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.

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.

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, 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 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. 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

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.

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.

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. Assuring the asteroid moves in the desired direction may require active control of the direction of the ejected material.

Kinetic Impactor

Directed energy laser ablation is a slow-push deflection technique that uses the material of the asteroid itself as the deflection propellant. 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. 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.

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.

Figure 1 depicts application of the JPL/Aerospace NEO Deflection App (NDA) 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 impact spacecraft at 3, 2, and 1 years before impact. Colored regions in Figure 2 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 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.

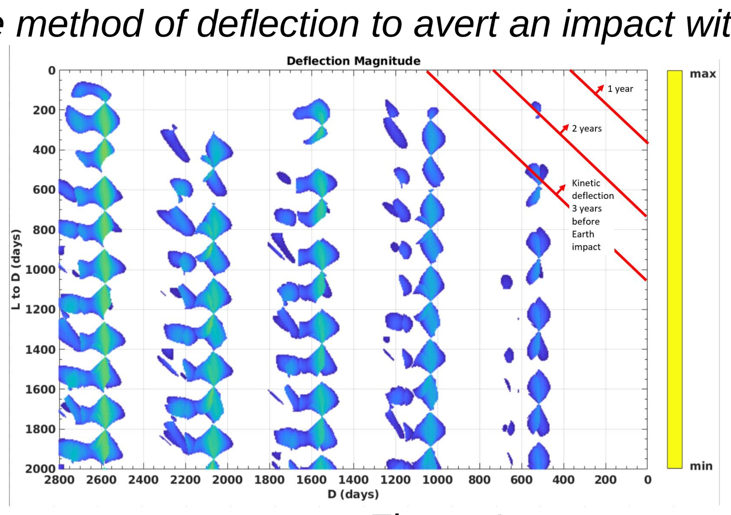

Figure 1

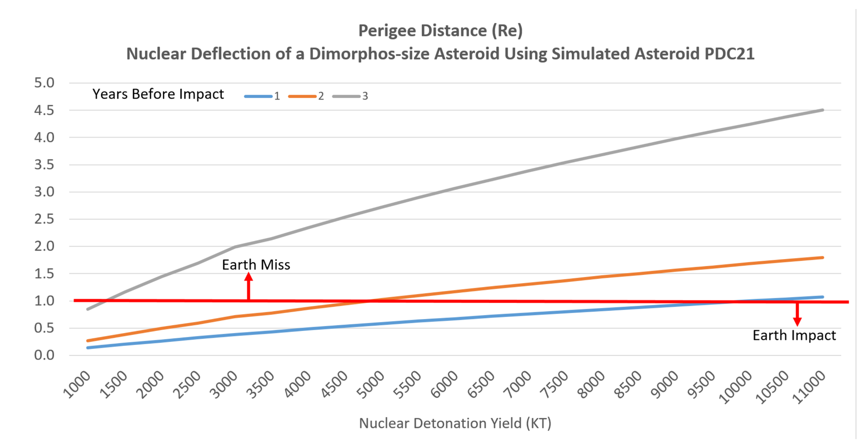

Figure 2

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.