An Optimal Mitigation Strategy Against the Asteroid Impact Threat with Short Warning Time*

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Abstract—This paper presents the results of a NASA Innovative Advanced Concept (NIAC) Phase 2 study entitled "An Innovative Solution to NASA's Near-Earth Object (NEO) Impact Threat Mitigation Grand Challenge and Flight Validation Mission Architecture Development." This NIAC Phase 2 study was conducted at the Asteroid Deflection Research Center (ADRC) of Iowa State University in 2012–2014. 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 (< 5 years). The mitigation strategy described in this paper is intended to optimally reduce the severity and catastrophic damage of the NEO impact event, especially when we don't have sufficient warning times for non-disruptive deflection of a hazardous NEO. This paper provides an executive summary of the NIAC Phase 2 study results.

Keywords—NEO impact threat mitigation, planetary defense, nuclear subsurface explosions, hypervelocity asteroid intercept vehicle (HAIV)

I. 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, such as nuclear explosions, kinetic impactors, and slow-pull gravity tractors (GTs), have been investigated by planetary defense researchers during the past two decades [1–10]. To date, however, there is no consensus on how to reliably deflect or disrupt hazardous NEOs in a timely manner. All of the non-nuclear techniques will require mission lead times much longer than 10 years, even for a relatively small NEO. When the time-to-impact with the Earth 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 to 2 cm/s). Thus, most non-nuclear options as well as a nuclear standoff explosion can be employed for deflection missions when we have sufficiently long warning times.

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 for storing energy with today's technology. Deflection methods with sufficiently high energy density are often preferred over a nuclear disruption approach. One of these deflection methods utilizes a nuclear explosion at a specified standoff distance from the target NEO, to effect a large velocity change by ablating and blowing off a thin layer of the NEO's surface. Nuclear standoff explosions are thus assessed to be much more effective than any other non-nuclear alternatives, especially for larger asteroids. The precise outcome of a NEO deflection attempt using a nuclear standoff explosion is dependent on myriad variables. Shape and composition of the target NEO are critical factors. These critical properties, plus others, would need to be characterized, ideally by a separate mission, prior to a successful nuclear deflection attempt. Other techniques involving the use of surface or subsurface nuclear explosives are assessed to be more efficient than the nuclear standoff explosion, although they may cause an increased risk of fracturing the target aster-

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*This research has been supported by a NASA Innovative Advanced Concept (NIAC) Phase 2 project, with a NASA Grant and Cooperative Agreement Number NNX12AQ60G.

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oid [10].

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, and independently detected the next night by the Pan-STARRS 1 telescope, located on the summit of Haleakala on Maui, Hawaii. We would have had only one week of warning time if 2014 RC was going to collide with Earth.

If a NEO on an Earth-impacting course is detected with a short warning time (e.g., much less than 5 years), the challenge becomes how to mitigate its threat in a timely manner. For a small asteroid impacting in a sufficiently unpopulated region, mitigation may simply involve evacuation [10]. 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 NEO becomes extremely large. Thus, for the most probable mission scenarios, in which the warning time is shorter than 5 years, the use of high-energy nuclear explosives in space will become inevitable [10]. A scenario in which a small (e.g., 50 to 150 m) Earth-impacting NEO is discovered with short warning time is 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 a short warning time will result in arrival closing velocities of 10 to 30 km/s with respect to a target asteroid. A rendezvous mission to a target asteroid that requires such an extremely large arrival ΔV of 10 to 30 km/s is not feasible.

A subsurface nuclear explosion is the most efficient use of nuclear explosives [10, 11]. The nuclear subsurface explosion, even with shallow burial to a depth of 3 to 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 (a nuclear explosion very close to the surface) [11]. The momentum/energy transfer created by a shallow subsurface nuclear explosion is at least 100 times larger than that of an optimal standoff nuclear explosion. However, state-of-the-art nuclear subsurface penetrator technology limits the impact velocity to no more than about 300 m/s because higher impact velocities prematurely destroy the fusing mechanisms/electronics of nuclear explosive devices [11].

Despite the uncertainties inherent to the nuclear disruption approach, disruption can become an effective strategy if most fragments disperse at speeds in excess of the escape velocity of an asteroid so that a very small fraction of fragments impacts the Earth. When the warning time is very short, disruption is likely to become the only feasible strategy, especially if all other deflection approaches were to fail, as was concluded in the 2010 NRC report [10]. However, it is again emphasized that non-nuclear techniques should be preferred for non-destructive deflection of hazardous NEOs whenever we have sufficient mission lead times (>10 years).

II. THE MAJOR STUDY RESULTS

A. Hypervelocity Asteroid Intercept Vehicle (HAIV) Mission Concept

Our NIAC Phase 2 study was focused on a planetary defense strategy that exploits the innovative concept of blending a kinetic impactor with a subsurface nuclear explosion for mitigating the most probable impact threat of NEOs with a warning time shorter than 5 years. A hypervelocity asteroid intercept vehicle (HAIV) concept has been developed through NIAC Phase 1 & 2 Studies [12–15]. The HAIV is a two-body space vehicle consisting of a leading kinetic impactor and a trailing body carrying nuclear explosives, as illustrated in Fig. 1. Its flight validation mission architecture has also been designed, and we have identified various key enabling technologies required for the HAIV mission of optimally intercepting and disrupting a target asteroid [12–15].

Most direct intercept missions with a short mission lead time will result in arrival closing velocities of 10 to 30 km/s (relative to a target asteroid). A rendezvous mission to a target asteroid, requiring such an extremely large arrival ΔV of 10 to 30 km/s, is not feasible. A nuclear subsurface explosion, even with shallow burial to a depth of 3 to 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 [11]. 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 [11].

In order to overcome such practical constraints on the penetrated subsurface nuclear explosion, the HAIV system concept has been developed, which will enable a last-minute, nuclear disruption mission with intercept velocities as high as 30 km/s. The proposed HAIV system 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 for the follower spacecraft carrying nuclear explosive devices (NEDs) to make a more effective explosion be-

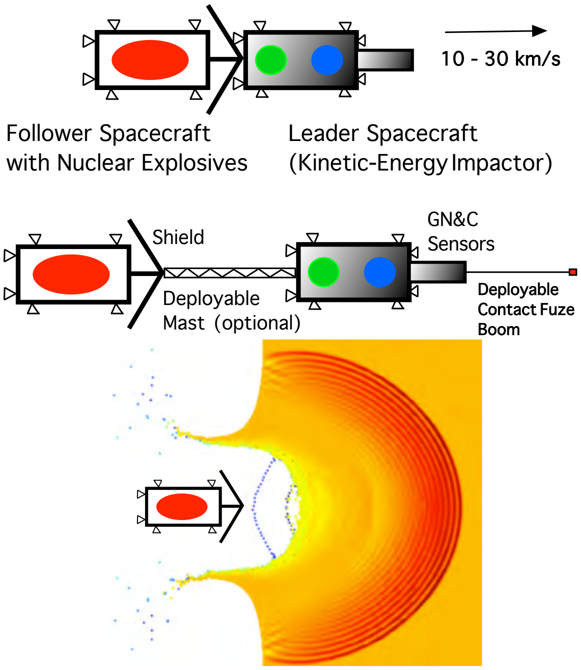

Figure 1: Initial conceptual illustration of a two-body hypervelocity asteroid intercept vehicle (HAIV) system, which was proposed for a NIAC Phase 1 Study in 2011 [12].

low the surface of a 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.

For a small (50 to 150 m) target asteroid, the terminal guidance phase may begin 2 hrs 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 optical/IR cameras located on the leader spacecraft and an intercept impact location is identified on the target asteroid body. The high-resolution optical/IR cameras provide successive images of the NEO to the terminal guidance system for a few trajectory correction maneuvers. The leader spacecraft and the follower spacecraft must separate before the leader (leading kinetic impactor) collides with the target NEO.

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 ranging from 300-kg (with approximately 300-kt yield) to 1,500-kg (with approximately 2-Mt yield). Conceptual design of an interplanetary ballistic missile (IPBM) system architecture for launching the HAIV system can be found in [16].

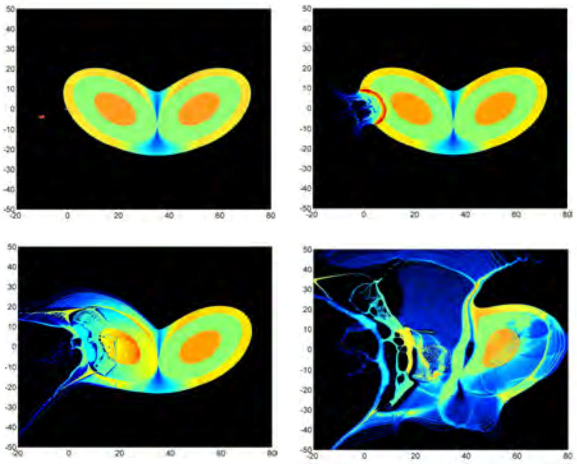

Figure 2: A 70-m asymmetric asteroid model disrupted by a 10-km/s kinetic impact and a subsequent 70-kt nuclear subsurface explosion of the HAIV system [17–19].

Because the hypervelocity kinetic impact and nuclear subsurface explosion simulations rely heavily on energy transmission through shocks, the simulation research work conducted for the HAIV mission concept study [17–19] 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. 2. 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 (Graphics Processing Unit) desktop computer, has been developed for the HAIV mission study [17–19] using the research results of Owen et al. [20]. However, a more computationally efficient, modern GPU-based hydrodynamics code needs to be further developed by incorporating more accurate physical models of a nuclear subsurface explosion [21, 22].

Various approaches have been employed in [23] to be computationally efficient and accurate for several examples with a large number of fragments (e.g., 500,000). An N-body orbit simulation code was also used for orbital dispersion simulation and analysis in [23, 24]. To assess the degree of mitigation, the code includes gravitational focusing effect of the Earth on those fragments that pass near the Earth, and provides a census of those that hit the Earth (i.e., those with a minimum distance to Earth that is <1 Earth radius).

B. Planetary Defense Flight Validation (PDFV) Mission Design

A one-week design study was conducted by the MDL (Mission Design Lab) at NASA Goddard Space Flight Center for our NIAC Phase 2 study in 2012 [15]. Its objective was to assess the technical feasibility of deploying a spacecraft to intercept a small (50 to 150 m) NEO within 10 m of its center with 3σ confidence at high relative velocity (>10 km/s) in order to provide a viable planetary defense solution for short warning time scenarios. The MDL performed this assessment by developing a preliminary spacecraft systems concept for the HAIV capable of reliably delivering a notional NED payload to a target NEO and transmitting adequate telemetry for validation of system performance. In addition to the conceptual spacecraft design, the MDL created associated plans for the supporting mission and ground operations in order to provide an overall mission architecture [15].

The MDL worked to design a fully capable HAIV (rather than a simplified test platform) and apply the fully capable design to a suitable practice target NEO. The MDL endeavored to make the flight validation mission affordable through judicious mission design rather than via a scaled-down less expensive flight demonstration platform [15]. The primary design drivers are the high relative velocity at impact and the precision timing required for detonation of the NED in the shallow crater excavated by the leading kinetic impactor portion of the vehicle. The MDL carefully considered what systems equipment should be placed on the lead portion (kinetic impactor) of the HAIV and what should be placed on the follower portion (NED payload carrier). Additionally, high reliability is required because there will only be one opportunity to successfully strike the target NEO. These considerations make it clear that the HAIV will need to be a highly responsive system with onboard autonomous control because of the latency inherent in ground commanding and the highly dynamic environment of the terminal approach phase.

Yet another challenging aspect of this mission is that the size, shape, and rotational state of the NEO will generally not be known in advance of the intercept mission. Design, selection, fuzing, and so on for the NED was purposely placed outside the scope of the MDL study. For the purposes of the study, it was assumed that a dummy mass proxy for the NED payload is installed in the HAIV for the flight validation mission. The NED proxy is modeled as a cylinder 1 m in length with a 0.5 m face diameter and a mass of 300 kg.

The overall configuration/system design of an experimental HAIV flight system is illustrated in Fig. 3. 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.

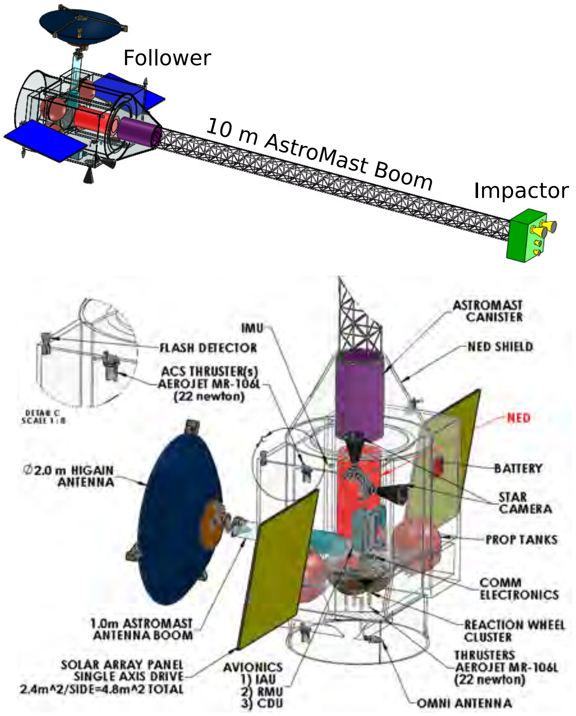

Figure 3: An experimental HAIV flight system designed by the MDL of NASA GSFC [15].

For launch vehicles, the MDL considered 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. All of these launch vehicles provide sufficient mass capability at the desired Earth departure C_3 but the Atlas V is the only EELV currently covered under the NASA Launch Services Program II contract.

The estimated cost of an experimental HAIV flight validation mission is approximately $530M, including the launch vehicle. An approximate cost of $150M is assumed for the notional launch vehicle, which is the Atlas V 401. The cost estimate is comprehensive and includes the complete design, construction, integration, and testing of the spacecraft itself, launch vehicle integration and test, project management, mission operations, ground system, systems integration and test, education and public outreach, and project reserves [15].

III. RECOMMENDATIONS FOR PLANETARY DEFENSE

With a mandate from the U.N. Committee on the Peaceful Uses of Outer Space (COPUOS), the Space Mission Planning

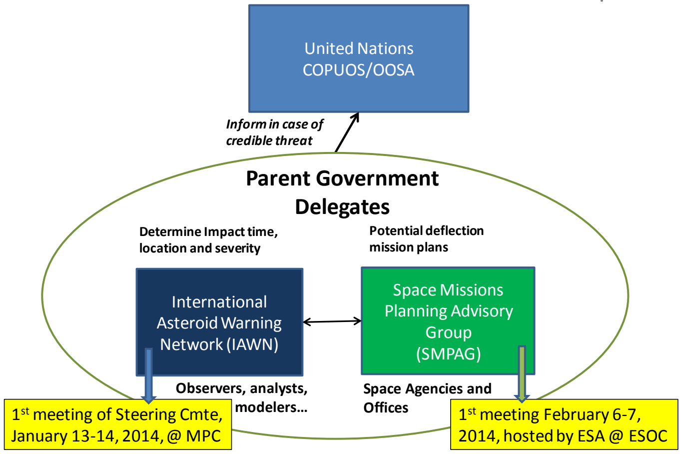

Figure 4: International efforts in preparing for a planetary defense mission. Image courtesy of Lindley Johnson at NASA/NEOO.

and Advisory Group (SMPAG) has been established in 2013 to coordinate a global response should a threatening asteroid be found heading toward Earth, as illustrated in Fig. 4. The NEO Observation (NEOO) Program Office of NASA has been coordinating all efforts related to NEO survey, detection, and impact warning.

However, no agency of the U.S. federal government has been officially designated for planning and/or preparing for planetary defense actions prior to detection of a real impact threat (the warning time for which, as noted previously, may be quite short). Therefore, we recommend that a U.S. government agency be formally designated by the Congress for the coordination of all R&D activities of preparing for all planetary defense options, prior to detecting any impact threat.

If we have sufficient warning time (>10 years), then various options, including kinetic impactors, gravity tractors, and nuclear standoff explosions, can be employed for a non-destructive deflection mission. For the more probable impact threat scenario, in which the warning time is less than 5 years, a disruption/dispersion mission employing nuclear explosions 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).

The mission effectiveness of the proposed HAIV system can be further enhanced by exploiting an asteroid warning system, which is being developed at the University of Hawaii with $5 million funding from NASA. Once this system, called the ATLAS (Asteroid Terrestrial-impact Last Alert System), becomes fully operational in early 2016, it is expected that it will offer a one-week warning for a 45-m asteroid and three weeks for a 140-m asteroid. Provided that such one-week warning from the ATLAS can be assured, a target asteroid >45 m in size can be intercepted and disrupted far outside of Earth's gravitational sphere of influence and, consequently, avoid a potentially troublesome suborbital intercept. It is emphasized that a suborbital intercept may become inevitable for situations with ultra-short warning times of only 1 to 24 hrs as discussed in [25–27].

With regard to the need for planetary defense spacecraft system testing, it is important to note that there is currently no solicitation for planetary defense flight validation mission proposals. Such missions are necessarily similar in cost to science missions (e.g., Discovery or New Frontiers), yet there is no established mechanism for funding planetary defense flight validation missions. So, there is a need for planetary defense flight validation mission funding. It is worth pointing out that such missions will naturally, by their intrinsic nature, return significant amounts of science data even though they are not primarily science missions.

Finally, the very nature of the HAIV design (and the motivation for its design) underscores the need for a dedicated space-based NEO survey telescope located far from Earth's vicinity. Such a telescope would be an affordable and cross-cutting system that simultaneously serves the planetary defense, science, and exploration communities. Completing the NEO population survey as soon as possible is the best way to maximize the amount of warning time available to us should we find a NEO on an Earth-impacting trajectory. That cannot be done using Earth-based telescopes, and such telescopes will always be blind to the sunward direction (from which the Chelyabinsk impactor approached); a space-based NEO survey will not have the same blind spot. Although we are designing the HAIV to address short warning time situations because they are the most stressing cases and there will always be a risk of such a case occurring, we want to emphasize that doing our best to avoid short warning time scenarios by deploying a space-based NEO survey telescope is the most prudent course of action. Unfortunately, as with planetary defense flight validation missions, the NEO survey telescope cannot seem to find a funding source within NASA. Therefore, we recommend that NASA make the funding of a dedicated space-based NEO survey telescope a top priority, followed by funding for planetary defense flight validation missions.

IV. CONCLUSIONS

It is time to initiate a planetary defense flight validation program, mandated by the Congress, for demonstrating, validating, and refining planetary defense technologies in space, so that we will be properly prepared to respond effectively when a near-Earth object (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.

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