

IAA-PDC-25-07-172-Paper

Operationalize the Didymos-Dimorphos Test Site to Assess Various Asteroid Deflection Technologies

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Abstract

On September 26, 2022, the DART spacecraft collided with the 160-meter asteroid Dimorphos and shifted its orbital period relative to its 700-meter companion asteroid Didymos by approximately 33 minutes. The Double Asteroid Redirection Test (DART) successfully demonstrated deflection of an asteroid by a high-speed kinetic impactor and enabled in-depth analysis of the experimental results.

The Didymos-Dimorphos binary system was chosen as a test site for this demonstration because the change in Dimorphos' orbital period is directly measurable from the Earth, thus providing an immediate and precise indication of the test outcome. DART's success suggests that, given sufficient time before impact, an Earthbound asteroid could be deflected away from the threatening trajectory via this technique.

This study considers new experimental mission scenarios that reuse Dimorphos as a testbed environment for evaluation of additional asteroid deflection technologies and operationalization of abstract concepts into measurable capabilities. As the Didymos-Dimorphos binary system poses no threat to the Earth, further tests would incur no new risks. Experience gained from DART also provides ample context about the specific binary asteroid system as a testing environment.

The 2022 test revealed previously unknown details about the material composition of Dimorphos. This foundation can inform future tests using the Didymos-Dimorphos system, preempting the need to identify and evaluate a new experimental environment. Improved characterization of Dimorphos by the upcoming HERA mission can also further refine testing parameters for new methods of asteroid deflection. Thus, new tests conducted on this binary system can provide valuable information on the science and technology of asteroid characterization and planetary defense.

Furthermore, future deflection technologies, such as the ion beam shepherd and the centrifugal mass driver, may provide additional benefits if tested in an international collaborative format. Cooperation and transparency can help identify and resolve the

wide array of political, legal, programmatic, and operational issues that would arise in any actual campaign to prevent a NEO impact scenario.

Reusing the Didymos-Dimorphos test site can build upon the foundation of previous test missions, validate assumptions and models, demonstrate new asteroid deflection technologies, and expand the planetary defense toolbox that can be applied with confidence at the time of need.

Keywords: Deflection Technology, Deflection Test Site, DART, HERA

Introduction

On September 26, 2022, The NASA Double Asteroid Redirection Test (DART) spacecraft impacted Dimorphos, the secondary in the Didymos binary asteroid system, and altered the trajectory of Dimorphos around Didymos, reducing the orbit period by around 33 minutes [1]. The use of the Didymos-Dimorphos binary system has proved especially useful for testing experimental planetary defense technologies; primarily the effectiveness of the high-speed kinetic impactor technique. Its relative proximity to the Earth and its nature as a binary asteroid provided near-instantaneous results after DART's impact.

The DART test was an important first step towards developing the technologies that would enable deflection of a future asteroid impactor. The unprecedented impact risk from 2024 YR4, as reported in early 2025, shows that a serious impact, especially from smaller asteroids, may come on short notice. Thankfully, additional observations have since all but ruled out the risk posed by 2024 YR4, giving the world more time to develop the deflection technologies to address a future impactor .

Post-impact observations have refined both the assessment of the DART mission's success as an asteroid deflection method, as well as the understanding of Dimorphos and its material composition. Further characterization of both aspects will continue with the European Space Agency's Hera probe. This new mission will rendezvous with Dimorphos in 2026 to perform a detailed post-impact survey and advance our understanding of the kinetic impact planetary defense technique [2].

The success of the DART mission lends credibility to planetary defense efforts and serves to validate kinetic impactors as a viable model, but these takeaways need not be the end of either planetary defense testing or the exploration of the Didymos-Dimorphos binary system. Rather, the 2022 and 2026 missions reveal a unique opportunity for scientific and policy communities to build on DART's legacy in the coming years.

While the class of kinetic impactors tested by DART are only applicable to a subset of potential planetary defense mission profiles, future testing is necessary to both further develop kinetic impactors and expand the range of deflection techniques to match a fuller scope of potential hazards, including asteroids of various sizes and compositions as well as warning and impact timelines.

Towards this objective, our comparative familiarity with Dimorphos and its utilization to approximate asteroid deflection has already provided near-laboratory conditions for in-space testing, and declaring Didymos-Dimorphos as a dedicated testbed location could serve as a generalizable in-space test facility for a variety of planetary defense assets, and later other

potential projects. Even though reusing Didymos-Dimorphous will not have benefits that could be gained from visiting a new asteroid of a different size or composition, it will utilize our familiarity with the test site to approximate in-space laboratory conditions and will save on costs of identifying a new site.

Therefore, we suggest that this binary system can be reused as a dedicated test site for evaluation of additional deflection technologies, techniques, and procedures prior to the inauguration of any operational planetary defense platform.

Revisiting Dimorphos serves two key purposes: one technical/procedural and another sociopolitical. On the technical side, practicing a variety of asteroid deflection techniques is necessary to establish a viable and redundant planetary defense capability, adapt to additional potential mission profiles, validate and improve designs, and identify and address potential practical obstacles. Feedback on the functionality and effectiveness of these techniques is necessary to increase our confidence in experimental designs before any active deflection systems become operational.

Dimorphos might also serve a parallel function as a site for establishing and implementing elements of international space cooperation. As the Hera mission demonstrates, the Dimorphos system is already servicing multiple space programs and facilitating joint missions, and continued use of this site can extend this cooperation by reinforcing existing norms and establishing new standards for conducting planetary defense activities. Planetary defense is a global concern, and codification of these behaviors through trust-and-confidence-building measures can help maintain the current cooperative outlook of planetary defense.

Likewise, the continued development of a common framework for planetary defense may require such cooperation to facilitate the use of dual use space technologies for planetary defense and other purposes without raising concerns over militarization. Utilizing Didymos-Dimorphos for this step may lower obstacles to the development of some of the dual use technologies such as high-power lasers and nuclear explosives that could prove to be effective and even necessary deflection methods, while also setting the normative groundwork necessary to make these activities politically and legally feasible.

History of Didymos-Dimorphos as a Testing Location

The Didymos-Dimorphos system was discovered in 1996 by the Spacewatch Project at the University of Arizona, and its orbit and binary nature were confirmed in 2003 by astronomers and planetary scientists at the Ondřejov Observatory in Czechia, NASA's Jet Propulsion Laboratory, and the Arecibo Observatory in Puerto Rico. [3]. The two asteroids were chosen as the target for the DART mission because they are not a threat to Earth, and they pass relatively close to our planet, thereby making them both accessible in terms of delta-v required to reach the system and readily observable from Earth. [4]. The physical and dynamical properties of the binary system were derived or constrained from the photometric observations and radar observations over several years.

Observations determined that the Didymos system is an eclipsing binary, meaning that Earth-based telescopes can measure the regular variation in brightness of the combined Didymos-Dimorphos system as they pass in front of each other. [5, 6]. This attribute provides for a nearly instantaneous determination of how long it takes Dimorphos to orbit Didymos and permitted NASA to move DART from concept development to the preliminary design phase in 2017 [7].

The DART experiment revealed the composition of the system to be that of a rubble pile [8], rather than a pair of rigid bodies. This is an important finding as previous observational research had suggested a relatively high percentage of potential asteroid impactors are rubble piles, for which kinetic deflectors may be less effective. Initial indications were that Dimorphos' orbit was changed by approximately 33 minutes as a result of the test. Additional data taken 20 to 30 days later suggests that the change in period was closer to 34 minutes and deviates from previous measurements by 3.5σ [9]. These differences suggest that additional observations of the (65803) Didymos system can further refine the outcome of the 2022 test and continue to improve our comprehension of the characteristics of this binary system post-impact.

A Dedicated Test Site for Planetary Defense Activities

DART has done much to demonstrate the feasibility of one particular type of a planetary defense mission, but there are additional steps needed before we can consider the Earth adequately protected.

DART only tested a single method on a single asteroid that could be quite different from an actual object needing deflection. Hence, the DART experiment, while useful, may not cover the full scope of impactor threats. It is thus beneficial to generalize our understanding of how asteroids respond to hypervelocity impacts to inform a possible future situation where a kinetic impact deflection may be necessary and feasible [10].

However, kinetic impact deflection methods are inadequate for the full scope of potential asteroid impact threats. Notably, they are likely less effective against rubble piles than solid body asteroids, as they are likely to disrupt the target asteroid's physical structure without sufficiently deflecting it. Similarly, for short-warning or large-mass threats, kinetic impactors are noticeably inefficient, in terms of the ratio of launch mass-to-momentum imparted, compared to nuclear explosives and thus could require a greater number of launches.

For long warning threats, or for the use of dual-use technologies with applications outside planetary defense, kinetic impactors are also potentially too expensive to justify relying on their relatively limited usability. Furthermore, the kinetic deflection method relies heavily on the shape and composition of the target object, while other methods more flexibly rely simply on the target's mass. Even if considering further use of the kinetic impactors, additional tests may be necessary to improve on the experimental design. Therefore, additional field testing of planetary defense technologies may be necessary, for which we argue Didymos-Dimorphos would serve as the ideal and reusable test site for evaluating the feasibility of asteroid deflection technologies, platforms, techniques and procedures.

Such a dedicated Didymos-Dimorphos test site would provide the ideal environment to realistically simulate a variety of planetary defense scenarios in realistic conditions. Similarly to common practice in terrestrial testing facilities [11, 12], actuation of a "test as you would deflect and deflect as you test" approach would enable the development of a generalizable "pre-deflection checklist" requiring simulation in controlled quasi-laboratory settings, both to replicate the conditions of a real deflection campaign and to allow precise comparison across different tests.

The initial factors which made this specific binary system a valid use-case for DART are all still present for future tests. Didymos-Dimorphos remain on a non-threatening trajectory after the 2022 test, yet proximate enough to allow easy observation and access for future missions.

With the wealth of data collected from the previous test, and the new characterization by the upcoming Hera mission, there is also now a more accurate notion of the system's material and structural composition. Previous analysis treated the mission targets as rigid objects, but their revelation as rubble piles [8] can be factored into future tests.

Even presuming future missions to test planetary defense technologies, any alternative site would incur disadvantages relative to Didymos-Dimorphos. Unlike the rich understanding of this recently visited system, other sites would require their own lengthy reconnaissance to characterize. The aforementioned identification of the system as a rubble pile also places the system in character with a large subset of celestial bodies a planetary defense mission might encounter. Before and after the missions to visit the system, a growing scientific community, both within and beyond the teams directly involved in DART and Hera, have accrued a great deal of experience with this specific system's features that would not be present for alternative mission targets.

Potential Mission Profiles for Future Tests

Given enough time and preparation, many deflection methods have been proposed over the years to defend Earth communities and infrastructure from a dangerous asteroid by imparting small nudges to its path, turning a direct hit into a near-miss [13]. The following section is an overview of techniques and technologies that could be considered for future asteroid deflection tests. For each design, Didymos-Dimorphos offers unique advantages as a testing location.

Kinetic impactor

As previously mentioned, the kinetic impactor is the only planetary defense technique that has been tested in realistic conditions with the 2022 DART mission. DART validated a key planetary defense capability by demonstrating it is possible to send a spacecraft millions of kilometers from Earth to intercept an asteroid less than a kilometer wide while making final steering adjustments autonomously. The initial test successfully changed the orbital period of Dimorphos, but future tests may seek to replicate, modify, or improve upon this method. The 2022 test and Dimorphos test site have established a viable baseline to measure any future kinetic impact against.

The downside of a kinetic impactor is that it is less efficient against a rubble pile asteroid [14]. The relatively low density of such an asteroid could mean that the force imparted by the impactor might not be fully transmitted across the whole body. Moreover, the materials that make up a rubble pile asteroid may be loosely held together by their local gravity, leading to a situation where a kinetic impactor could disperse them. In the worst-case scenario, that could lead to a deflection mission that turns a single oncoming object into a blast of projectiles far more difficult to intercept.

To avoid disruption, both the kinetic impact and nuclear detonation approaches benefit dramatically from deploying multiple, iterated launches in place of a single large-scale interception. This strategy allows for the adjustment of the total effect on the target's orbital adjustment when its response to an interception is not accurately predictable in advance.

Future planetary defense tests are unlikely to be limited to the countries involved in previous research. Likewise, even states intending to collaborate operationally on planetary defense may develop their capabilities in separation prior to an active mission. States preferring to

autonomously develop planetary defense technologies may seek to test their own kinetic impactors, and therefore might perform their own replication or modification of the DART mission's methodology.

For such experiments, Dimorphos may provide not only material metrics to compare to the NASA DART test, but also a social benchmark for other planetary defense programs as cutting-edge accomplishments become standardized goals for space programs to demonstrate their capabilities, achieve public prestige, and form exclusive clubs for social capital [15].

Space programs often integrate novel mission parameters to also distinguish their accomplishments from foreign predecessors (e.g., selection of new landing locations on the far side and south pole for post-Apollo Lunar missions). But these sites still use the same celestial body as an overarching category, suggesting that future missions intending to build upon DART's legacy need not search for a new target to receive acclaim and credit for innovation.

Ion Beam Shepherd

The ion beam shepherd method relies on using the particles exhausted from a nearby spacecraft's ion engines to impart force on an asteroid to modify its orbit without physical contact between the spacecraft and the asteroid. An advantage of this technique over the kinetic impactor is that the force would be transmitted irrespective of the object's surface shape and structural properties, which could be irregular.

With the ion beam shepherd method, the momentum of impinging propellant ions accelerated from the spacecraft propulsion system is used to achieve a contactless slow-push deflection whose magnitude does not depend on the spacecraft and asteroid mass [16]. Another advantage of this technique is that the deflection system is part of the spacecraft's system that can operate continuously over long periods of time (the spacecraft would also need a secondary propulsion system to fire in the opposite direction to station-keep the spacecraft at an optimal distance from the asteroid). Active testing of this method is necessary prior to development of a field model to determine the ideal hovering distance for the ion beam satellite, as optimizing beam divergence and accuracy remains an open question for the technique.

A dedicated Didymos-Dimorphos asteroid deflection test site could be used to test and advance the ion beam deflection method. Its orbit does not threaten Earth, and the slow rate of the ion beam method can more easily assuage concerns of redirection relative to impulsive methods.

As with the kinetic test, the binary system is ideal for testing this kind of slow push method because Dimorphos' orbit is easily observable, whereas other testing sites might not be as accessible. Observability is critical because the instantaneous magnitude of relative deflection from an ion beam shepherd is orders of magnitude less than might be provided by a kinetic impactor, and only meets or exceeds a kinetic impactor in aggregate over a long-time horizon.

Centrifugal Mass Driver

The centrifugal propulsion method is essentially the reverse of the ion beam shepherd. Instead of bombarding the asteroid with particles from the outside, the centrifugal mass driver

ejects mass from the asteroid itself. It involves landing a centrifuge and power supply on a target asteroid and leverages the very low local gravity to collect and incrementally eject small portions of the asteroid itself to outer space. In this way, momentum transfer of the recoil gradually adjust the trajectory away from Earth. This sequentially flexible process allows “ejection, measurement, and repetition” to gradually fine-tune the trajectory needed for course correction. The centrifuge approach adds a sustainable and repeatable slow-push tool to the planetary defense toolbox, mitigating the cost, risk, and uncertainty of single-impulse methods [17]. Assuring the asteroid moves in the desired direction may require active control of the direction of the ejected material.

Didymos-Dimorphos provides similar advantages for slow-push methods here as it does in the ion beam shepherding scenario. However, the system’s status as a rubble pile both supports and complicates use of the centrifugal method. The loose grouping of matter may ease extraction, but the structural integrity of the asteroid remains a concern for landing, emplacing, and maintaining the position of the centrifugal launcher. Therefore, the justification for testing a centrifugal mass driver lies in opportunities to directly access the asteroid while preserving the slow push methodology.

Sample collection from celestial bodies forms an integral part of planetary science, and asteroid mining is expected to contribute to the future space economy. A centrifugal mass driver is the only method that potentially combines both the planetary defense mission and direct economic utilization. Following successful deflection of the asteroid from Earth, the same in-situ equipment can be diverted to explore civil/commercial utilization of its resources.

Testing for this method therefore can prove useful even if an active threat does not materialize within the near future, laying the groundwork for mining applications regardless. Because rubble piles may form a significant portion of asteroids future mining operations may target, Dimorphos’ material structure should not necessarily dissuade testing of a centrifugal mass driver, but rather may serve as a challenge to overcome in order to both secure the Earth and simultaneously facilitate long term applications beyond planetary defense.

Directed Energy Deflection

Directed energy laser ablation is a slow-push deflection technique that uses the material of the asteroid itself as the deflection propellant [18, 19]. The laser directed energy system projects a large flux onto the surface to heat and vaporize it and produce an ejection plume that will impart a thrust on the asteroid. Using a laser to redirect an asteroid can be performed without landing, it does not require extra fuel, and it can be used on a variety of targets [20]. Some of the challenges associated with this technique are the rotation or tumble of astronomical bodies, laser beam divergence and pointing accuracy, and sensitivity to focal length.

A Didymos-Dimorphos test facility could be used to test methods and systems for production of optical power output, typically between 1 and 1000 kW, required for application and verification of this technique. This test site is especially well suited to test asteroid laser ablation because in-situ observations can be made of thermal effects on the surface, such as a melt front that may appear given enough time [19].

Nuclear Deflection

In the event of a planetary emergency, nuclear explosive devices exist as a potential last-resort option for a small set of potential scenarios that involve either little to no warning or larger objects. Simulations show that a standoff blast near a threatening asteroid could effectively change its orbital trajectory in the most cost-effective and efficient manner, in terms of its mass-to-deflection force ratio.

The fast neutrons emitted by such an explosion would impact the entire facing surface of the asteroid, mitigating concerns about loose rubble piles. Superheating the surface causes the target to ablate, adding further delta-v to the momentum imparted for deflection. However, high porosity of an asteroid can significantly reduce the momentum of ejecta upon interception, somewhat limiting the effective change in momentum [21]. Additionally, a nuclear explosive device could potentially be used as a last-ditch attempt to disrupt an impactor to mitigate damage on Earth. Simulations have shown that a disruption mission is carried out at least a month before impact, over 90% of the object's material will miss the Earth entirely for a 1 Mt device detonated 15 m from a 100 m asteroid [22].

Figure 1 depicts application of the JPL/Aerospace NEO Deflection App (NDA) [23] to examine deflection possibilities of a Dimorphos-size object (using 2021 Planetary Defense Conference simulated asteroid PDC21 as a proxy) from an impact with Earth by a high-speed kinetic impactor spacecraft at 3, 2, and 1 years before impact. Colored regions in Figure 1 signify that deflection missions are feasible. The NDA shows that kinetic impactor-based deflection of a Dimorphos-like PDC21 asteroid 3 years before Earth impact requires about 3 SLS 2B rockets, or between 10 and 15 Falcon Heavy launch vehicles. Therefore, this approach is clearly impractical. Kinetic impact deflection 2 or 1 years before impact is even less practical or simply impossible. As kinetic deflection is not an option in this short timeline scenario, nuclear deflection of the same object could be a viable method of deflection to avert an impact with Earth.

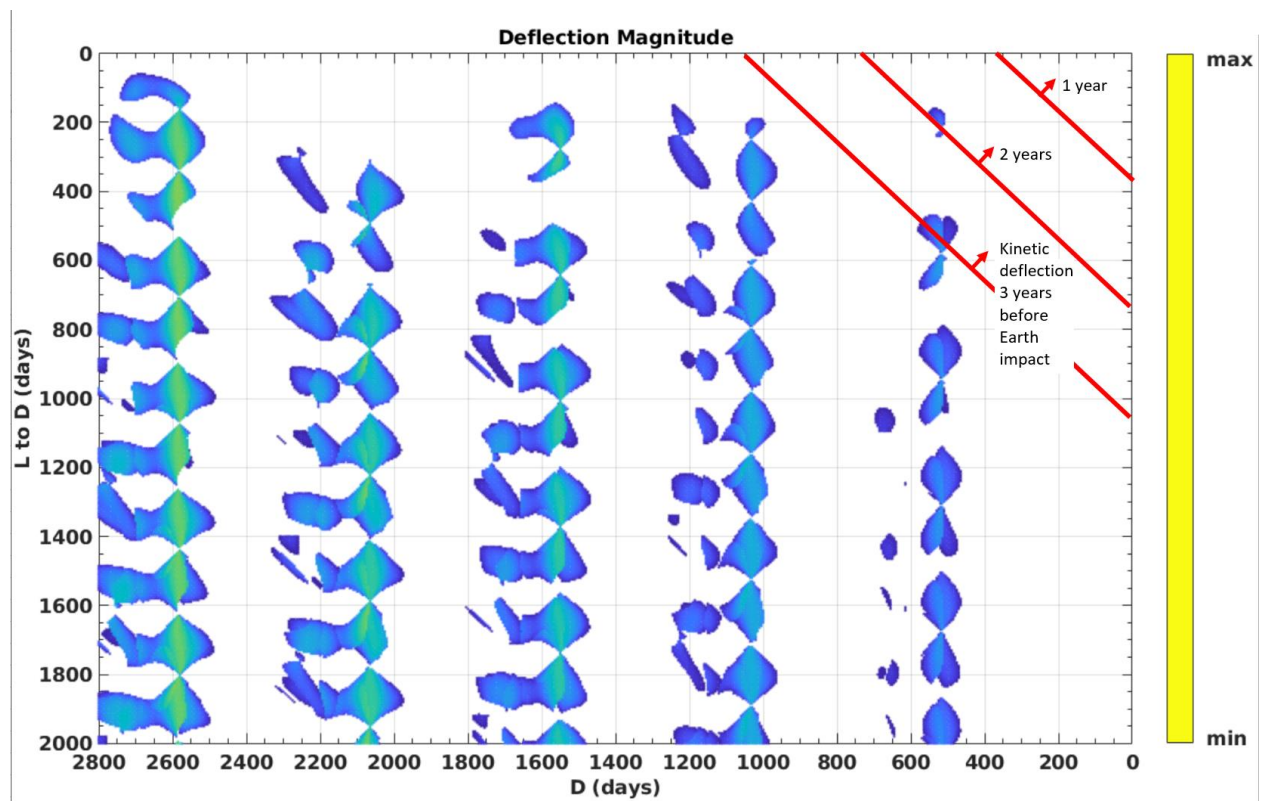


Figure 1. Simulated PDC21 asteroid is adjusted to Dimorphos size in JPL/Aerospace NEO Deflection App [23] to examine feasibility of kinetic deflection 3, 2 and 1 years before impact with Earth. The colored regions indicate feasibility. Successful deflection requires multiple launch vehicles, which is impractical.

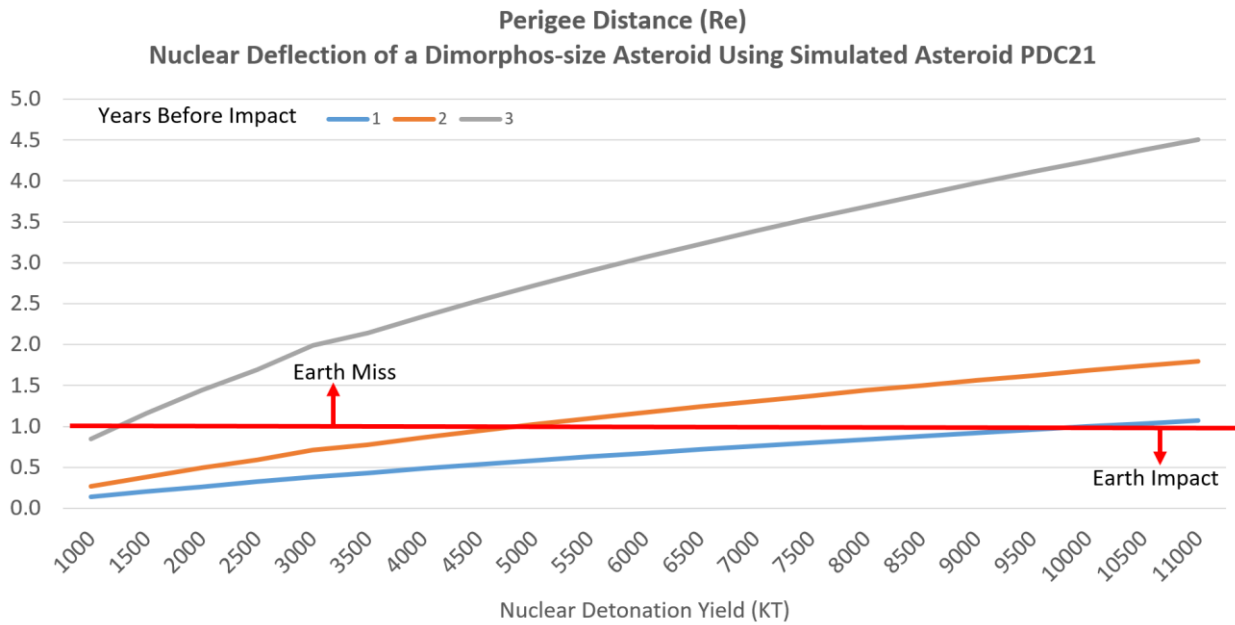


Figure 2. Simulated asteroid PDC21 is used to estimate the amount of nuclear detonation yield required to deflect an Earthbound Dimorphos-size asteroid 3, 2, and 1 years before Earth impact. Shorter time to impact requires higher nuclear energy to achieve Earth miss, assuming no disruption.

The primary restriction of this method is the legal prohibition on placement or use of nuclear weapons in space, under the 1967 Outer Space Treaty [24]. There are concerns that nuclear explosives as a planetary defense method may be indistinguishable from nuclear weapons, and that testing and development of such capabilities for planetary defense may contribute to the weaponization of outer space [25]. Survey experiments also reveal a significant and cross-national opposition to nuclear explosives as a planetary defense method [26]. For planners seeking to integrate nuclear explosives into planetary defense strategy, they must address the legal prohibition, demonstrate that their use would not enflame international tensions, and align public opinion. Presuming the success of any potential legal reform that designates public security as an exceptional circumstance, Dimorphos may serve as a testing ground to bring the methodology into compliance with international cooperation and public opinion.

A Dimorphos test site would be clearly observable for all states and provide evidence of what a nuclear explosion for planetary defense purposes would resemble. To preclude risk of misinterpretation of motives or practices, particularly to avoid armed conflict by misunderstanding during a planetary defense campaign [27], a transparent testbed would be critical to set expectations in advance. In parallel, experience with prior tests could contribute to public confidence in this methodology, preventing controversy or opposition that might otherwise complicate or prevent use of this method.

Using massive amounts of conventional explosives has been proposed as a means to replicate the methodology of a nuclear device without the legal barrier, although their capabilities are more limited due to a lower mass-yield ratio [28]. If planners proceed with this test, the dual-

use nature and retention of a rapid and impulsive deflection mission profile may benefit from similar treatment of experiments to nuclear explosives. For deflection techniques with a longstanding background in military technologies, and with more overt dual-use potential, Dimorphos can serve as a common nexus for determining the proper conditions for their limited deployment.

Political and Policy Considerations of Revisiting Didymos-Dimorphos

The technical merits of these various deflection techniques aside, there is a strong political and legal dimension to planetary defense that also needs to be taken into consideration. Political scientists have recognized the potential for planetary defense asteroid missions to be repurposed for opportunistic military, economic, or social objectives, including planetary defense. Some argue that the mere existence of planetary defense as a policy topic may contribute to the redefinition of what has traditionally been a scientific and public safety issue to a national security enterprise, thus contributing to arms races and the broader militarization of space [29, 30]. Even some of those that cite the necessity for planetary defense recognize that its inherently dual-use infrastructure has the capacity to not only inflame tensions but actively incite conflict [27, 31]. Legal scholars also point out additional unanswered questions on responsibility, liability, and authority obligations and responsibilities under international law to undertake planetary defense response missions [32]. To address these possibilities, the standardization and reapplication of Didymos-Dimorphos as a planetary defense site may have value as an asset for preserving and expanding international cooperation on space policy and public security.

While it is unlikely that one or even several additional planet defense tests will fully resolve all the political and legal questions, they are a promising route towards resolutions. To date, these questions have been debated in primarily academic or limited political contexts, which can be illuminating but may struggle to move beyond more abstract aspects into practical prerequisites of an active mission. In contrast, engaging with the legal and political questions associated with a specific test mission or campaign can concentrate the attention of stakeholders on a more tangible and accessible component of planetary defense.

Incremental progress can be just as useful in narrowing the unsolved legal and political solution set as it can be for the engineering solution set. The 2022 DART test has already become a focal point for international cooperation between the U.S. and member states of the European Space Agency by facilitating the upcoming Hera test. Future missions may continue and learn from this initial collaboration.

Because survey experiments identify a strong public preference for multilateral planetary defense missions [26], new joint missions may lay the groundwork for just such coordination. These opportunities would allow participating states to develop their experience with common operations, with value for planetary defense and other comparable in-space projects. As the scope and membership of space cooperation develops into larger and more coherent blocs [33], the chance to train and develop interoperable infrastructure will be useful.

Furthermore, the institutionalization of Didymos-Dimorphos as a global test site could expand upon the success to further international cooperation on space policy more generally. Beyond incidental collaborations, having a permanent site with internationally recognized behavioral standards draws upon the success of UN-facilitated bodies to preserve such unity after missions conclude. The International Asteroid Warning Network (IAWN) and Space

Mission Planning Group (SMPAG) formed in the wake of the 2013 Chelyabinsk bolide incident to institutionalize and internationalize the identification of potentially hazardous objects and coordination to address such threats, respectively. Their continued coordination in the years following demonstrates the durability of cooperative international institutions in this issue area, and thus offers a favorable template for utilizing a common planetary defense testing site as part of a broader coalition..

Each additional mission to the Didymos site serves not only as technological proof of concept, but also as an example of proper procedure for experimentation and implementation of planetary defense. Therefore, every mission conducted in line with the general parameters of the DART mission also serves to develop and deepen specific norms of responsible behavior. Likewise, compliance with these norms would allow missions to serve as trust and confidence building measures [34]. Setting a proper procedure, and then showcasing compliance with set standards can demonstrate the peaceable intentions of planetary defense and commitment to the needs and concerns of the international community.

Conclusion

An effective planetary defense campaign has underlying social and material needs, many of which can be addressed with the development of a fixed test site in the Didymos-Dimorphos binary system. An established history of technology readiness tests must come before relying on novel techniques for threat mitigation. Identification of credible performers of planetary defense is necessary to assuage concerns about motives or effectiveness of any would-be planetary defender states, particularly for governments reliant on foreign protection. Development of familiar procedural routines and the social infrastructure for any desired international cooperation both require establishing these behaviors and sustaining them over time. Therefore, whether planetary defense proceeds as a unilateral or multilateral endeavor, or utilizes any particular technology, a fixed test site can serve a broad range of needs prior to the deployment of an active planetary defense mission.

Didymos-Dimorphos is the most well-known test site for planetary defense, owing to a recent concentration of missions. These efforts highlight its value, and instead of exhausting what we can learn from this location, findings from current research only serve to enhance the site's value for future missions. A viable baseline has been established for future observation and deflection test missions; one that any other test site might sacrifice. Previous tests have also not yet established the full range of technologies and techniques that might contribute to planetary defense. The use of a testbed with known qualities comes closest to providing laboratory conditions for any attempts to explore, deploy, and improve these technologies.

The political realities of planetary defense also situate the practice at the very least within the scope of international coordination. To prevent misunderstandings, address perceived perverse motives, and prevent social barriers to the conduct of efficient missions, set standards of behavior are useful. These efforts may also have an agenda-setting effect on the development of international norms on proper practices in outer space, leaving a legacy beyond the planetary defense mission and informing expectations for state and commercial actors' behavior in the long term. Utilizing Didymos-Dimorphos for these purposes could prove just as vital as any technological exercise for maximizing chances of mission success. If cooperation is to go further, development of standardized procedures, cooperative experience across organizations, and co-development of interoperable assets may also depend on a promising test site to lay the groundwork.

As we approach a new policy environment for planetary defense, planners have opportunities to initiate a shared and sustained use of a designated in-space test site. Established, recent, and future practitioners of planetary defense alike can benefit from further testing, comparison, and coordination across programs. In turn, their use of this site can contribute to the technological maturation of planetary defense technologies, and potentially new applications beyond. These tests can continue to build upon recent successes and continue to prepare for any eventual call to action.

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