (HLLV)

A large launch vehicle capable of lifting between 20,000 and 50,000 kg to low-Earth orbit is referred to as a heavy-lift launch vehicle (HLLV). The Delta IV Heavy, Ariane V, and Proton-M rockets are such HLLVs that are currently in service. This section provides a brief system-level overview of the HLLVs of the United States, including Falcon Heavy and the SLS.

In Fig. 14, the interplanetary mission capabilities of Delta IV Heavy, Falcon Heavy, and three variations of the SLS are shown in comparison with Atlas V 551 [44]. As can be seen in this figure, if all these launch vehicles were available for planetary defense missions employing a 10,000-kg MKIV system, the Delta IV Heavy would be capable of lifting the MKIV system to orbits that would have a C3 of up to only about 2 km^2/s^2. Based on the curves, the Falcon Heavy could outperform the Delta IV Heavy, lifting 10,000 kg to C3 orbits up to about 18 km^2/s^2. The launch vehicles with the most versatility are the SLS Block 1, Block 1B, and Block 2B configurations capable of lifting a 10,000-kg spacecraft to C3 orbits of about 40, 75, and 90 km^2/s^2, respectively.

7.1 Falcon Heavy

The Falcon Heavy is scheduled for its first test flight soon, and is said to be the most powerful rocket in the world at the time of its operation [45–47]. The Falcon Heavy is capable to lift over 53 tons into low-Earth orbit, more than twice the payload of the Delta IV Heavy, at one third the cost. Missions using the Falcon Heavy will deliver large payloads to orbit inside a composite fairing, but will be capable of carrying

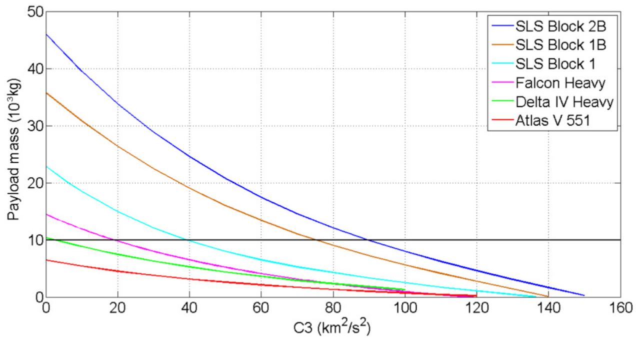


Fig. 14 Interplanetary mission capabilities of heavy-lift launch vehicles (Delta IV Heavy, Falcon, Heavy, and the SLS) compared to Atlas V 551 [44]. Reproduced with permission from Ref. [44], © AAS 2015.

the Dragon spacecraft. Exploiting the proven heritage and reliability of the Falcon 9, the second-stage Merlin engine (identical to its counterpart on the Falcon 9) delivers the payload to orbit after main engine cut off and first-stage cores separate. The second-stage engine is capable of restarting multiple times in order to place payloads into a variety of orbits, including low-Earth orbit (LEO), geosynchronous transfer orbit (GTO), and geosynchronous orbit (GEO). Made up of a single engine, the Falcon Heavy second stage is capable of producing 801 kN of thrust in a vacuum, and has a burn time of 375 s. The Falcon Heavy's first stage is made up of three cores. The side cores (boosters) are connected at the top and base of the center core's liquid oxygen tank. Each of the Falcon Heavy's side cores (boosters) is equivalent to the first stage of a Falcon 9 rocket with 9 Merlin engines. With a total of 27 Merlin engines, the first stage is capable of generating 17,615 kN of thrust at liftoff. Not long after liftoff, the center core engines of the first stage are throttled down, until after the side cores separate, at which time they are throttled back up to full thrust. For missions that have exceptionally heavy payloads ($>$ 45,000 kg), the Falcon Heavy offers a unique cross-feed propellant system that feeds propellant from the side cores to the center core. This enables the center core to retain a significant amount of fuel after the boosters separate. Originally designed to carry humans into space and to fly missions with crew to the Moon or Mars, this launch vehicle could also be used to carry a large spacecraft into orbit to meet a potentially hazardous NEO.

7.2 Space Launch System (SLS)

The design of the SLS serves to accommodate greater mass/volume to orbit, shorter transit time to destination, larger interplanetary science payloads, and enhanced reliability and safety for a variety of different missions. It is projected that the SLS Block 1 design will have the capability to carry up to five times greater mass to orbit than the Delta, Atlas, and Falcon launch vehicles. With the ability to launch such large payload masses, the SLS increases payload mass margins and offers greater propellant loads. It can also accommodate a range of fairing sizes including the existing 5 m diameter size, as well as new 8.4–10 m diameter fairings, and will have the capability to support up to six times greater payload volume over current launch vehicles.

Based on the currently accepted launch capabilities of the SLS, shorter mission durations are also possible to various mission destinations. Taking the Europa Clipper mission for example, the flight time could be reduced by 70% through the use of the SLS rather than the Atlas V 551. Launching into a C3 orbit of 15 km^2/s^2 and requiring three planetary flybys (Venus–Earth–Earth) before arriving at Jupiter 6.4 years later, the same mission launched with the SLS would launch directly into a C3 orbit of 82 km^2/s^2, would not require any planetary flybys, and would arrive at Jupiter in 1.9 years. The capabilities of the SLS would allow for longer launch windows and provide more mission margin, in addition to significantly reduced cost for each year of transit reduced. Larger interplanetary science payloads enable three to four times the mass to destination and single launch of larger payload reduces payload complexity. The SLS launch vehicle range allows for missions previously deemed very difficult or infeasible to be reconsidered, such as the Asteroid Redirect Mission, Mars Sample Return, Saturn/Titan Sample Return, Ice Giant Exploration, Outer Planet Sample Return, large telescopes, and in-space infrastructure. Additional payload volume simplifies orbital operations, requiring less orbital assembly for large spacecraft. With the amount of energy able to be generated by the launch vehicle and imparted to the payload, significantly less time can be spent in Earth orbit — reducing the amount of propellant boil-off, and would eliminate the Earth flyby nuclear safety concern [48].

8 MKIV mission design for fictional asteroid 2015 PDC

The shortest warning time for the fictional asteroid 2015 PDC examined in Refs. [44, 49] was 30 days — up to 15-day flight time (mission duration) and up to 15-day dispersion time. With such a worst-case short timespan for the MKIV to intercept the asteroid, the mission trajectory should be fairly simple in terms of the ease of getting into the orbit and getting to the threatening asteroid. However, as can be noticed in Table 3, a mission at this late stage is anything but

Table 3 A 30-day-warning intercept mission to fictional asteroid 2015 PDC [44, 49]

Mission parameter	Value
Asteroid	2015 PDC
Spacecraft designation	MKIV
Spacecraft mass (kg)	10,000
Departure ΔV (km/s)	4.425
C3 (km^2/s^2)	27.806
Departure date	August 12, 2022
Flight time (day)	15
Dispersion time (day)	7
Arrival angle (deg)	25.411
Impact velocity (km/s)	16.571
Arrival date	August 27, 2022
Launch vehicle	SLS

easy. Requiring over 4.5 km/s from low-Earth orbit to enter into a hyperbolic escape orbit of almost 28 km^2/s^2 to intercept the fictional asteroid 2015 PDC [44, 49], the difficulty of this interplanetary trajectory can be seen in Fig. 15. It is assumed that the MKIV system was ready for an immediate launch after receiving such a short notice. The various technical and political issues associated with such a rapid deployment of planetary defense systems has been investigated in Ref. [13].

For a fictional asteroid 2015 PDC mission design with 30-day warning time [44, 49], the MKIV needs to depart from the ecliptic plane of the Earth to intercept the target asteroid in 15 days. The combination of the launch energy given to the MKIV to intercept asteroid 2015 PDC and the position of the asteroid in its orbit (going away from periapsis) explains the large relative impact velocity and relative arrival angle between the MKIV and asteroid 2015 PDC. The 30-day warning-time mission design can only be accomplished by the use of an SLS launch vehicle. Taking a closer look at the top 10 mission designs for this type of mission design conducted in Refs. [44, 49], only the top four missions would be able to be completed using the SLS Block 1 launch vehicle or larger — the rest of the top missions would require at least the SLS Block 1B configuration to be feasible.

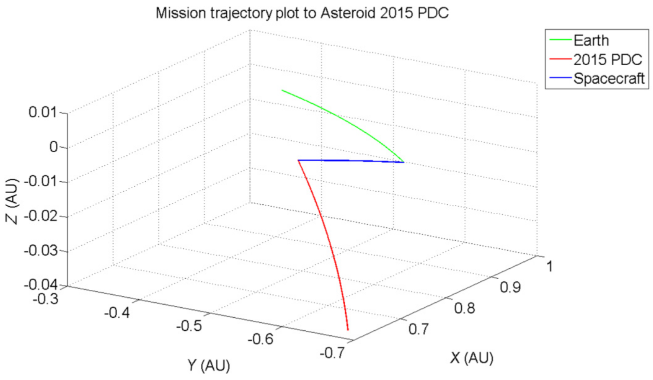


Fig. 15 A reference mission design for a fictional asteroid 2015 PDC with 30-day warning time [44]. Reproduced with permission from Ref. [44], © AAS 2015.

9 Concluding remarks for planetary defense

Provided that we have sufficient warning time (>10 years), various options such as kinetic impactors, gravity tractors, and nuclear standoff explosions can be employed for a non-destructive deflection mission. However, for the more probable impact threat scenario, in which the warning time is less than 10 years, a disruption mission employing a nuclear HAIV or a non-nuclear MKIV is likely to become the only option (other than evacuation of the area affected by the impact on Earth, assuming the impacting NEO is not large enough to be globally catastrophic).

As discussed in Ref. [14], most NEO science missions required at least several years, in some cases 5–6 years or more, for mission concept development and spacecraft construction prior to launch. It is also important to note that quite a few of these missions originally targeted different asteroids or comets than those that were actually visited. This is because the mission development schedules slipped and launch windows for particular asteroids or comets were missed. Additionally, several of these missions experienced hardware or software failures or glitches that compromised the completion of mission objectives. None of those things would be tolerable for a planetary defense mission aimed at deflecting or disrupting an incoming NEO, especially with relatively little advance warning. Thus, while the successful scientific missions that have been sent to asteroids and comets thus far have certainly provided future planetary defense missions with good heritage on which to build, we are clearly not ready to respond reliably to a threatening NEO scenario.

Furthermore, none of the potential planetary defense mission payloads (e.g., kinetic impactors, nuclear explosives) to deflect or disrupt NEOs have ever been tested on NEOs in the space environment. Significant work is, therefore, required to appropriately characterize the capabilities of those payloads, particularly the ways in which they physically couple with NEOs to transfer energy or alter momentum, and ensure robust operations during an actual emergency scenario [14].

In summary, it is time to initiate a planetary defense flight validation program for demonstrating, validating, and refining planetary defense technologies in space, so that we will be properly prepared to respond effectively when an NEO on a collision course with Earth is discovered. It will require at least 5 years of further development and space flight validation testing before operational planetary defense technologies could be employed in a real short-warning-time situation. Now is the time to initiate such preparations. Waiting until a threatening NEO is discovered will be far, far too late. In addition, it is time to build and launch a dedicated space-based NEO survey telescope stationed far from Earth's vicinity. Such a system will be a key asset that simultaneously benefits planetary defense, fundamental solar system science, and space exploration [14].

10 Conclusions

This paper has presented an overview of the nuclear HAIV (hypervelocity asteroid intercept vehicle) mission concept and its experimental flight validation mission design. This paper has also presented a new non-nuclear MKIV (multiple kinetic-energy impactor vehicle) mission concept for disruption or pulverization of asteroids smaller than 150 m in diameter detected with short warning time. A single large booster such as Delta IV Heavy, Falcon Heavy, or the SLS can be employed to launch the proposed MKIV system with its total mass in the range of approximately 5000–15,000 kg for disruption or pulverization of small asteroids with short warning time. However, a further study using a 3D hydrocode simulation model is necessary to validate the practical effectiveness of the proposed MKIV mission concept. A further study is also needed for an advanced precision multi-impact terminal guidance system employing visual/IR sensors.

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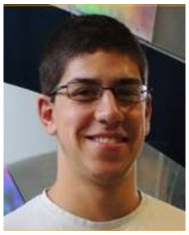

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