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INSIGHTS FOR NEO DEFLECTION

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ABSTRACT

The Aerospace Corporation has developed a physics based Near Earth Object (NEO) Deflection Simulator, or App for application, for NASA HQ under guidance and in collaboration with NASA's Jet Propulsion Laboratory (JPL). NEOs are asteroids and comets whose orbits bring them close to Earth's orbit and pose a collision possibility. The simulator was developed in response to findings and recommendations from studies, conferences, exercises and workshops on the NEO impact threat and defending the planet from such impacts. Hypothetical impact scenarios with simulated NEOs were created by JPL and feasible deflection mission options and factors influencing mission decisions were identified and incorporated into the deflection simulator. The tool uses astrodynamics data to determine possible launch windows using current and forthcoming launch vehicle capabilities. The tool approximates deflection using the kinetic impact technique and establishes Earth miss criteria that inform decisions as to the preferred option for a given scenario. The tool helps to understand and gain insight on deflection requirements, possibilities and limitations in the following categories: NEO discovery time, early vs. late decision to build and launch a deflection device; NEO orbit, size, composition and the associated uncertainties; NEO intercept direction and velocity; single vs. binary objects; U.S and international launch vehicle lift capability; and the number of launches required in a deflection campaign.

This extended abstract studies several simulated NEOs with different orbital characteristics using the NEO Deflection Simulator and reports the insights and recommendations derived from this work. Objects in Earth-similar, high inclination, and long period orbits are studied for their varying effects on mission parameters such as frequency of launch windows, attainable relative velocities, mass delivery, and deflection susceptibility. It was found that the problem of NEO deflection is highly non-linear and is heavily dependent on the NEO's orbital characteristics. Moreover, it is demonstrated that early NEO discovery increases mission options and deflection effectivity, that forthcoming heavy launch vehicles has better capability to deflect bigger NEOs and counter the effects of uncertainties associated with smaller NEOs. The tool also shows the limitations of the kinetic impact method and when a more energetic approach such as nuclear explosives might be required.

INTRODUCTION

At the 2015 IAA Planetary Defense Conference (PDC) a hypothetical asteroid impact scenario will be presented and used as a basis for discussion. This extended abstract focuses on that 2015 PDC hypothetical asteroid impact scenario which is introduced in Reference 1. The scenario synopsis is as follows: An asteroid "2015 PDC" is discovered on April 13, 2015 at absolute magnitude 20.9, declination -39 degrees and heading south respective to the ecliptic plane. The asteroid's mean distance from the Sun (semi-major axis) is 1.77 au, and the orbital eccentricity is 0.49. Its perihelion distance is 0.90 au and aphelion distance is 2.65 au; the orbital period is 864 days (2.37 years). The orbital inclination is fairly small: 5.35 deg. Very little is known about the object's physical properties. Its absolute magnitude is estimated to be about H = 21.3 +/- 0.4, which puts the asteroid's size at roughly 100 to 500 meters.

The web-based interactive NEO Deflection App (NDA) was delivered to JPL in late 2014. The tool’s public release notice is given in Reference 2. This app is designed to provide insights into the problem of deflecting a threatening asteroid using a Kinetic Impactor (KI) spacecraft. Given a simulated asteroid on an Earth impact trajectory, the app can answer such questions as:

- What are the best times to deflect the asteroid?
- How much velocity change is required to make the asteroid miss the Earth?
- When could an impactor spacecraft be launched in order to intercept the asteroid?
- What is the maximum size of asteroid that can be deflected with a single launch?
- In which direction will the asteroid be deflected most easily?

The app has been pre-loaded with the hypothetical asteroid 2015 PDC created for the impact scenario to be discussed at the 2015 Planetary Defense Conference. A quick overview of the app and a detailed tour of the app are given in Reference 2. The planetary defense goal is to prevent Earth surface impact by asteroid 2015 PDC if possible or to reduce its likelihood of collision. Preventing the imminent impact of asteroid 2015 PDC involves launching one or more spacecraft to deflect the asteroid before impact occurs.

Asteroid 2015 PDC Deflection Insights

Any attempt to deflect asteroid 2015 PDC before impact with Earth will require launching a spacecraft on a deflection/disruption mission. A key question that would be posed by decision makers is “What the shortest period of time before impact is when effective deflection can be attempted?”

Planetary defense options can be executed at the national level or at the international level since impact consequences may cross international boundaries. A state of emergency spanning several regions of the world would change priorities and any existing launch capabilities would be recruited and allocated for planetary defense objectives. The point of this study is to identify the asteroid 2015 PDC schedule drivers for mission design and intercept coordinates for loading to the flight computer. The NEO Deflection App is used to emulate the PDC 2015 threat scenario, examine the choices we have to deflect or disrupt the object, and seek deflection solutions over a period of about a decade. The assumption of a decade for action, longer than the hypothetical 7 years of the PDC

2015 scenario, was used to clearly demonstrate the advantage of early discovery and mitigation decisions.

Evaluation

This evaluation spans warning times of up to a decade in increments of 0.5 years and assumes the following range of object sizes: 100, 140, 200, 300 and 500 meters. When viable deflection opportunities exist between the discrete time increments defined above, they are inserted for each of these object sizes. This is first done in the App's "ΔV Mode," which simply delivers a velocity impulse at a specified time before impact. In this Mode, the velocity impulse is delivered to the asteroid in any combination of the the along-track (asteroid velocity direction), cross-track (in the asteroid orbital plane), and normal to orbital plane directions. This, however, is not a feasible aim for deflection in general because the spacecraft has to be launched from the Earth and travel through space obeying the rules of orbital mechanics. This is done to simply demonstrate the advantage of early discovery on deflection effectivity. The same evaluation is then repeated in the Intercept Mode which accounts for launch capability and asteroid size and density. Deflection solutions attained in this mode are more likely to be feasible in concept.

The NEO Deflection App includes over a dozen simulated NEOs of distinct orbital characteristics. This evaluation compared four NEOs and examined launch windows and deflection effectivity for the PDC 2015 object, one Apollo type object, one Aten type object, and one Earth-like object. Additionally, the ability to deflect asteroid 2015 PDC was also examined for object sizes ranging from 10 to 1000 meters in diameter at the most effective deflection times (4.68, 7.10 and 9.59 years before Earth impact). Asteroid 2015 PDC ΔV distribution in the along-track, cross-track, and normal directions was also examined at the most effective deflection times listed above. Deflection effectivity vs. detection time was also examined.

The NEO Deflection App includes performance approximations for the following four launch vehicles: Atlas V 551, Delta IV Heavy, Falcon Heavy and NASA SLS 2B. The attainable perigee distance was evaluated for each of these launch vehicles at the most effective launch times and deflection times for asteroid 2015 PDC over a size range from 100 to 500 meters in diameter. Finally, the minimum number of launches required to deflect a 500 meters size asteroid 2015 PDC was evaluated for each of the launch vehicles listed above.

Figure 1 sets the NEO Deflection App in the ΔV (Delta-V) Mode and examines deflection capability for the 140 meter asteroid 2015 PDC during a decade before Earth impact. Deflection of 10 mm/sec is performed in the along-track direction only and does not take into consideration launch capability. Note that the perigee distance is the point of closest approach of the asteroid with the Earth, and a value greater than one Earth radius signifies an impact was averted. The key insight derived from this Figure is that early detection matters. Many deflection opportunities are possible from 5 to 10 years before impact versus the last 5 years before impact. This is confirmed by the along-track deflection sensitivity which relates the amount of deflection at Earth impact epoch for a given deflection impulse at an earlier time. Deflection sensitivity grows with warning time and provides optimal deflection opportunities at around 5, 7 and 9.5 years before impact.

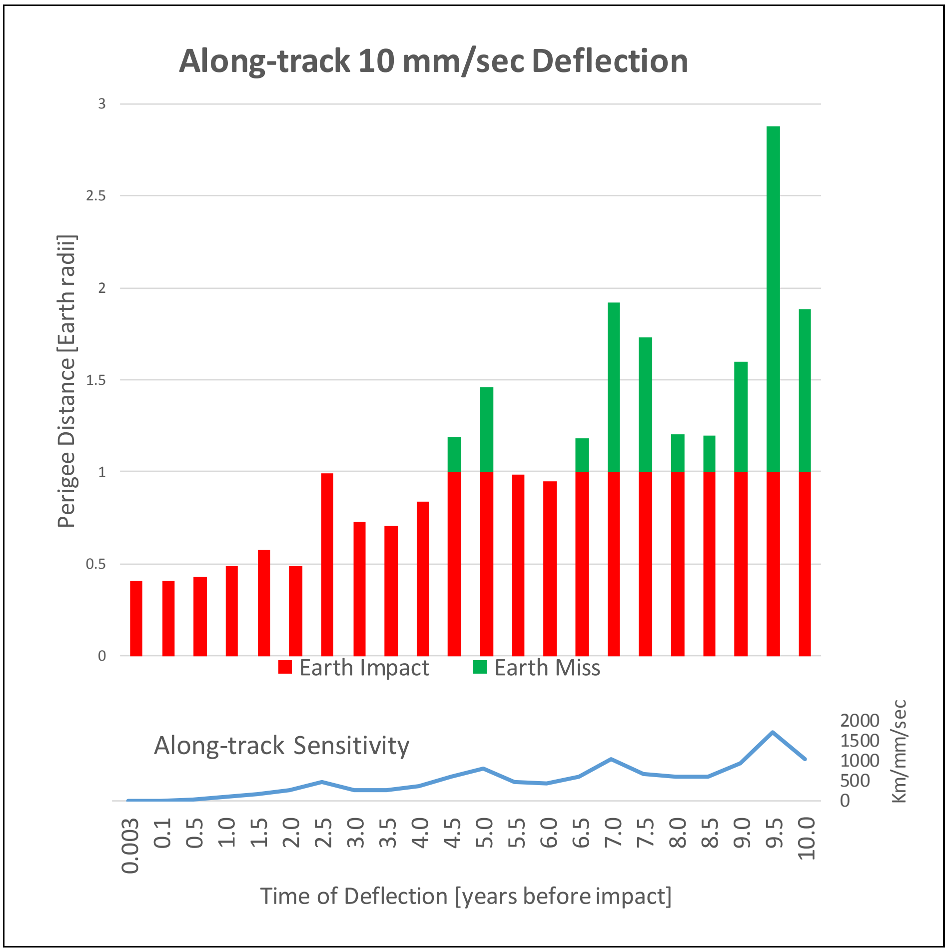

Figure 1. Along-track deflection capability during one decade before Earth impact for 140 meters asteroid PDC 2015

Figure 2 adds launch capability into the scenario described in Figure 1. Time of flight from the Earth to the asteroid was added to the time of deflection before Earth impact. Accounting for lift capability adds realism to the picture and essentially limits deflection opportunities to the optimal times identified by the deflection sensitivity at the bottom of the figure. The key insight derived from this figure is that deflection solutions are not continuously possible and delay in the decision to act may eliminate early launch windows from consideration and create large gaps in the ability to deflect.

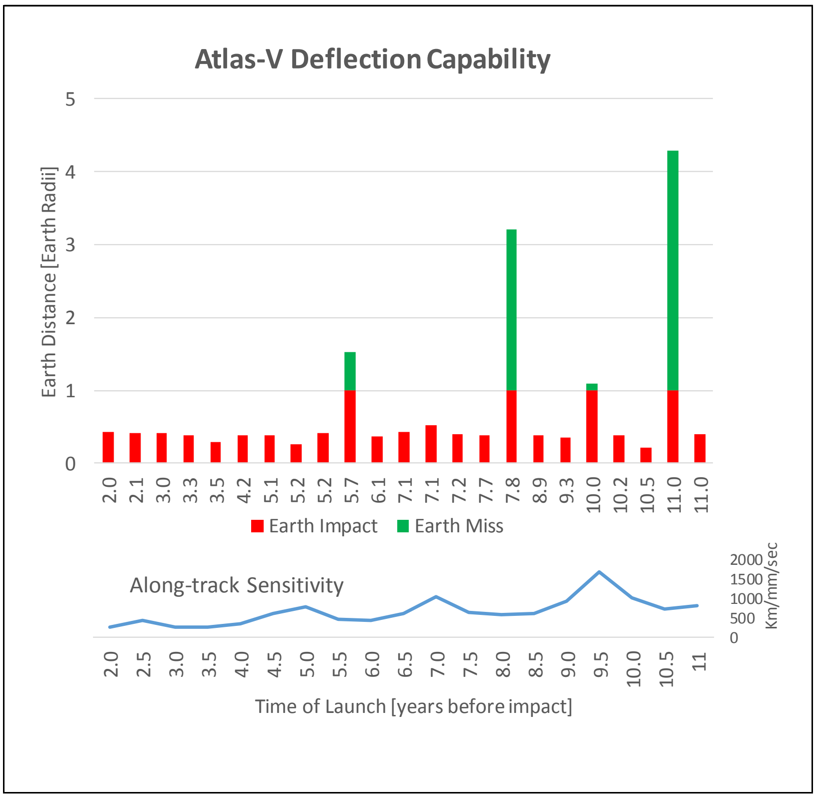

Figure 2. Atlas V deflection capability during one decade before Earth impact for 140 meters asteroid PDC 2015

Near Earth Objects (NEOs) are grouped by their orbital characteristics relative the Earth's orbit around the Sun. Apollo and Aten are Earth-crossing groups while Amor and Atira are either outside or inside Earth's orbit respecively[3]. Figure 3 picked four objects with distinct orbital characteristics and identified distinctly different deflection performance with each of the objects. The Apollo object presented seven sparse deflection opportunities and was not accessible most of the time. Asteroid 2015 PDC presented three deflection opportunities and showed improved deflection effectivity with increased warning time. The Aten and Earth-like object presented no deflection solutions in a decade before impact. All objects were 140 meters in diameter and 1.5 gr/cc in density. The key insight here is that orbits have distinct characteristics that necessitate a case-by-case decision process and mission design.

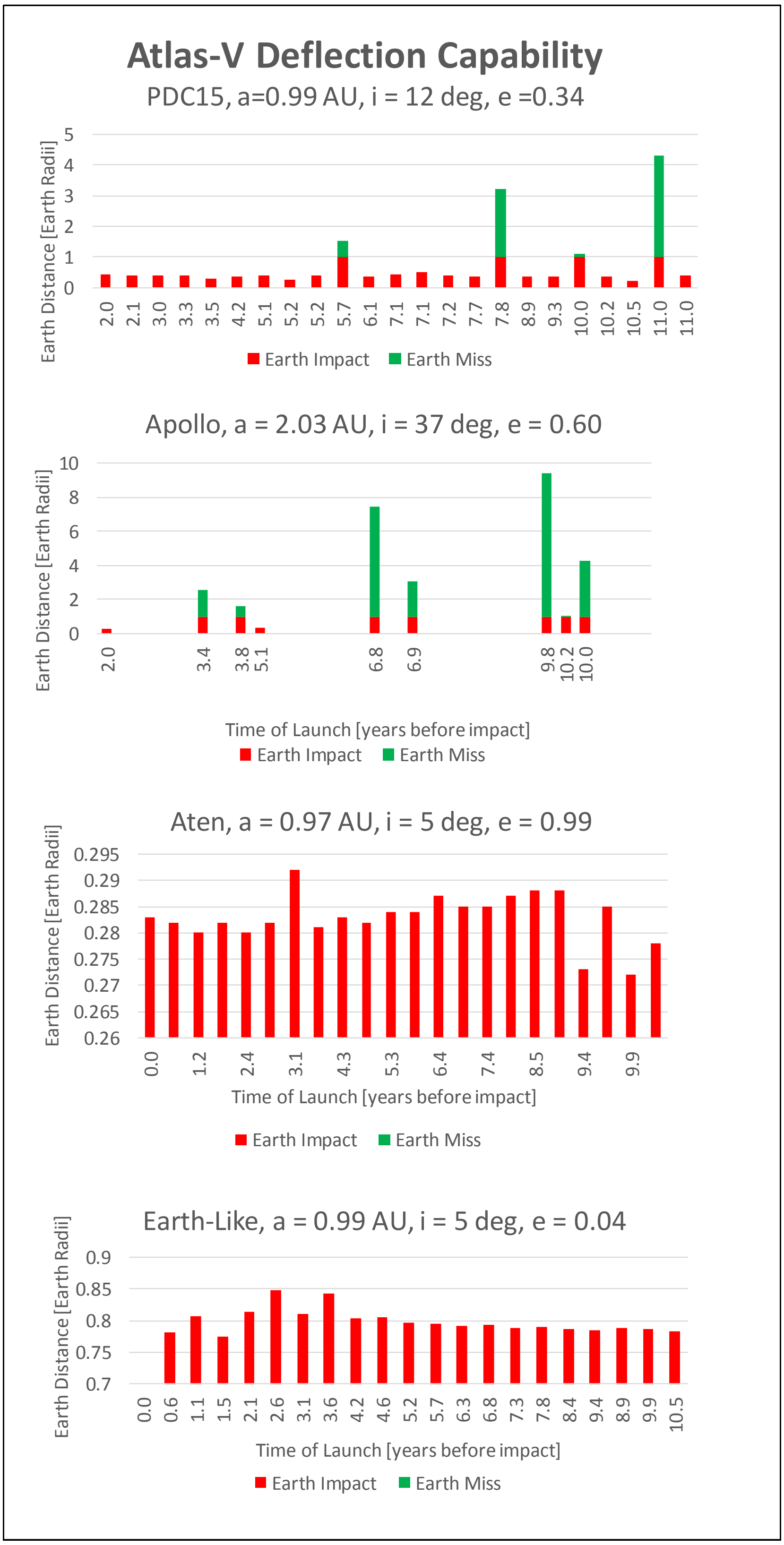

Figure 3. Atlas V deflection capability during one decade before Earth impact for four 140 meters simulated NEOs

Figure 4 examined deflection capability of asteroid "PDC 2015" over a range of object sizes and fixed density of 1.5 g/cc. As expected, larger objects present an increased deflection challenge to the kinetic impact method employed by the web tool. At about 200 meters in diameter no deflected solution was attainable on a single Atlas V launch. Key insight derived here is that multiple launches or heavy lift capability may be required to handle large objects.

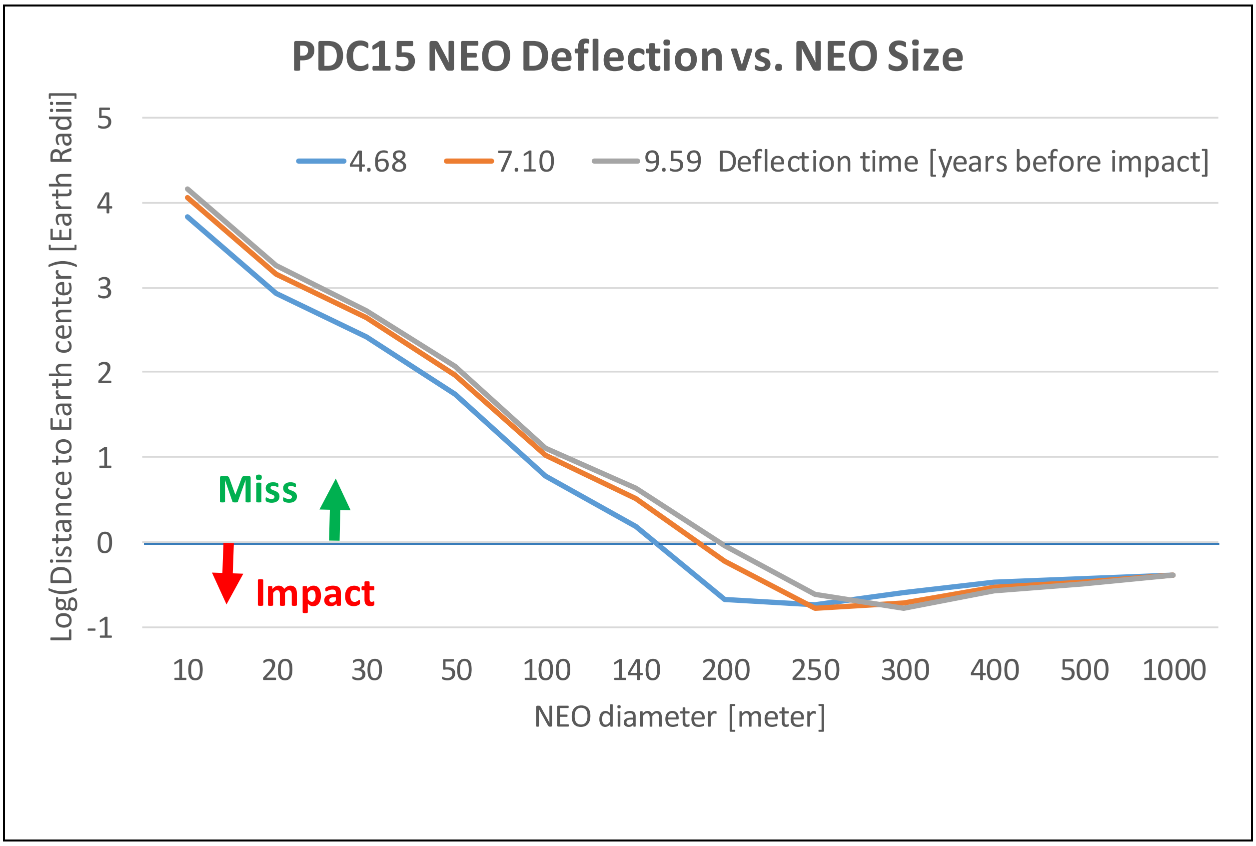

Figure 4. Atlas V deflection capability during one decade before Earth impact for 10 meters to 1000 meters asteroid PDC 2015

Figure 1 is the general ΔV solution and Figure 2 added flight time into the picture. These Figures illustrated the fact that a deflection impulse cannot realistically be imparted to the NEO without taking into consideration launch capability and problem geometry. Figure 5 adds NEO intercept geometry and includes launch capability for a 140 meters asteroid 2015 PDC deflection and breaks down the three ΔV impulse components in the along-track, cross-track and normal directions. Although the required magnitude of the total deflection impulse grows smaller as warning time grows bigger, in all three optimal deflection opportunities identified for the PDC asteroid, a significant component of the delivered deflection impulse is not in the most effective direction – the along-track direction. Thus, deflection impulses cannot be randomly imparted to the NEO at will.

Figure 6 strengthens this conclusion by looking at the total deflection impulse over a decade of warning time, and compares it against the attained deflection. As before, longer warning times provide more deflection opportunities and better deflection performance, and require smaller deflection impulses. Short warning times, or equivalently, late decisions to act, require large ΔV impulses and yield small deflections. Larger deflections and smaller impulses are attainable when early detection is available and a decision to act is made early.

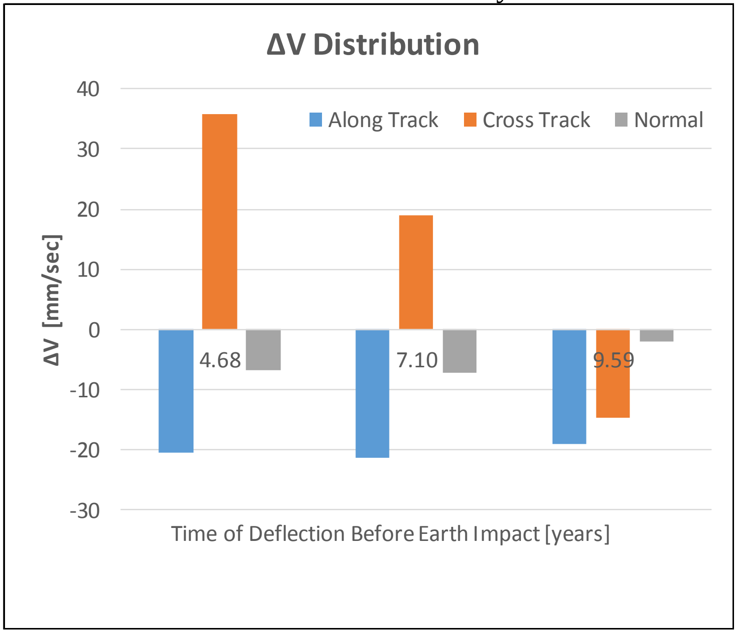

Figure 5. Atlas V ΔV distribution in the along-track, cross-track and normal directions at optimal deflection times before Earth impact for 140 meters asteroid "PDC 2015."

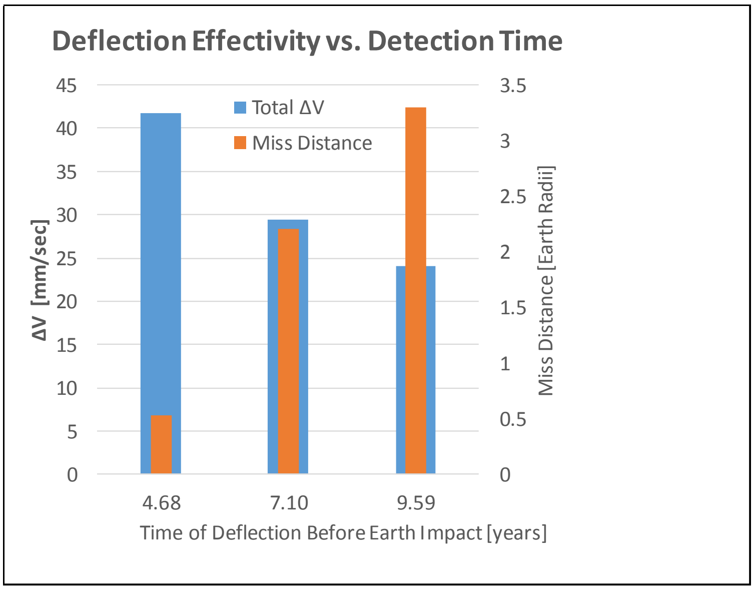

Figure 6. Atlas V deflection effectivity vs. detection time before Earth impact for 140 meters asteroid PDC 2015.

Figure 7 examines launch vehicle capability to execute a deflection mission on asteroid 2015 PDC over a size range of 100 meters to 500 meters. Clearly, heavy lift capability enables handling larger objects on a single launch. Objects in the 100 meters size range can be effectively deflected to some degree by all the launch vehicles considered here in all three optimal deflection opportunities. Only the future NASA SLS 2B vehicle can effectively deflect objects in the 300 meters size range on a single launch. Objects in the 500 meters size range cannot be effectively deflected at all on a single launch with any of the launch vehicles. Figure 7 also shows that deflecting 500 meters class objects to the edge of Earth requires fewer heavy launch vehicles and is therefore more realizable than with smaller launch vehicles.

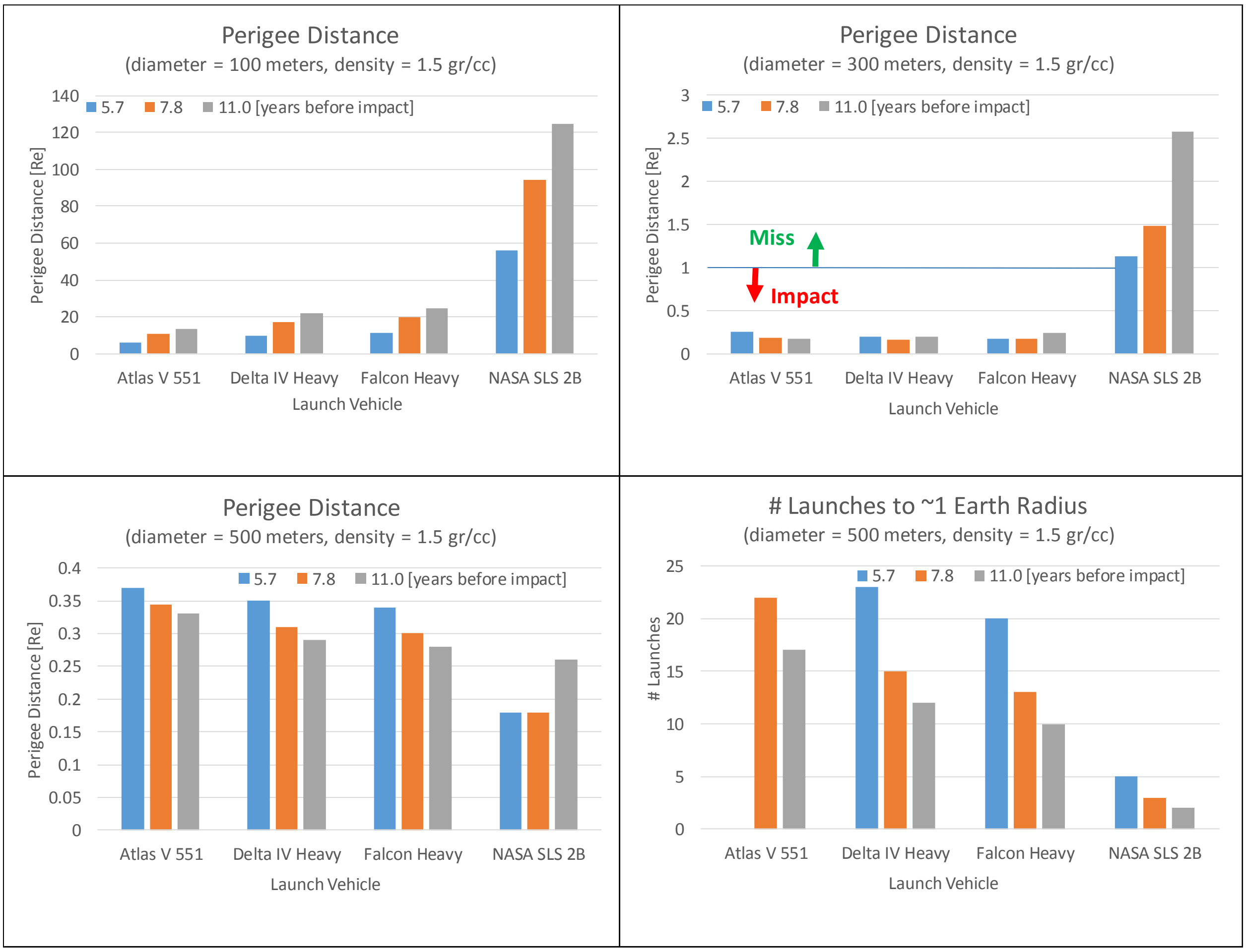

Figure 7. Lift capability at optimal deflection times before Earth impact for 100 meters to 500 meters asteroid 2015 PDC

CONCLUSIONS:

This study utilized a NEO deflection App developed by The Aerospace Corporation for NASA HQ to derive insights on NEO threat mitigation. Asteroid 2015 PDC and several other several simulated NEOs provided case studies for understanding deflection requirements and limitations in a range of object sizes and deflection times over a decade before Earth impact. Key insights show that early NEO detection and decision to act is critical for expanding mitigation options. Deflection ability strongly relies on available launch technology and readiness – heavier launch vehicles provide better deflection performance with fewer launches and may be the only realistic option for handling large NEOs. The problem of NEO deflection is nonlinear and is highly dependent on orbital characteristics and deflection geometry so deflection opportunities may not be available continuously. Hence, it cannot be assumed that a decision to mount a deflection mission can be taken at any time before impact and yield monotonously changing deflection results. The NEO

Deflection App is educational in nature, it informs the mitigation decision process, and it can help advance the defense of Earth.

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