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OPTIMAL TARGET SELECTION FOR A PLANETARY DEFENSE TECHNOLOGY (PDT) DEMONSTRATION MISSION

Tim Winkler,* Sam Wagner,† and Bong Wie‡

During the past two decades, various options such as nuclear explosions, kinetic impactors, and slow-pull gravity tractors have been proposed for mitigating the impact threat of near-Earth objects (NEOs). However, currently, there is no consensus on how to reliably deflect or disrupt hazardous NEOs in a timely manner. The use of nuclear explosives may become inevitable for the most probable impact threat with a short warning time. This paper presents potential NEO candidates selected for a planetary defense technology (PDT) demonstration mission, currently being envisioned by the planetary defense community. A flight demonstration mission is necessary to validate and verify the practical effectiveness of blending a hypervelocity kinetic impactor with a penetrated nuclear subsurface explosion.

INTRODUCTION

Although there is currently no known immediate threat of a near-Earth object (NEO) to the Earth, many new asteroids are being discovered each year, of which some could potentially pose a threat to the Earth with little to no warning. Every day there are numerous objects that impact the Earth. The majority of these impacts are small meteors no bigger than 10 m and are of little cause for concern. Collisions with much larger objects, while infrequent, do occasionally occur, and have the potential to cause unprecedented damage. Various technologies, including nuclear explosions, kinetic impactors, and slow-pull gravity tractors for mitigating the impact threat of NEOs, have been proposed and studied during the past two decades. However, currently, there is no consensus on how to reliably deflect or disrupt hazardous NEOs in a timely manner. Furthermore, there has not been any flight demonstration mission to verify and validate key technologies that will be employed in a real mitigation mission.

This study will determine a list of optimal asteroid targets for a planetary defense technology (PDT) demonstration mission, which would validate asteroid deflection or disruption capabilities. For the purposes of this study, only asteroids listed in NASA's Near Earth Object Program database will be considered. This database also contains a list of near-Earth comets, which will not be considered in this paper. Although comets are also at risk of impacting the Earth, they add unnecessary complexity to the spacecraft design as it must be shielded from the small, hypervelocity dust grains that form the coma. In addition, previous missions such as Deep Impact and Stardust have already

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*Graduate Research Assistant, Department of Aerospace Engineering, Iowa State Universtity, 1200 Howe Hall, Room 2362, twinkler@iastate.edu.

†Graduate Research Assistant, Department of Aerospace Engineering, Iowa State University, 1200 Howe Hall, Room 2348, thewags@iastate.edu.

‡Vance Coffman Endowed Chair Professor, Department of Aerospace Engineering, Iowa State University, 1200 Howe Hall, Room 2355, bongwie@iastate.edu.

flight-validated the necessary shielding and targeting capabilities for comets. As such, the asteroid targets identified in this study will allow a demonstration mission to focus on validating deflection/disruption technologies, which should prove equally effective against comets should the need arise.

Previous NEO Missions and Proposals

There have already been several exploration missions to asteroids and comets successfully accomplished by NASA, ESA, and JAXA. Two notable missions that involved NEO targeting technologies that would be involved in an asteroid defense mission were Deep Impact by NASA and Hayabusa by JAXA. The Hayabusa spacecraft contained a small lander called MINERVA that was to be guided to the surface of the asteroid Itokawa, but unfortunately drifted into space due to the low gravity. The Deep Impact spacecraft on the other hand was comprised of an impactor and a flyby spacecraft. Approximately 24 hours before impact with the comet Tempel 1, the impactor was released and autonomously navigated to ensure a hypervelocity impact of 10 km/s with the 5-km target.

In recent years, the ESA proposed a demonstration mission for a kinetic-impactor, based entirely on conventional spacecraft technologies, called the Don Quijote mission.[1,2] The mission concept called for two separate spacecraft to be launched at the same time, but follow different interplanetary trajectories. Sancho, the orbiter spacecraft, would be the first to depart Earth's orbit, and rendezvous with a target asteroid approximately 500 m in diameter. Sancho would measure the position, shape, and other relevant characteristics before and after a hypervelocity impact by Hidalgo, the impactor spacecraft. After Sancho has studied the target for some months, Hidalgo approaches the target at a closing speed of about 10 km/s. Sancho then observes any changes in the asteroid after the kinetic impact to assess the effectiveness of this deflection strategy. Don Quijote was planned to launch in early 2011, and conclude in mid to late 2017. However, the mission concept was never realized due to higher than expected mission costs.

Table 1. Target Selection Criteria for the Don Quijote Mission.

Orbit Characteristics	Preferred Range
Rendezvous ΔV	< 7 km/s
Orbit type	Amor
MOID	large and increasing
Orbit accuracy	well determined orbits
Physical Characteristics	**Preferred Range**
Size	< 800 m
Density	$\sim$1.3 g/cm^3
Absolute magnitude	20.4 - 19.6
Shape	not irregular
Taxonomic type	C-type
Rotation period	< 20 hours
Binarity	not binary

The selection process for the Don Quijote mission was based on a set of NEO characteristics defined by ESA's NEOMAP in Table 1.[3] Their analysis resulted in the selection of the asteroids

Table 2. Properties of Candidate Targets Considered for the Don Quijote Mission.

	2002 AT4	1989 ML
Orbital period (yr)	2.549	1.463
e	0.447	0.137
i (deg)	1.5	4.4
ΔV (km/s)	6.58	4.46
Orbit type	Amor	Amor
MOID	large	large
Absolute magnitude	20.96	19.35
Taxonomic type	D-type	E-type
Diameter (m)	380	800
Rotational period (hr)	6	19

2002 AT4 and 1989 ML. As can be noticed in Table 2, 2002 AT4 is roughly half the size of 1989 ML, but requires a higher ΔV in order to intercept. A realistic deflector spacecraft would require a versatile design capable of intercepting and deflecting or disrupting both kinds of targets on short notice.

Currently at the Asteroid Deflection Research Center (ADRC), a hypervelocity nuclear interceptor system (HNIS) concept is being investigated for a high-energy disruption/fragmentation mission that may be inevitable for the most probable impact threat with a short warning time.[4,5,6] While the Don Quijote mission concept considered deflecting an asteroid with a kinetic impactor, the ADRC is focusing on a high-energy deflection/disruption demo mission by means of a standoff or contact explosion or disrupting/fragmenting the asteroid into smaller, less threatening pieces using a penetrating subsurface nuclear explosion. The latter option is accomplished by an innovative, two body penetrator design, which allows a nuclear explosive device (NED) to be detonated inside the asteroid itself to facilitate a more efficient energy transfer from the explosion.[4,5,6] To aid in helping the spacecraft intercept the target, an orbital transfer vehicle (OTV) is also being investigated for the purpose of providing additional ΔV at orbit injection.

OPTIMAL TARGET SELECTION PROCESS

For the purposes of this study, only asteroids in the near-Earth asteroid (NEA) groups Apollo, Aten, and Amor were considered. Asteroids in these groups all have perihelion distances of 1.3 AU or less, and many of them also cross the Earth's orbit at some point. Asteroids in these groups are relatively close to the Earth, and have low ΔV requirements to achieve intercept. As such, objects in these groups are the most likely candidates for an asteroid deflection/disruption demonstration mission. Apollo and Aten class asteroids are characterized by asteroids with orbits that intersect that of the Earth, which could potentially lead to lower ΔV requirements for a mission. On the other hand, this same fact means that any significant perturbation in the object's trajectory could cause it to later impact the Earth. While unlikely, a demonstration of deflection technologies could cause this to happen. The ESA also had this in mind when they selected the asteroids 2002 AT4 and 1989 ML from the Amor group for the Don Quijote mission concept.[1] With that in mind, the Amor group shall be the focus for determining suitable candidates in this paper.

As illustrated in Figure 1, the Amor asteroid group is characterized by asteroids that approach the

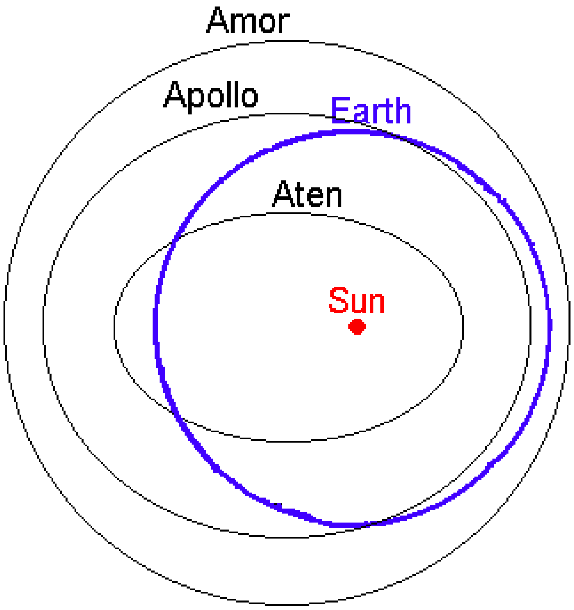


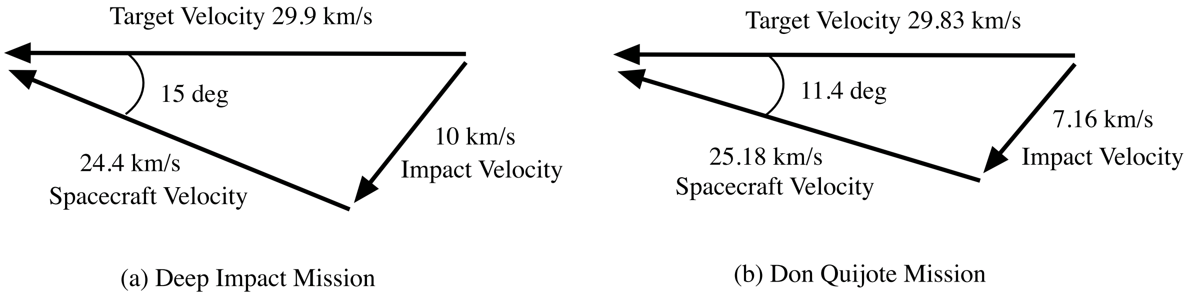
Figure 1. Illustration of Typical Orbits of Apollo, Aten and Amor Asteroids.

Earth, but do not actually cross its orbit. By definition the perihelion distances of these asteroids lie between 1.017 and 1.3 AU. As the entire orbit is outside that of the Earth, any disturbance in the trajectories of these asteroids is even less likely to cause them to later impact the Earth. As of 10/20/2011, there are 3084 Amor class asteroids listed in NASA's Near Earth Object Program database. This number is first reduced by only considering asteroids that are at least 100 m in diameter. This is done by only considering objects with an absolute magnitude (H value) of 22 or lower. Assuming that the asteroids albedo falls within the presumed 0.25 to 0.05 albedo range, this H value corresponds to an object at least 110 to 240 m in diameter. Applying this minimum size limit reduces the number of asteroids to be considered to a little more than 2200.

Table 3. Targe Selection Criteria.

Characteristic	Preferred
Orbit type	Amor
Absolute Magnitude	18 - 21
Diameter	300 – 1000 m
Total ΔV	$<$ 5 km/s

Table 3 summarizes the selection criteria used in this study. While asteroids as small as 100 m are studied, optimal candidates will have a diameter between 300 to 1000 m. This large diameter



(a) Deep Impact Mission

(b) Don Quijote Mission

Figure 2. Velocity Vector Diagrams and Impact Approach Angles for the Deep Impact and Don Quijote Missions.

requirement is utilized due to constraints imposed by current targeting technologies, and a necessity to assess the effectiveness of nuclear fragmentation on larger, threatening objects. Should the mission successfully disrupt a larger object, it will prove equally effective on smaller sized asteroids as well. A limit on the ΔV required for intercept is due to the limitations imposed by current launch vehicle and spacecraft capabilities. This limit also takes into account the requirement of a relative closing velocity of approximately 10 km/s. This is enforced in order to simulate a situation with a short warning time of Earth impact. The limit on total ΔV ends up being the same upper limit for the Don Quijote mission selection process. This number was chosen due to the total ΔV capabilities given in Table 4, which are based on maximum payload masses for each launch vehicle. These represent conservative estimates for the total payload masses, which tend toward the worst case heavier options. An additional requirement which could be used, is the impact approach angle shown in Figure 2. The impact approach angle is defined as the angle between the velocity vectors of the target and spacecraft at the time of impact. This is an important piece of information for a two body HNIS as the leading body must impact the asteroid ahead of the NED to successfully achieve a subsurface detonation. Furthermore, there may be cases when it is more advantageous to impact the target from a certain direction to greater facilitate the desired amount of deflection. For the purposes of this study, no constraints on the impact approach angle will be enforced

Launch Options

Based on the target criteria discussed above, ephemeris data from NASA's Horizons database was used in conjunction with programs developed at the ADRC to calculate the minimum ΔV for missions of varying duration to each asteroid. The details of this program can be found in Reference 7. The targets will be restricted to the estimated capabilities of the spacecraft with three different launch vehicles: the Delta II 7920H, Delta IV Heavy and Atlas V 551. The estimates used in this study can be viewed in Table 4. These were calculated using a combination of publicly available information on each launch vehicle provided by their respective companies and the ideal rocket

Table 4. Estimated Performance Capabilities for Various Mission Configurations.

Launch Vehicle	S/C mass (kg)	NED mass (kg)	Total ΔV (km/s)	C3 (km^2/s^2)
Delta II	1543	300	3.43	4.5
Atlas V	3251	1000	4.23	23
Delta IV Heavy	4220	1500	4.72	35

equation for the OTV using a bipropellant fuel of N_2H_4/hydrazine. Given the current estimates of the spacecraft mass for each of the launch configurations, the Atlas V and Delta IV Heavy do not require the use of an OTV as the third stage options can already achieve C3 values well above above 20. The Delta II on the other hand, relies completely on the OTV to act as a third stage and provide ΔV after launch. It should be noted that the Delta II will most likely be replaced by Orbital's Antares launch vehicle in the near future.

Target List

The majority of the data used to evaluate target asteroids was generated using a FORTRAN 90 program, which executed a grid search approach for potential launch dates spanning a period of twenty-five years (Jan. 1, 2015 to Jan. 1, 2040) in conjunction with various transfer durations up to a maximum of five years. Ephemeris files for 2140 Amor asteroids were automatically downloaded via a program written specifically to access NASA's Horizons system via TELNET. Using this information, each asteroid was searched using a three day time step for both the launch date and mission length. Only direct transfer orbits were considered in this program. This search was parallelized using OpenMP to utilize each core on the workstation, and required a run time of approximately 20 hours. Although data as for as 2040 was generated, only the results for the first five year time span (Jan. 1, 2015 to Jan. 1, 2020) and a maximum mission length of one year were analyzed in greater detail. As can be seen in Figure 3, there is no benefit to looking at mission lengths beyond that of a year for most targets in terms of ΔV. While there are some possible mission designs at the very edge of the maximum mission length, they would not be any lower than the minimum ΔV pockets found between 100 and 150 days. The data was then inserted into a cost function based on the hyperbolic excess velocity and the arrival burn magnitude to ensure a 10 km/s closing velocity. Ten asteroids that minimized this function were selected as optimal targets to be studied in greater detail.

The optimal asteroid targets selected in this study are listed in Table 5 along with their corre-

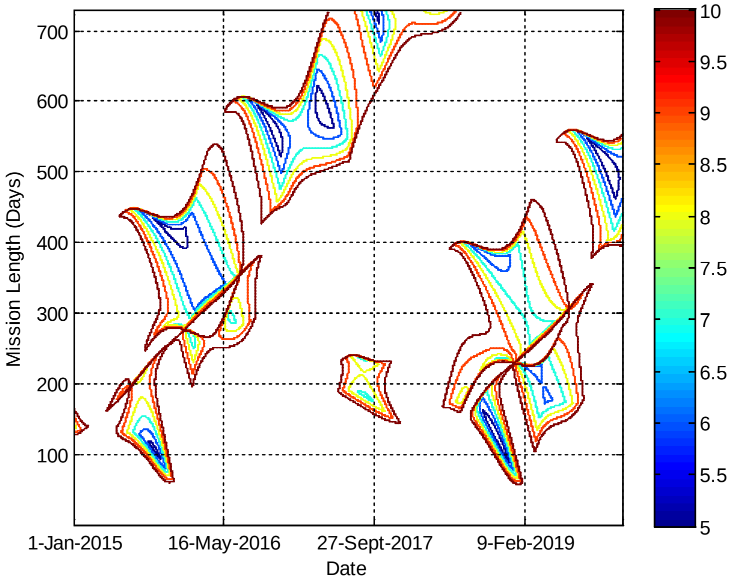


Figure 3. Total ΔV (km/s) Contour Plot for 1989 ML.

Table 5. Optimal Targets with Corresponding Minimum Total ΔV, Launch Date, and Mission Duration.

Asteroid	Launch Date	Departure ΔV (km/s)	Mission Length (days)	C3 (km^2/s^2)
2003 GA	12/3/2015	3.519	111	6.5
2006 SJ198	3/17/2015	4.596	337	32.01
2009 TB3	1/27/2018	3.6	97	8.35
2007 FS35	2/4/2015	3.473	272	5.47
2003 QC	1/1/2015	4.479	331	29.14
2004 GY	6/30/2015	4.354	365	26.1
2001 SX269	5/2/2019	3.572	114	7.7
1998 SB15	5/5/2017	3.335	159	2.37
2004 KE1	2/8/2017	4.539	365	30.62
1989 ML	11/17/2018	4.027	120	18.26

Table 6. Orbital and Physical Characteristics of Target Asteroids.

Asteroid	Semi-Major Axis (AU)	Eccentricity	Inclination (deg)	Absolute Magnitude	Diameter (m)*	Mass (kg)†
2003 GA	1.28	0.191	3.84	21.08	300	3.67E10
2006 SJ198	2.09	0.456	2.43	17.95	1200	2.35E12
2009 TB3	1.32	0.219	12.22	21.09	300	3.67E10
2007 FS35	1.92	0.390	0.32	19.56	620	3.24E11
2003 QC	2.57	0.532	7.85	20.54	400	8.71E10
2004 GY	1.45	0.218	23.44	20.11	480	1.50E11
2001 SX269	1.88	0.346	4.03	21.29	280	2.99E10
1998 SB15	1.27	0.161	15.63	20.9	330	4.89E10
2004 KE1	1.30	0.181	2.88	21.63	240	1.88E10
1989 ML	1.87	0.446	1.50	19.5	630	3.40E11

* Assuming a nominal albedo of 0.07 (Reference 8)

† Assuming a sphere with a density of 2.6 g/cm^3 (Reference 9)

sponding launch date, ΔV requirements and mission length. When compared to the upper limits on the estimated launch vehicle and OTV performance in Table 4, it can be seen that the Delta II launch vehicle could only be used to reach the target 1998 SB15. The other targets have ΔVs above the estimated capabilities of the Delta II configuration, and could only be reached using the Delta IV Heavy or Atlas V launch vehicles.

Some of the asteroid diameters in Table 6 are slightly outside the desired range of 300-1000 m. Without knowing the albedo, there is some uncertainty in either direction for these diameters. There is not too much concern for asteroids with diameters greater than 1000 m, but for those such as 2003 KE1, which has a diameter of 240 m, the targeting accuracy of the instruments may not be high enough to reasonably ensure an impact. As such, it will be left as a potential target to assess targeting capabilities of future spacecraft, but will not be seriously considered as a target for any of the mission configurations used in this study.

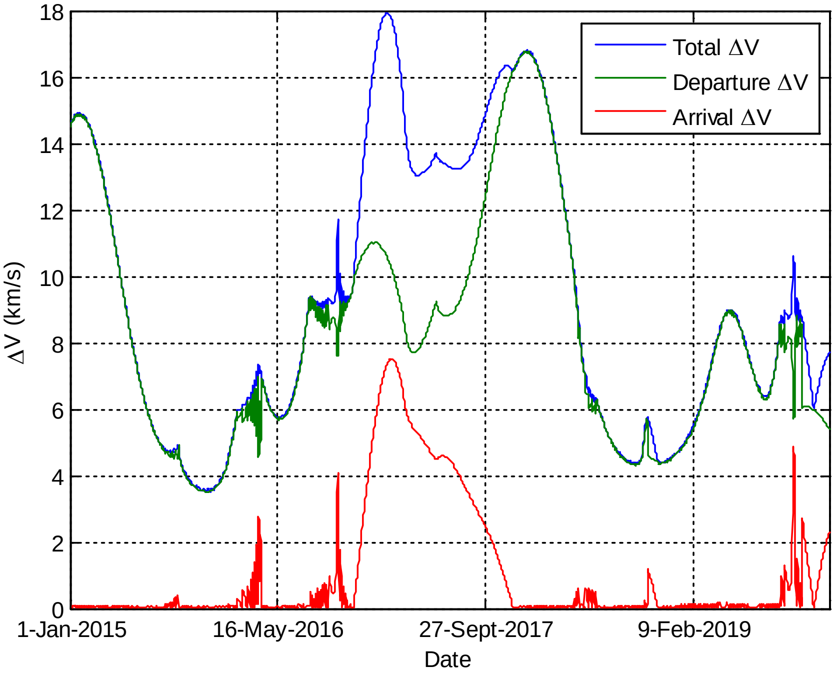


Figure 4. Minimum ΔV Required Versus Launch Date for 2003 GA.

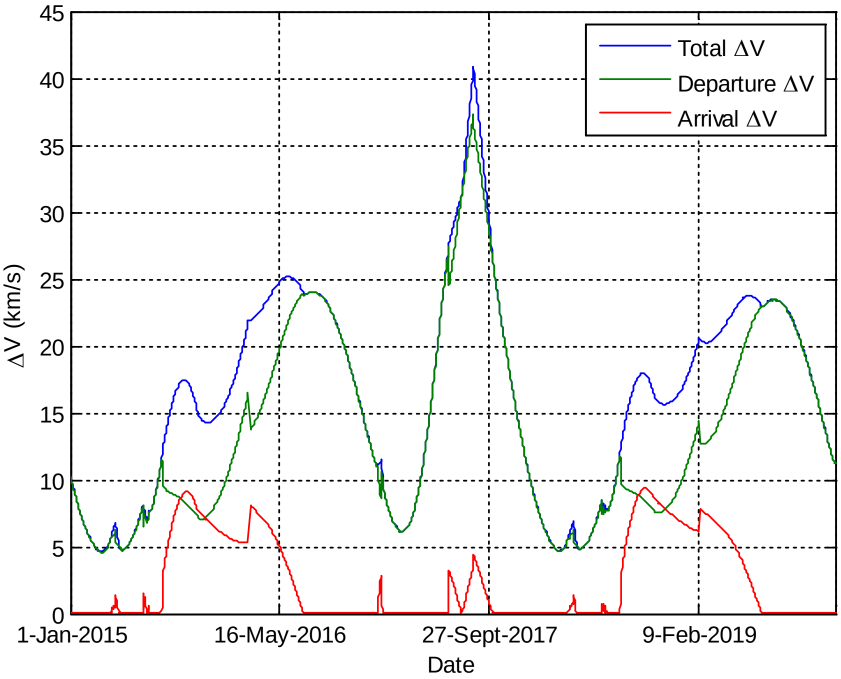


Figure 5. Minimum ΔV Required Versus Launch Date for 2006 SJ198.

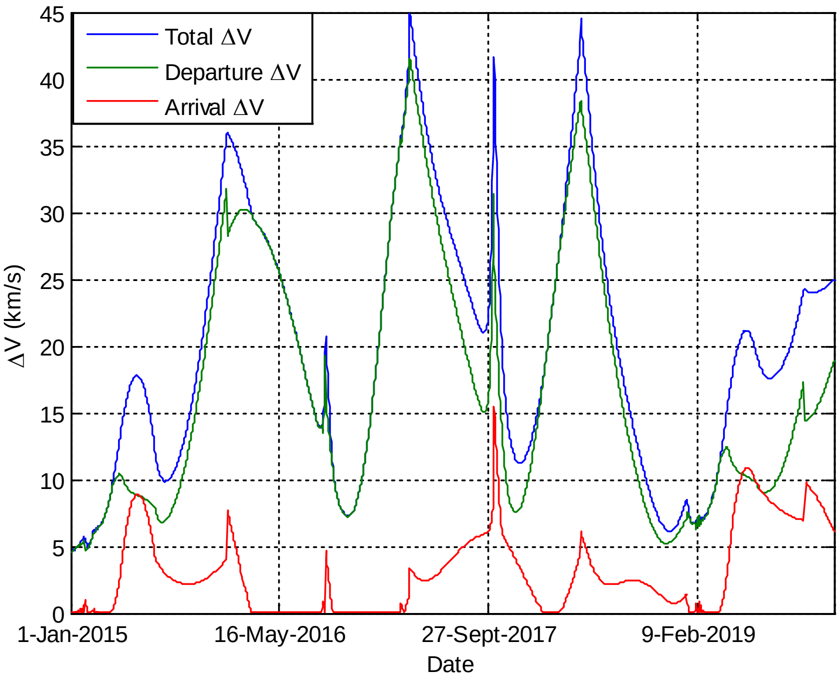


Figure 6. Minimum ΔV Required Versus Launch Date for 2003 QC.

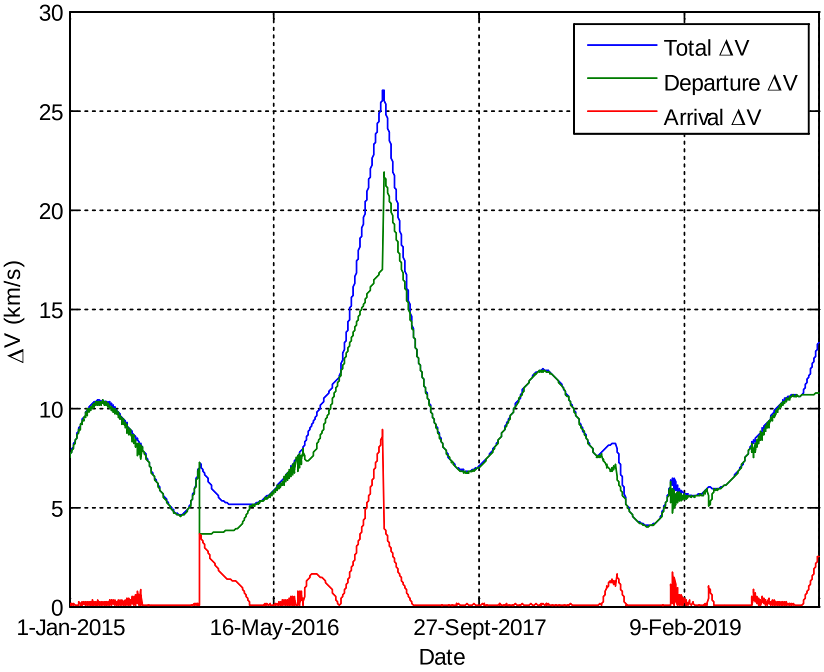


Figure 7. Minimum ΔV Required Versus Launch Date for 1989 ML.

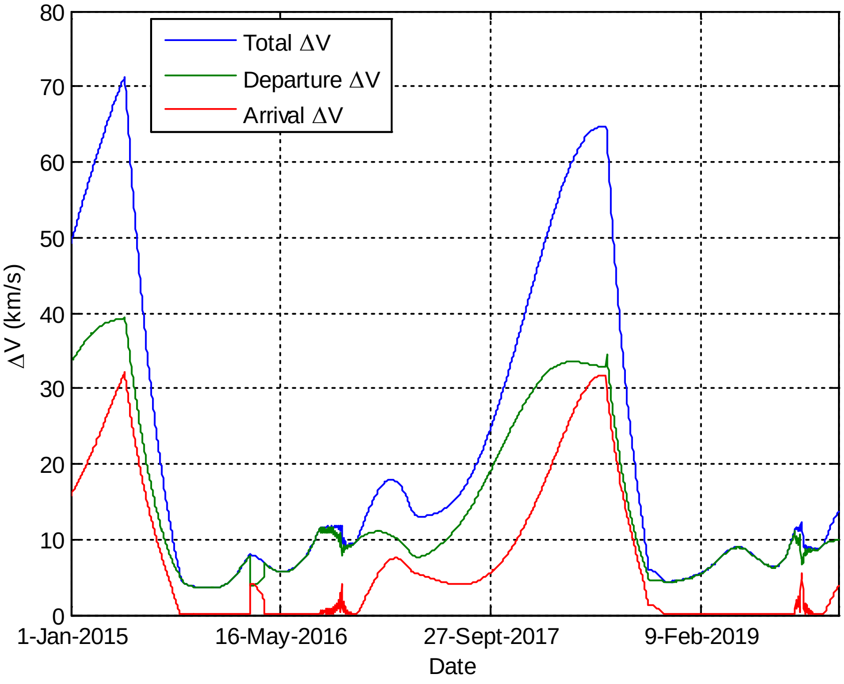


Figure 8. Minimum ΔV Plot for 2003 GA Using the Universal Variables Method.

Once ten targets were selected, a separate analysis was conducted to verify if the optimal targets were indeed suitable for a PDT demo mission. Using the ephemeris data for the Earth and the asteroids, Lambert's problem was solved for the given time frame with a varying transfer duration. To this end, a program capable of solving this problem using either Battin's method or the universal variable method was written in MATLAB R2011b. Currently the universal variable method will always solve for the orbit that results in the shortest path between the start and end points regardless if it is prograde or retrograde. At times, this could result in total ΔVs as high as 90-100 km/s. Battin's method, however, always kept the transfer orbit as prograde or retrograde unless specified otherwise, and has a much higher computational efficiency.[7] Therefore, Battin's method was the preferred algorithm of the two for solving Lambert's problem. Two main assumptions made were a departure from a 185 km altitude circular orbit and the arrival ΔV is only that necessary to ensure a 10 km/s relative velocity upon impact. The program was based on the proven methods presented in Reference 7, and was able to reproduce the ΔV plots. For this reason, the program was assumed to be functioning properly, and producing accurate results. Figures 4-7 are select plots which were generated using this program. At times, odd oscillations or sudden, sharp spikes can be observed where normally smoother flowing curves are expected to take place. To verify these results, the ΔV plot in Figure 8 was produced using the universal variables method. When the ΔV curves are below 20 km/s, the plot is pratically identical to the one produced by Battin's method (see Figure 4). When the total ΔV in Figure 8 climbs over 20 km/s, the universal variables method reverts to a retrograde orbit, which resulted in the shortest distance between the initial and final positions. In the areas where the results are similar to Battin's method, the same unusual oscillations and sudden spikes also appear. Each plot required approximately 30 minutes of run time using Battin's method compared to the nearly 2 hours for the universal variables method.

Table 7. Early Launch Windows.

Asteroid	Launch Date	ΔV (km/s)	Transfer Time (days)	C3 (km^2/s^2)
2003 GA	12/3/2015	3.519	111	6.5
2006 SJ198	3/17/2015	4.596	337	32.01
2009 TB3	9/22/2017	3.689	202	10.37
2007 FS35	2/4/2015	3.473	272	5.47
2003 QC	1/1/2015	4.479	331	29.14
2004 GY	6/30/2015	4.354	365	26.1
2001 SX269	12/27/2015	4.952	252	40.97
1998 SB15	5/5/2017	3.335	159	2.37
2004 KE1	2/8/2017	4.539	365	30.62
1989 ML	9/29/2015	4.58	106	31.63

Table 8. Late Launch Windows.

Asteroid	Launch Date	ΔV (km/s)	Transfer Time (days)	C3 (km^2/s^2)
2003 GA	9/28/2018	4.333	173	25.57
2006 SJ198	3/16/2018	4.686	340	34.26
2009 TB3	1/28/2018	3.601	97	8.35
2007 FS35	10/3/2019	3.962	289	16.72
2003 QC	12/6/2018	5.293	365	49.78
2004 GY	5/23/2018	4.398	285	27.17
2001 SX269	3/5/2019	3.572	114	7.7
1998 SB15	6/22/2017	3.335	104	2.38
2004 KE1	10/29/2019	4.862	113	38.67
1989 ML	11/17/2018	4.027	120	18.26

The results given in Table 5 show launch dates that are scattered over the five year span. This is not completely unexpected as the launch dates shown only correspond to the minimum total ΔV possible in the time frame. Figures 4-7 show that there do exist other potential launch dates with similar or slightly higher requirements that can still be reached with the given launch vehicles. Although not shown, almost all of the target asteroids have at least two launch opportunities with acceptable ΔV requirements. Table 7 shows the optimal launch dates for the first half of the time span. Even when the launch dates are clustered closer to one another like this, all the targets still have ΔV requirements below 5 km/s. The majority of them actually retain the same launch date as presented previously in Table 5. These similar launch dates provide several convienent backup targets should a primary launch date be missed.

Should a later launch date be desired, there are viable options available for each target. As seen in Table 8, the total required ΔV for the other targets is generally below 5 km/s with the exception of 2003 QC. The minimum ΔV requirement to reach this asteroid jumps to about 5.3 km/s, and cannot be reached using any of the assumed launch configurations. For this date, the transfer time is as the maximum 365 day limit. In this particular case, extending the mission length may be beneficial and

Table 9. Categorization of Target Asteroids Based on Launch Vehicle Capabilities and Target Size.

Launch Vehicle	Asteroid	Minimum ΔV (km/s)	Diameter (m)
Early Launch Window			
Delta II	1998 SB15	3.335	330
Atlas V	2007 FS35	3.473	620
	2003 GA	3.519	300
	2009 TB3	4.689	300
	1998 SB15	3.335	330
Delta IV Heavy	2006 SJ198	4.596	1200
	2007 FS35	3.473	620
	2004 GY	4.354	480
	1989 ML	4.58	630
Late Launch Window			
Delta II	1998 SB15	3.335	330
Atlas V	2009 TB3	3.601	300
	2007 FS35	3.962	620
	1989 ML	4.027	630
Delta IV Heavy	2006 SJ198	4.686	1200
	2007 FS35	3.962	620
	2004 GY	4.398	480
	1989 ML	4.027	630

reduce the require ΔV below 5 km/s as with the other targets.

The recommended targets for each launch vehicle configuration for both the earlier and later launch windows is given in Table 9. Up until this point, only the total ΔV requirement was examined to match launch vehicles with potential targets. Now the different diameters are matched with corresponding NED sizes. There is some overlap between the categorization for asteroids with diameters that could be suited for different size NEDs meaning that either configuration could be used with the target. Should the albedo of these asteroids be known with greater certainty, a more accurate diameter can be calculated, which could then reduce the amount of overlap. It should be noted that this does not have to be strictly followed. If desired, it is entirely possible to use the larger size NEDs on targets with smaller diameters than paired with in the table or vice versa.

Target Mission Examples

In this section, preliminary mission trajectories to the targets 1998 SB15, 2006 SJ198 and 1989 ML will be studied based on the results found in the previous section. Each mission design will be assigned to different launch configurations based on the recommendations in Table 9. The characteristics of each transfer trajectory is given in Table 10. Only direct transfer trajectories will be considered in these examples.

From Table 10, the departure ΔV in every case makes up the majority of the total ΔV required

Table 10. Orbital Parameters of Transfer Trajectories and Burn Magnitudes.

Asteroid	Semi-Major Axis (AU)	Eccentricity	Inclination (deg)	Departure ΔV (km/s)	Arrival ΔV (m/s)
1998 SB15	1.1	0.271	2.10	3.34	1.3
2006 SJ198	1.4	0.294	5.76	4.60	12.2
1989 ML	1.36	0.271	3.76	4.03	8.8

for each mission. This is due to the fact that upon arrival, the spacecraft is already traveling at approximately 10 km/s relative to the target asteroid. The largest arrival ΔV here occurs for the 2006 SJ198 mission, but is only 12 m/s. This means that the relative velocity upon arrival is already approximately the nominal closing velocity of 10 km/s and can be disregarded.

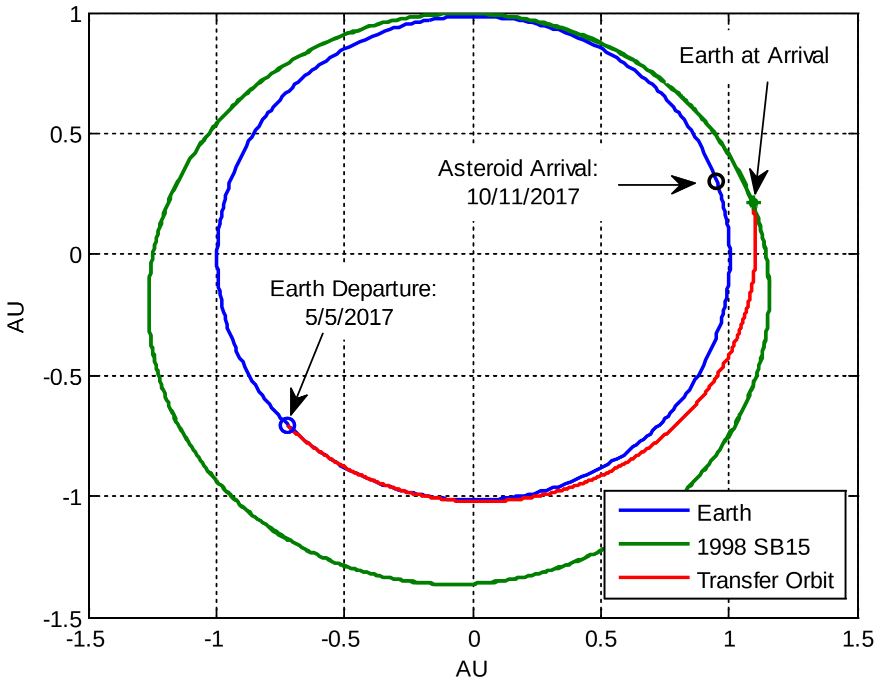


Figure 9. Mission Trajectory to 1998 SB15 for the 5/5/2017 Launch Date.

Delta II Mission. The target 1998 SB15 is the only asteroid that the Delta II launch vehicle configuration can reach. This asteroid is one of the smallest selected in this study, and will most likely not require the larger size NEDs to disrupt. Its small size will also be used to test the limits of the terminal phase guidance technology. The launch date for the minimum ΔV takes place on 5/5/2017 with a mission length of 159 days.

As can be seen in Figure 9, the orbit of 1998 SB15 is contained entirely within the orbits of the Earth and Mars. Unlike many asteroids whose orbits go beyond that of Mars, missions to this target do not have to wait until the close approach date as it can be reached at any point on its orbit. The trajectory depicted in Figure 9 results in an impact approach angle of 19.82 degrees and a Sun-S/C-Earth angle of 44 degrees.

Delta IV Heavy Mission It may be desirable to explore the effects on objects larger than 2003 GA. There is also the concern of having an NED orbiting so near to the Earth should the spacecraft fail to impact. As the largest asteroid in this study, 2006 SJ198 was paired with the Delta IV Heavy launch configuration as it could carry the largest size NED. Being 4x as large as 2003 GA, the chances of failing to impact are greatly reduced. The minimum ΔV launch date for this target takes place on 3/17/2015 with a mission length of 337 days.

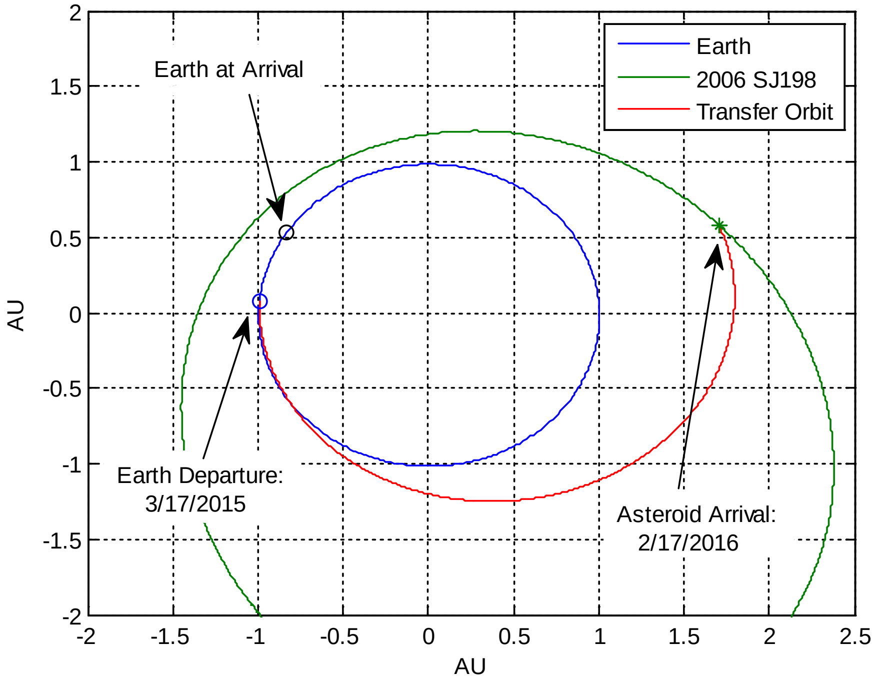


Figure 10. Mission Trajectory to 2006 SJ198 for the 3/17/2015 Launch Date.

The designed trajectory for this mission initially follows closely to that of the Earth, and extends out beyond Mars. Towards the arrival date, the spacecraft approaches almost from behind the target asteroid. Upon arriving at the target asteroid, the trajectory in Figure 10 results in an impact approach angle of 23.78 degrees and a Sun-S/C-Earth angle of 17.7 degrees.

Atlas V Mission The final mission design is for 1989 ML. This asteroid is also one of the largest selected in this study, and falls within the estimated capabitlities of the Atlas V configuration. As with 2006 SJ198, it is significantly larger than 2003 GA, and decreases the chance of impact failure due to targeting errors. Of all the selected targets in this study, this is the only one that was also seriously considered by the ESA for the Don Quijote mission. It is also the asteroid with the most number of observations in determining its orbital elements (322 as of 1/16/2012), making its orbit the best known out of the ten targets. The impact approach and Sun-S/C-Earth angles for this mission design are 22.7 and 34.31 degrees respectively.

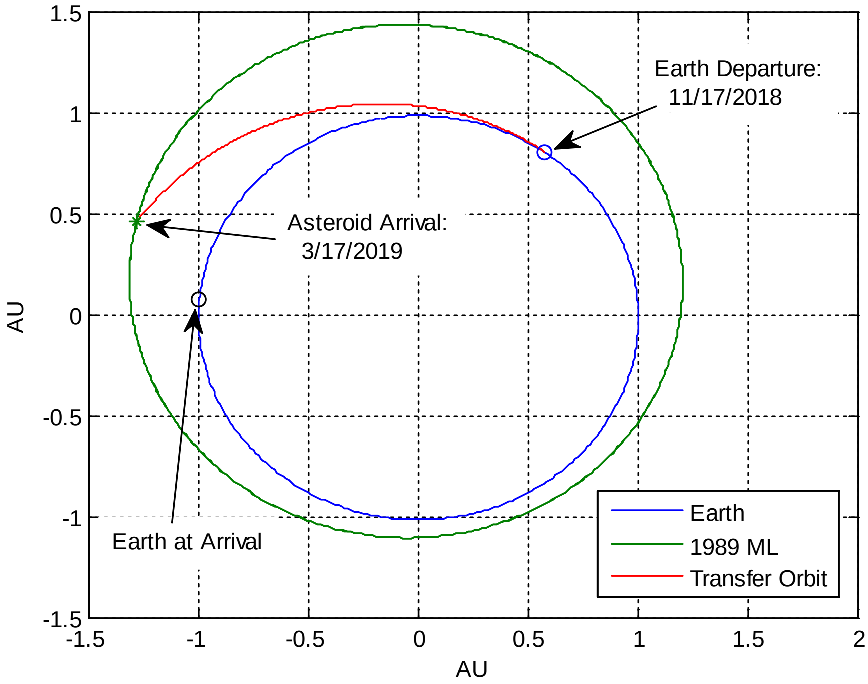


Figure 11. Mission Trajectory to 1989 ML for the 11/17/2018 Launch Date.

Table 11. Computer Information for the Workstations Used to Run Programs.

	Fortran 90 Code	MATLAB Codes
Model	Dell T3500	Dell Precision T1600
Operating System	Windows Vista Enterprise 64 bit	Windows 7 Enterprise 64 bit
Processor	Intel(R) Xeon(R) W3520 2.67 GHz - 4 cores	Intel(R) Xeon(R) CPU E31270 @ 3.40 GHz - 4 cores
Memory	6.00 GB 1066 MHz DDR3	8.00 GB

FUTURE WORK

Future work will expand this selection process beyond the current five year time frame. Realistically, the current time frame would not provide sufficient time to develop and launch an HNIS. The ultimate goal will be to both streamline and automate the target selection process into a single integrated computer program capable of generating a target list for any NEO mission with associated physical and mission characteristics based on user-provided criteria and constraints. With the way the process is currently setup, many of the steps in the selection process are separate and require someone interpret the results before moving onto the next step. For example, once the asteroid candidates are first run through the Fortran 90 code, the outputs must be manually copied and input into the code containing the cost function. User options would include, but are not limited to, target bodies to investigate, launch vehicle, maximum mission duration, time frame, and target arrival constraints. For now the program will continue to be used to select optimal Amor class asteroids for a PDT demo mission, but could be applied to other missions as well.

Additional study of the results shown in Figures 4-7 will also be conducted. As was mentioned before, there are several locations where the ΔV curves begin to oscillate rapidly as in Figure 4 or suddenly spike as in Figure 6. Whether these are caused by a fault in the computational method, programming, or something else entirely is currently unknown. Therefore, a further investigation of Lambert's solvers to determing the source of these oscillations and spikes is of principal interest.

CONCLUSION

This paper presented a list of ten potential targets for a PDT demonstration mission to take place sometime between the years 2015 and 2020. The launch dates given all result in close to a relative closing speed of 10 km/s without requiring any large burn upon arrival. The list encompasses asteroids ranging from the smallest desired diameter (300 m) to the largest (1000 m).

For the three given launch configurations, only the Delta II is severely restricted in terms of ΔV requirements to the various targets. Recommendations were also made to match the listed targets with these launch configurations based on the estimated size of the asteroids and the ΔV requirements. These results would only be valid for the given five year time span. The list of targets could be altered if a mission was to take place after Jan. 1, 2020. Additional study would be required if such a mission date after 2020 is desired or if the sun phase angle requirement was to be strictly enforced.

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