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SUBORBITAL INTERCEPT AND FRAGMENTATION OF ASTEROIDS WITH VERY SHORT WARNING TIMES

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The threat of an asteroid impact with very short warning times (e.g., 1 to 24 hrs) is a very probable, real danger to civilization, yet no viable countermeasures currently exist. The utilization of an upgraded ICBM to deliver a hypervelocity asteroid intercept vehicle (HAIV) carrying a nuclear explosive device (NED) on a suborbital interception trajectory is studied in this paper. Specifically, this paper focuses on determining the trajectory for maximizing the altitude of intercept. A hypothetical asteroid impact scenario is used as an example for determining simplified trajectory models. Other issues are also examined, including launch vehicle options, launch site placement, late intercept, and some undesirable side effects. It is shown that silo-based ICBMs with modest burnout velocities can be utilized for a suborbital asteroid intercept mission with an NED explosion at reasonably higher altitudes ($>$ 2,500 km). However, further studies will be required in the following key areas: i) NED sizing for properly fragmenting small (50 to 150 m) asteroids, ii) the side effects caused by an NED explosion at an altitude of 2,500 km or higher, iii) the rapid launch readiness of existing or upgraded ICBMs for a suborbital asteroid intercept with short warning times (e.g., 1 to 24 hrs), and iv) precision ascent guidance and terminal intercept guidance. It is emphasized that if an earlier alert (e.g., $>$ 1 week) can be assured, then an interplanetary intercept/fragmentation may become feasible, which requires an interplanetary launch vehicle.

INTRODUCTION

On October 7th, 2008, asteroid 2008 TC3 was discovered by the Catalina Sky Survey 20 hours before breaking up above the Saharan desert. It was the first asteroid impact ever to be predicted before reaching the atmosphere. Fortunately, it was only 4 meters in diameter and broke up in the atmosphere over a remote part of the world [1]. As detection efforts become more advanced, it is likely that future impactors will be discovered with similar limited warning times.

In recent years, most of the largest asteroids in the neighborhood of Earth have been found and catalogued. These asteroids greater than 1 km diameter would devastate the planet, but such an impact will be a rare event. There are millions more small asteroids (50 to 150 m) that are still undetected. These small, city killer objects strike the Earth much more frequently than the larger ones. The Tunguska event occurred in 1908 was caused by a relatively small ($<$ 50 m) asteroid or comet, but the subsequent airburst released an explosion energy of 10-15 Mt. The impact leveled over 2,000 km^2 of Siberian forest, an area equivalent to the size of a large city. If such an asteroid is discovered days or hours before impact, there would be no time to deflect the asteroid or even

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evacuate the impact zone. There is currently no planetary defense planning against such a short-warning event.

Despite the lack of a known immediate impact threat from an asteroid or comet, historical scientific evidence suggests that the potential for a major catastrophe created by an asteroid impacting Earth is very real, and humankind must be prepared for it. Due to a recent asteroid impact event (now referred to as Chelyabinsk meteor event) that occurred in Russia on February 15, 2013 and a near miss by asteroid 2012 DA14 (45 m diameter) on the same day, there is now a growing national and international interest in developing a global plan to protect the Earth from a catastrophic impact by a hazardous asteroid or comet. Note that the Chelyabinsk event had no warning while asteroid 2012 DA14 was detected about one year before its close flyby of the Earth.

To date, planetary defense research efforts by NASA and the planetary defense community have mainly focused on discovering, tracking, and characterizing asteroids to provide situational awareness of the threat they pose to Earth. While those efforts are crucial to having advance warning of an asteroid on an Earth-impacting trajectory, now is the time to develop an effective means of responding to an asteroid impact threat with short warning time ($<<$ 1 year). For such a worst-case, yet most probable mission scenario, suborbital intercept and fragmentation of an asteroid using a hypervelocity asteroid intercept vehicle (HAIV) carrying nuclear explosive devices (NEDs) may be the only practically viable option other than civil defense (evacuation).

An innovative concept being developed in a NASA Innovative Advanced Concepts (NIAC) Phase 2 study utilizes the concept of blending a hypervelocity kinetic impactor with a subsurface nuclear explosion for optimal fragmentation of an asteroid with short warning time [2–5], The secondary goal of this NIAC study is to develop major technology development programs that will lead to flight-validated planetary defense technologies capable of handling such short warning time scenarios.

The objective of this paper is to initiate a technology readiness assessment study in preparation for the threat of an asteroid impact with a very short warning time [6] and present example mission design scenarios, including optimized intercept trajectories. Current anti-ballistic missile (ABM) technology could be adapted for use against asteroids. The United States has deployed Ground Based Interceptor (GBI) missiles that are launched from silos and can intercept an enemy missile in the midcourse phase of flight with an Exoatmospheric Kill Vehicle (EKV). SM-3 missiles have a similar capability and are designed to be launched from ships. The higher altitude and larger payload requirements for a suborbital asteroid intercept are beyond current GBI missiles that are launched from silos and can intercept an enemy missile in the midcourse phase of flight with an EKV. However, ICBMs such as the Minuteman III do have adequate launch mass capability. In this paper, we assume that the Minuteman III based interceptor will be able to deliver a HAIV payload into a precision intercept trajectory against an incoming asteroid.

When we don't have sufficient mission lead times for large orbital dispersion of fragments, full neutralization of the asteroid impact threat is infeasible and most of the fragments will still hit the Earth. However, if the asteroid is fractured or fragmented into sufficiently small pieces prior to reaching the atmosphere, each of those small pieces will break up sooner and the resulting airbursts will occur at safer (higher) altitudes. The goal of a suborbital intercept and fragmentation mission is basically to reduce the probable impact damages of a 50 m asteroid to the damage level of multiple Chelyabinsk events. That is, the mission goal is to transform another future Tunguska-like event into multiple Chelyabinsk-like events in a worst-case situation.

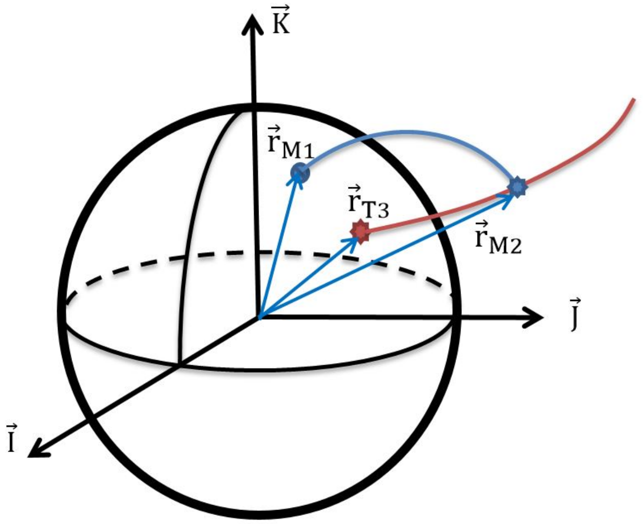

Figure 1. ECI Reference Frame

IDEAL OPTIMAL INTERCEPT

Problem Formulation

For a given hyperbolic asteroid orbit that intersects the Earth and a fixed launch site on Earth, the goal is to determine the optimal suborbital intercept trajectory. The performance of the missile is limited to its available total ΔV. The criterion for optimal intercept is defined as the maximum altitude of intercept from a fixed launch position on Earth. Because the asteroid is on a hyperbolic encounter orbit, maximum altitude is equivalent to earliest intercept.

Our preliminary conceptual orbital intercept study is characterized as

- Orbital elements of the target asteroid at acquisition are assumed to be exactly known.
- A few locations of the interceptor missile on Earth's surface (latitude and longitude relative to the ECI frame) are assumed.
- Interceptor missile is simply characterized by its available ΔV.
- Earth model is assumed to be a rotating sphere with negligible atmosphere.
- Missile launches from Earth's surface with a single impulse. A multi-stage rocket model will be used in a future study.
- Two-body orbital dynamics is assumed.

Coordinate System. The orbits of the asteroid and interceptor and positions on Earth's surface are defined with respect to the Earth-Centered Inertial (ECI) reference frame, shown in Figure 1. The time, distance, and speed units used here are seconds, km, and km/s, respectively. For nomenclature purposes, a subscript T refers to the target asteroid, and the M for the missile.

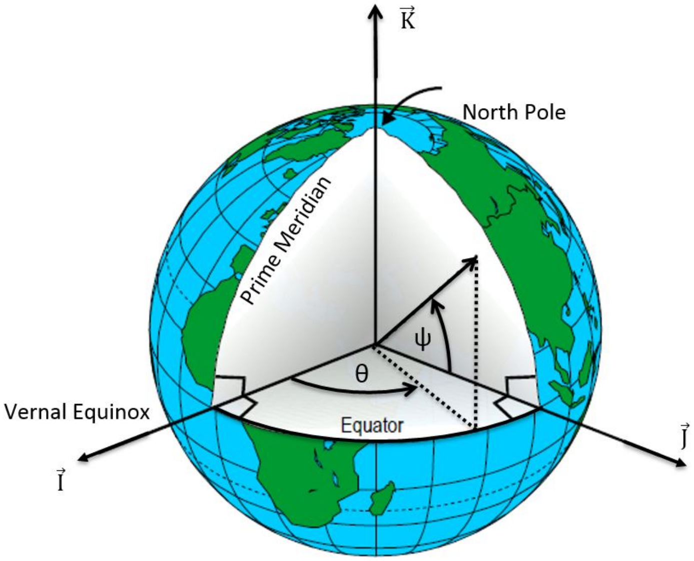

Figure 2. Relation of Earth's Surface to ECI Frame

Table 1. Time Frame Definition

t_0	Time of Target Detection
t_1	Time of Intercept Missile Launch
t_2	Time of Intercept
t_3	Time of Projected Earth Impact

Because the vectors are defined with respect to the ECI frame, it is not necessary to correlate the problem to a specific sidereal time. Instead, it is assumed that the prime meridian is aligned with the vernal equinox direction at the moment of interceptor launch. This makes it convenient to map the surface longitude to the ECI frame without having to calculate sidereal time. Figure 2 shows the orientation of the Earth's surface with respect to the ECI frame. The latitude and longitude positions are transformed into ECI position vectors as follows:

$$\vec{r} = R\cos\theta\cos\psi\vec{I} + R\sin\theta\cos\psi\vec{J} + R\sin\psi\vec{K} \tag{1}$$

where θ is longitude, ψ is latitude, and R = 6378.15 km is the radius of the Earth.

Time Frame. The asteroid intercept scenario is independent of time. The timing of the major events such as target acquisition, missile launch, and intercept are all relative to an arbitrary time of impact. Each point in time is measured in seconds until impact. The times will be identified using subscripts as described in Table 1.

Target Orbit. A valid target asteroid orbit is hyperbolic and intersects with the Earth's surface. The orbit is defined in terms of the geocentric orbital elements at acquisition point. The acquisition point is arbitrary for this problem, but should be outside the range of any missile and inside the sphere of influence of Earth. For the example problem in this paper, the target asteroid orbit is chosen specifically to impact the east coast of the United States with an incidence angle and velocity typical for near-Earth asteroids (NEAs).

Technical Approach

Equations of Motion. The interceptor missile and the asteroid are considered point masses, and are modeled in geocentric Keplerian orbits as follows:

$$\dot{\vec{r}} = \vec{V} \tag{2}$$

$$\dot{\vec{V}} = -\frac{\mu\vec{r}}{r^3} \tag{3}$$

where $\vec{r}$ and $\vec{V}$ are the position and velocity vectors of the point mass, and μ is the gravitational parameter of Earth (3.986$\times 10^5$ km^3/s^2). The position and velocity are related to the semimajor axis of the orbit through the vis-viva equation and the trajectory equation, as follows:

$$\frac{V^2}{2} - \frac{\mu}{r} = -\frac{\mu}{2a} \tag{4}$$

$$r = \frac{a(1-e^2)}{1+e\cos\nu} \tag{5}$$

where a is the semimajor axis, e is the eccentricity, and ν is the true anomaly.

Optimization. The optimal suborbital intercept of an asteroid from a fixed launch site is found by maximizing the altitude of intercept. The high altitude will limit the effects of the nuclear blast felt on Earth and give fragments more time to disperse. The optimal orbit will utilize the full ΔV available to the missile, and account for the rotational boost from the Earth. There are only two free variables that determine the suborbital trajectory, the time-of-intercept (TOI), measured as seconds until impact and the time-of-flight (TOF) of the missile. It can be shown that there is a unique optimal solution for typical intercept scenarios.

Accounting for the Rotation of Earth. The Earth's eastward rotation needs to be considered because it can give an effective ΔV boost to the interceptor, allowing it to reach a higher altitude. The speed at the equator (in units of km/s) is estimated as

$$V_E = \frac{2\pi R}{24 \times 3,600} = 0.4638 \tag{6}$$

The speed of the Earth's surface in the ECI frame is dependent only on the latitude and longitude of the launch site. The inertial velocity vector of the launch site, $\vec{V_L}$ is then found as

$$\vec{V_L} = -V_E \sin\theta\cos\psi\vec{I} + V_E\cos\theta\cos\psi\vec{J} \tag{7}$$

The velocity vector due to rotation at the launch site is added to the burn-out velocity vector of the booster to get the initial velocity of the missile as

$$\vec{V_1} = \vec{V_{bo}} + \vec{V_L} \tag{8}$$

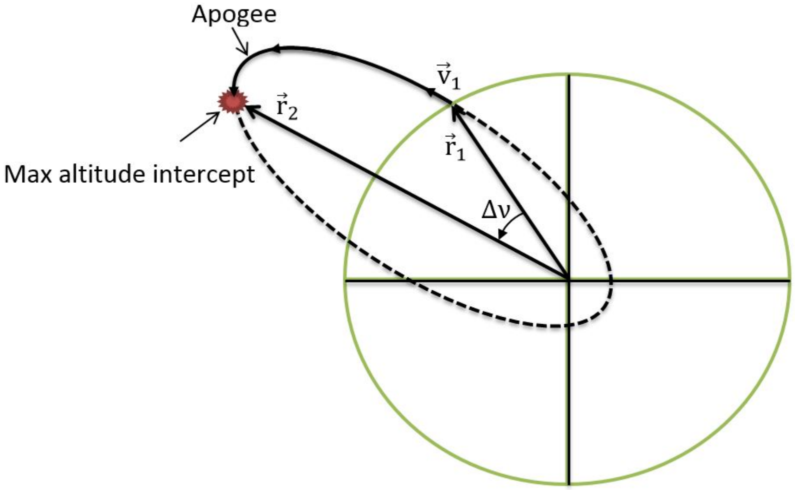

Figure 3. Intercept Orbit Diagram

Determining Target Position and Velocity as a Function of Time. The position of the asteroid in the ECI frame must be known at any given point in time. From the orbital elements of the asteroid at the acquisition point, the initial perifocal position and velocity vectors $\vec{r}_1$ and $\vec{v}_1$ are calculated and transformed into the ECI frame. For a given time-of-flight of the asteroid, the new position can be found by solving Kepler's time-of-flight equation in reverse.

$$t_2 - t_1 = \sqrt{-\frac{a^3}{\mu}}\left[(e\sinh H_1 - H_1) - (e\sinh H_2 - H_2)\right] \tag{9}$$

where H is the hyperbolic eccentric anomaly and

$$\tanh\frac{H_i}{2} = \sqrt{\frac{e-1}{e+1}}\tan\frac{\nu_i}{2} \tag{10}$$

Lambert Solver. Using the known positions of the launch site and the asteroid at a given time t_2, along with the missile TOF, the required initial velocity vector for the missile can be found by solving Lambert's problem. The Lambert solver used in this paper is a slightly modified version of the universal variable method described in [7]. This represents the open-loop guidance that is central to the optimization scheme.

MATLAB Optimization Routine. The solver used to find the optimum solution is the fmincon funciton available in the Matlab Optimization Toolbox. This is a constrained nonlinear multivariable minimization routine. There are two independent variables involved: TOF and TOI. Both variables are given upper and lower bounds to keep the solver from testing unreasonable points. An interior set point is chosen within the search window as the starting point. A constraint is placed on the solution so that the required ΔV does not exceed the maximum ΔV available to the missile. The asteroid's altitude decreases monotonically with time because the asteroid is on a hyperbolic trajectory. Thus, maximizing TOI is thus equivalent to maximizing intercept altitude. A graphical representation of an example search window is presented in Figure 4. Each of the contours is a line of constant ΔV

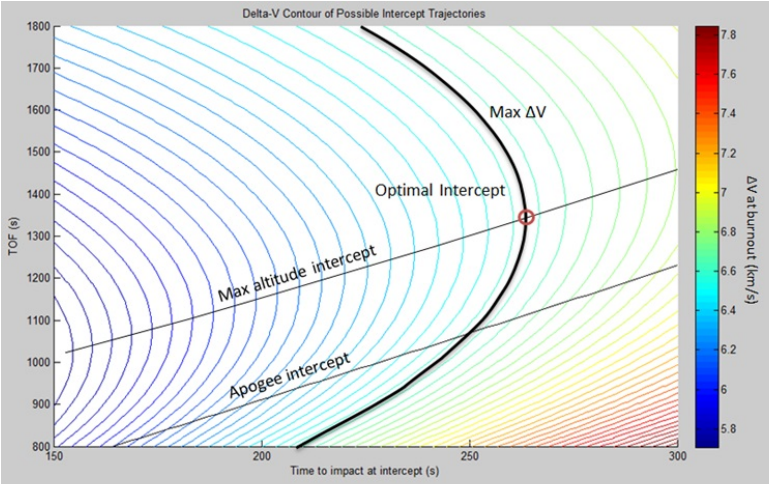

Figure 4. ΔV **Contour Across Interceptor Launch Window**

required for intercept. For each ΔV curve, there is one TOF at which TOI is a maximum. This is the unique solution point for that ΔV at which intercept altitude is maximized. The locus of the optimum altitude intercepts is shown on the graph, as well as the set of intercepts for which the interceptor reaches the target at apogee. It is interesting to note that the optimum intercept follows a near linear relationship.

Asteroid Intercept Examples

A few typical intercept scenarios and solutions are presented here. For these examples, the asteroid is discovered heading toward the East Coast of the United States less than 11 hours before impact. Interceptors based on the Minuteman III and the SM-3 Block IIA will be launched from silos at Minot AFB, North Dakota. The maximum intercept altitude for each vehicle will be compared. Because the smaller SM-3 can be launched from a ship, a second SM-3 will be launched from a position in the Gulf of Mexico. This is intended to show how positioning the launch site directly beneath the asteroid's path can increase the intercept altitude.

Target Orbit. The orbital elements of a target asteroid are provided in Table 2.

Interceptor Characteristics. The Minuteman III and the SM-3 Block IIA are known to have a ΔV capability of 6.6 km/s and 5.5 km/s at burnout, respectively. They are launched from a silo field in North Dakota with coordinates 48.5 N°, 101.4 W°. For clarity, these interceptors will be referred to as interceptors A and B, respectively. Interceptor C will be a SM-3 Block IIA launched from a ship located at 25 N°, 90 W°.

Results. Interceptor A reaches the highest intercept altitude of 2,625 km. Both of the smaller SM-3 missiles are able to achieve intercept, but at lower altitudes. The intercept details are included in Table 3. Figure 5 shows the asteroid's path and the three interception trajectories over a map of Earth. Interceptor C is launched from a point nearly directly beneath the asteroid's path. Because of this, it can reach a higher intercept than the same vehicle launched further away. Due to the unpredictable nature of asteroid impacts, however, it would not always be practical to move the launch site on short notice or have many launch sites around the country. Increasing the ΔV performance

Table 2. Target Orbital Elements

Orbital Element	Value
a	-4067.1 km
e	2.154
i	59°
Ω	256°
ω	100°
ν_0	243.4°

Table 3. Optimal Intercept Parameters

Interceptor	A	B	C
Vehicle	Minuteman III	SM-3 IIA	SM-3 IIA
ΔV (km/s)	6.6	5.5	5.5
Launch Site	48.5°N 101.5°W	48.5°N 101.5°W	25°N 90°W
Impact Altitude (km)	2,625	1,269	2,044
Time Until Impact at Intercept (s)	264	133	209
Time of Flight (s)	1341	971	817
Intercept Closing Speed (km/s)	14.2	14.4	13.7

of the booster vehicle is much more effective. The Minuteman III has 16.7% higher ΔV than the SM-3 used in this example, yet it can achieve intercept at 50% higher altitude when launched from the same location at the same target.

PLANETARY DEFENSE DOMES

For the purposes of planetary defense planning it is important to choose launch sites that maximize coverage of critical areas. The Minuteman III has sufficient range to protect most of North America if the silo location is chosen carefully. It is assumed that a reasonably safe intercept must occur above 1,000 km of altitude. Figure 6 shows example defense coverage areas for the following three launch sites: i) Minot AFB, ND, ii) Vandenberg AFB, CA, and iii) Cape Canaveral, FL.

All of these sites are already used for testing/deployment of missiles, and together they create an even spread across the entire continent. It should be noted that a simplified model was used to create the defendable area for each site. The domes in Figure 6 are terminated at the apogee of the interceptor, creating a more conservative estimate of their range. This is loosely equivalent to keeping within the pink ellipse in the 2-D special case described in Figure 7. The actual useful range of each missile site thus larger than shown in Figure 6.

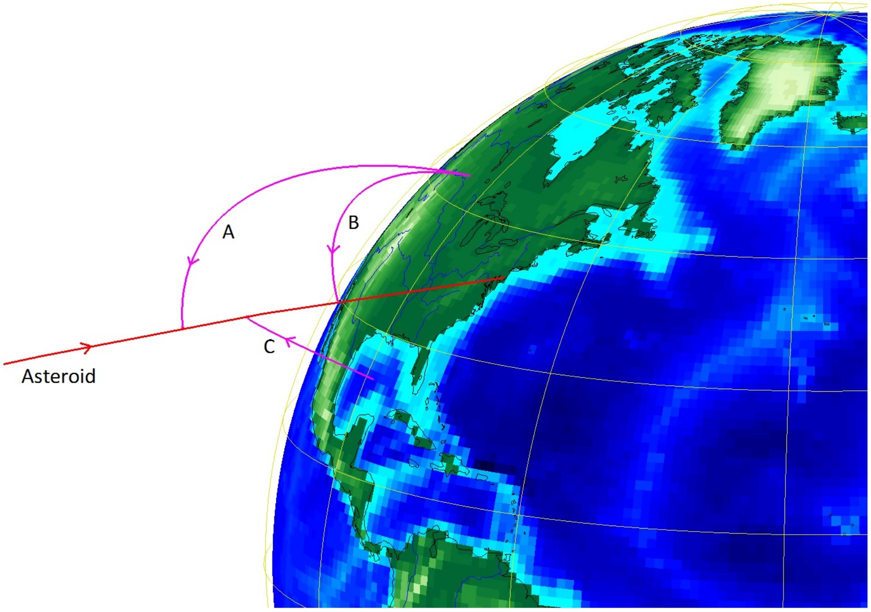

Figure 5. Ideal Optimal Intercept Trajectories

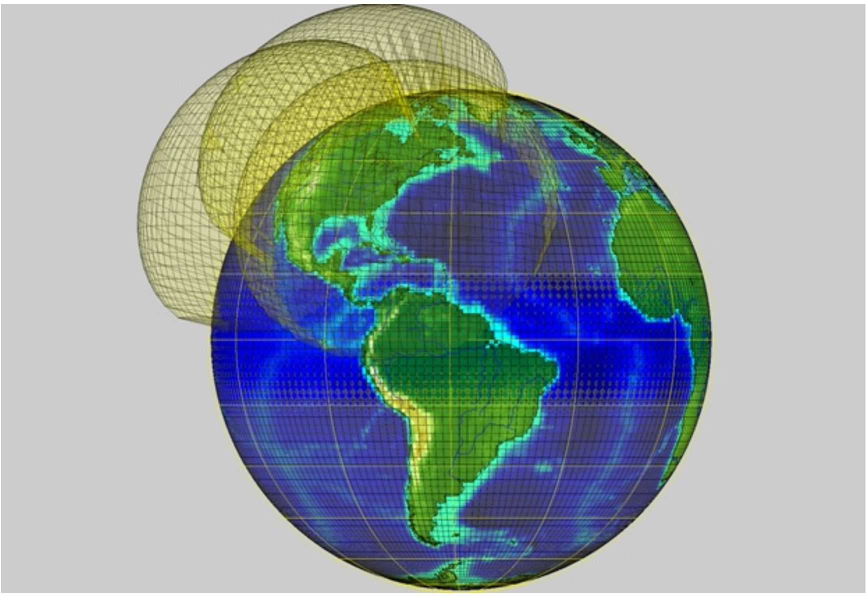

Figure 6. Planetary Defense Domes

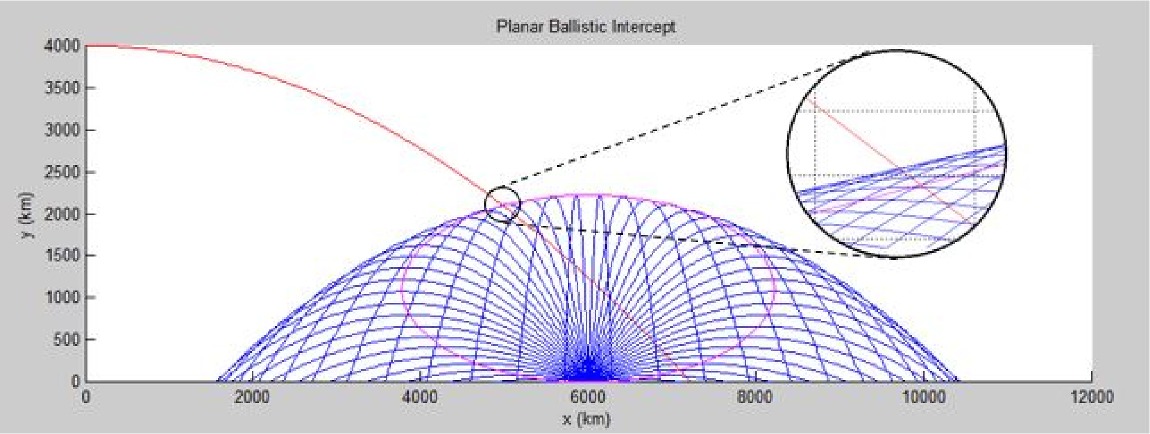

Figure 7. Planar Ballistic Intercept for Uniform Gravity Case

SPECIAL CASES

Uniform Gravity Case

An example with uniform gravity is included here to show that for such simple case, a unique optimal solution is possible and that the optimal trajectory does not necessarily occur at apogee. The missile is launched from a flat surface in an airless uniform gravity field on the same plane as the asteroid. Thus, both the asteroid and interceptor have parabolic trajectories. The asteroid trajectory, missile launch site, and missile ΔV are fixed. The launch angle is varied to show all possible trajectories for the interceptor. Figure 7 shows the possible paths of the missile. The pink ellipse represents the locus of the apogees for the interceptor paths. The insert clearly shows that the maximum altitude intercept occurs outside of the pink ellipse, meaning the missile will reach apogee before coming down to meet the asteroid. This can seem counterintuitive, but similar situations occur in most cases of Keplerian orbits as well.

Coplanar Intercept

A slightly more realistic case than the uniform gravity case is presented here. Two-body Keplerian dynamics are used, but the asteroid path and the missile's trajectories are restricted to the equatorial plane. Again, the asteroid path is constant and the ΔV is fixed. Figure 8 displays the optimal orbits for several launch sites. It is shown that the intercept at apogee case is not equivalent to the optimal case.

Late Intercept Solutions

After the optimal launch time for a certain target and interceptor configuration has passed, it is still possible to achieve intercept, albeit at a lower altitude. The launch time window for post-optimal solutions is bounded by the optimal launch time and the latest possible launch time for which intercept is still possible. The latter bound is equivalent to the minimum-TOF ballistic trajectory between the launch site and the target impact site. For every post optimal launch time, t_1, there is a unique interception trajectory that maximizes altitude. It can be shown that the maximum altitude possible for intercept decreases monotonically with later t_1. Therefore, the best time to

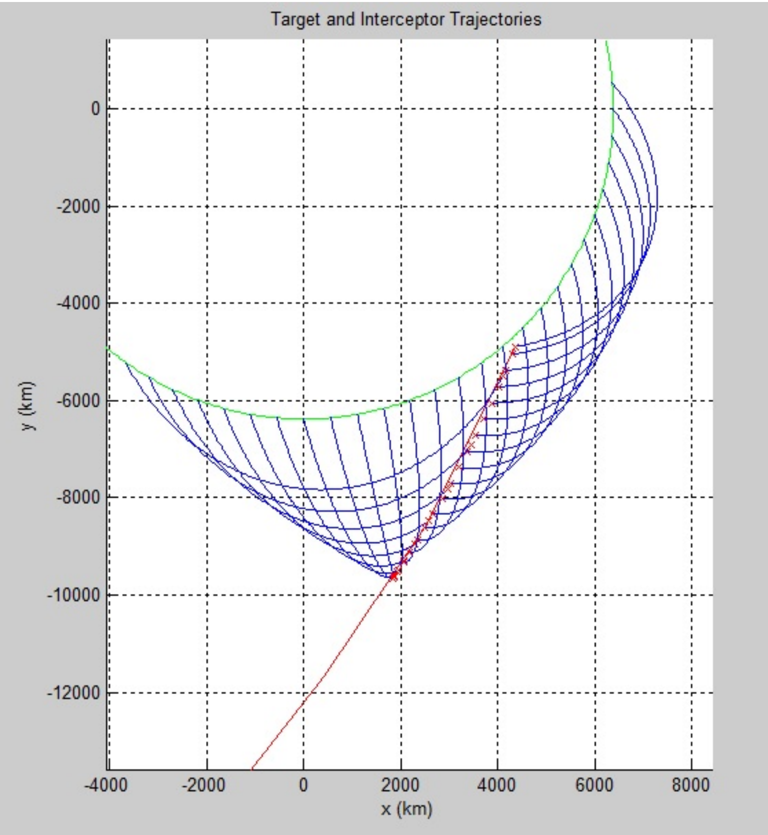

Figure 8. Two-Body Planar Ballistic Intercept

launch after the optimal t_2 has passed is as soon as possible. Because t_1 is considered fixed for each trajectory calculation, the minimization parameter becomes TOF to get the earliest possible intercept. Figure 9 shows the locus of solutions across the post-optimal solution window. This plot was generated using Interceptor A from the above example. The maximum time to impact at intercept on the chart represents the actual optimum solution. This calculation also serves to validate the original algorithm described in this paper, as the both calculations result in the same optimum trajectory for the Interceptor A example.

Figure 10 shows a sampling of post-optimal trajectories. The leftmost trajectory is the optimum solution, and the right most trajectory is the last chance solution.

HIGH ΔV INTERCEPTORS

In this section, interceptors with higher ΔV performance are considered as summarized in Table 4. Firstly, the Minotaur-V launch vehicle with five solid fueled stages can loft a 300 kg payload with a ΔV of 9.5 km/s. This is much greater than the Minuteman III considered earlier, however the Minotaur-V must be assembled on a launch pad and cannot be launched from a silo. The second case to consider is a fictional booster vehicle that can deliver the interceptor out near the moon's radius of 384,000 km. The asteroid orbit and launch site are kept the same as the example in the previous section.

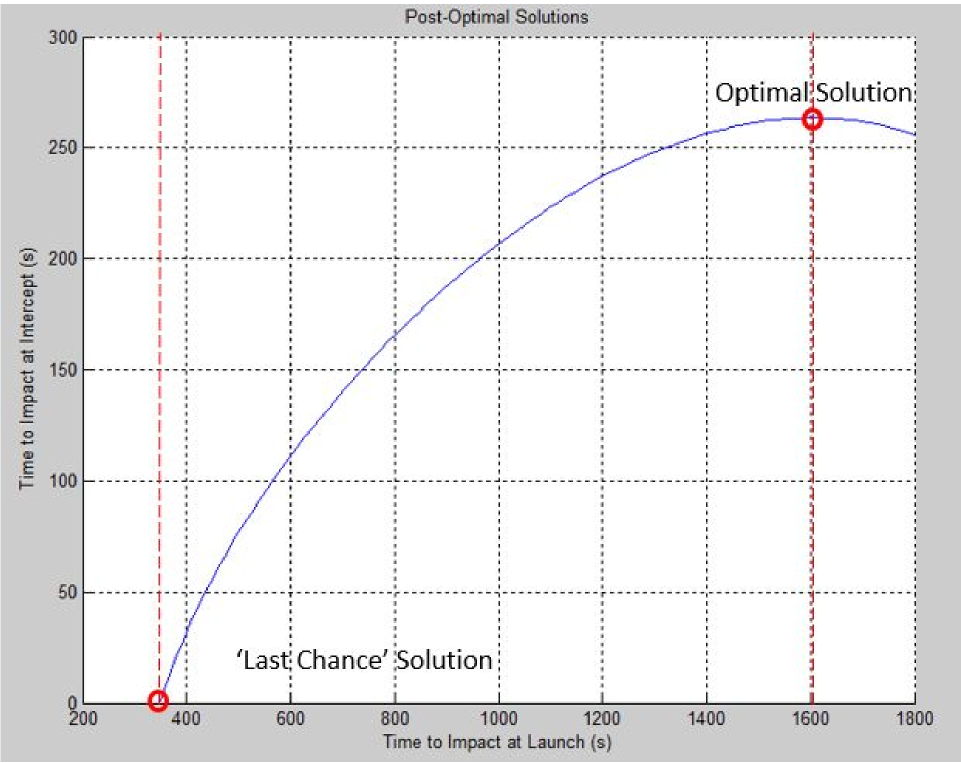

Figure 9. Late Intercept Solution Window

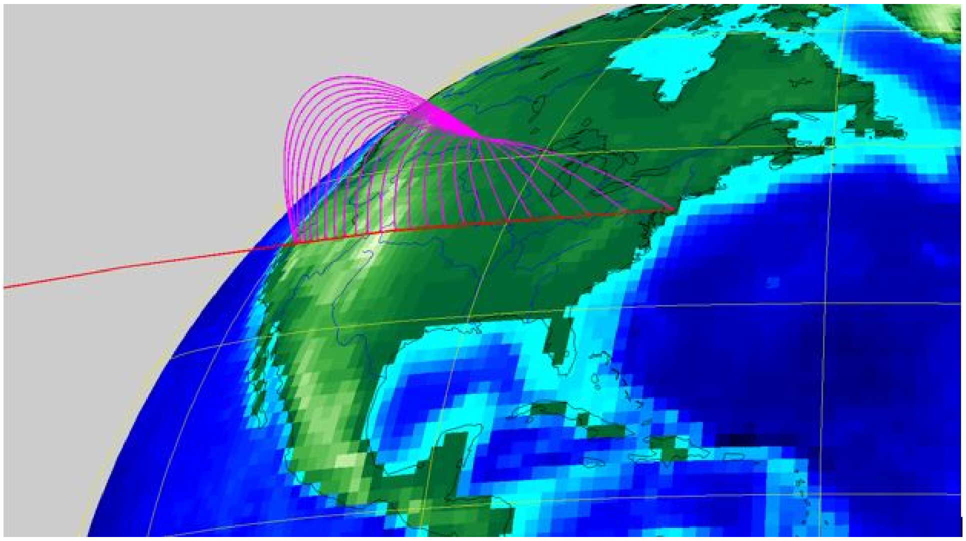

Figure 10. Late Intercept Trajectories

Table 4. High ΔV Intercept Scenarios

Vehicles	Minotaur-V	Fictional Booster
ΔV (km/s)	9.5	11.12
Launch Site	48.5°N 101.5°W	48.5°N 101.5°W
Impact Altitude (km)	15,101	393,620
Time Until Impact at Intercept (s)	1,388	38,623
Time of Flight (s)	5,779	414,030
Time of Flight	1.6 hrs	4.79 days

It should be noted that the fictional booster approaches a parabolic escape orbit, although it remains a suborbital trajectory. Because of this, the results are very sensitive to small changes in ΔV. The Minotaur-V can reach the asteroid at an altitude nearly 5 times higher than the Minuteman III. The intercept altitude increases exponentially with increasing launch ΔV. The time of flight is a limiting factor here. For the case of the fictional booster, intercept occurs 10 hours before impact, but the interceptor must be launched nearly 5 days before impact. The important aspect to take away from these examples is that a small improvement in ΔV allows a large increase in intercept altitude. This can be achieved by using a larger booster or reducing the payload size.

OTHER LAUNCH VEHICLE OPTIONS

Although the Minuteman III ICBM is the primary example considered in this paper, it does not represent the only viable option for last-minute suborbital asteroid interception. This section looks at some of the alternatives provided in Tables 5 and 6. The list is limited to active or recently deactivated boosters that can lift at least a 300 kg payload into LEO and large ICBMs. Liquid fueled launch vehicles are excluded from the list, as they require a more complicated and time-consuming fueling procedure that may not provide enough time for a short warning launch. It is important to note that if there is enough time to assemble a large rocket on a pad before launching the interceptor, sending the interceptor into a parking orbit is more practical than a purely suborbital mission.

Both conventional launch vehicles and ballistic missiles are listed, along with a comparison of relative power. For each launch vehicle, an estimate of the payload to LEO is given, and for the ballistic missiles, an estimate of the burnout velocity and throw weight are given. While not specific to a suborbital intercept mission with a 300 kg payload, these numbers provide a rough comparison between the vehicles.

PRACTICAL CONSIDERATIONS AND LIMITATIONS

Fragmentation and Airbursts

In any scenario where suborbital intercept is the only option, it is unlikely that such an intercept will result in a complete neutralization of the threat. At such close proximity to the Earth, most if not all fragments will still strike the Earth. Similarly, any attempt to completely disrupt a large asteroid would require a prohibitively large nuclear payload that would itself be dangerous to the

Table 5. Non-Ballistic Missile Options

Vehicle	Stages	Country	Platform	Payload to LEO (kg)
Minotaur I	4	US	Launch Pad	580
Minotaur IV	4	US	Launch Pad	1735
Minotaur V	5	US	Launch Pad	532 (GTO)
Pegasus	3	US	Air Launch	443
Shavit	3	Israel	Launch Pad	350
Start-1	4	Russia	Launch Pad	532
Taurus/Antares	4	US	Launch Pad	1320

Table 6. Ballistic Missile Options

Vehicle	Stages	Country	Platform	Burnout Velocity (km/s)	Throw-Weight (kg)
Minuteman III	3	US	Silo	6.6	1150
Peacekeeper	4	US	Silo	6.7	3950
Trident II	3	US	Submarine	6.3	2800
R-36	3	Russia	Silo	$\sim$7.0	8800
GBI	4	US	Silo	6.0	$\sim$ 100
SM-3	4	US	Ship	5.5	$\sim$ 100

Earth. For these reasons, this method of defense is only effective against smaller (50 m to 150 m) asteroids. In the scope of the problem considered in this paper, however, it has been assumed that large asteroids are more likely to be discovered ahead of time, therefore the small, 50 to 150 m class asteroids are the most probable, real, threat considered in this paper. Asteroid much smaller than 50 m may break up in the atmosphere, depositing at most a shower of less dangerous fragments. The events at Tunguska in 1908 and Chelyabinsk in 2013 both provide evidence that large airbursts over land are capable of massive damage. However, a fragmented or fractured asteroid will further break up at a higher altitude, limiting the damage caused by low-altitude airbursts.

EMP Effects

During the 1960s, the US and USSR both experimented with high altitude nuclear detonations. It has been found that smaller yields and sufficiently high altitudes limit the effects on the ground. Additionally, we may be able to appropriately shape an NED explosion such that most explosion energy can directed toward the target asteroid and away from the Earth. However, a further examination of the EMP effects must be conducted.

Launch Vehicle Mission Planning Issues

The entire ascent flight of a launch vehicle from lift-off to the final target point in space basically consists of two phases: the atmospheric (or endoatmospheric) ascent and the vacuum (or exoatmospheric) ascent. Most launch vehicles during the atmospheric ascent flight are often operated in open-loop guidance mode (but, obviously, in closed-loop flight control mode). That is, launch vehicle guidance commands for achieving optimal flight trajectories are pre-computed in pre-mission planning. They are updated using the day-of-launch wind profile prior to launch, loaded into the launch vehicle guidance computer, and then used as pre-programmed guidance commands in actual ascent flight. Trajectory optimization tools are used to pre-compute optimal ascent trajectories for various flight conditions and path constraints.

Once a launch vehicle reaches an altitude of approximately 50 km or above, where the atmospheric effect could be ignored, the vehicle is then operated in closed-loop guidance mode for its exoatmospheric ascent. For example, the Space Shuttle was operated in open-loop ascent guidance mode for the powered first stage (ascent flight with the solid rocket boosters). The powered second stage (after solid rocket booster jettison) utilized a closed-loop guidance algorithm for its exoatmospheric ascent.

The open-loop guidance during the atmospheric ascent is not capable of autonomously adapting to significant off-nominal flight conditions. Pre-mission planning for generating optimal ascent trajectories has been known to be an extremely time-consuming and labor-intensive process. Consequently, rapid generation of optimal ascent trajectories and autonomous/adaptive closed-loop atmospheric ascent guidance have been a research topic of practical interest for many decades [8–12]. Advanced ascent guidance technology need to be further developed for operationally responsive launch vehicles required for planetary defense with very short warning times (1 to 24 hrs).

ATLAS: THE ASTEROID TERRESTRIAL-IMPACT LAST ALERT SYSTEM

Although this paper has focused on a suborbital intercept/fragmentation of an asteroid with such very short warning times of 1 to 24 hrs, the mission effectiveness of the proposed HAIV system can be further enhanced by exploiting an asteroid warning system, which is being developed at the University of Hawaii with $5 million funding from NASA [13].

Once this system, called the ATLAS (Asteroid Terrestrial-impact Last Alert System), becomes fully operational by the end of 2015, it is expected that it will offer a one-week warning for a 45-m diameter asteroid and three weeks for a 140-m diameter asteroid. Provided that such one-week warning from the ATLAS can be assured, a target asteroid can be intercepted/fragmented far outside of Earth's gravitational field and consequently, by avoiding a troublesome suborbital intercept (with an EMP concern). Again, a suborbital intercept will be inevitable if we have very short warning times of only 1 to 24 hrs.

FUTURE WORK

A suborbital intercept and fragmentation mission architecture studied in this paper is expected to be able to transform a Tunguska-like event into a heavy, but tolerable, meteor shower or multiple Chelyabinsk-like events in a worst-case situation. However, further studies are necessary in the following key areas: i) NED yield sizing for properly fragmenting 50 to 150 m asteroids, ii) the side effects caused by an NED explosion at an altitude of 2,500 km or higher, iii) the rapid launch readiness of existing or modified ICBMs for a suborbital asteroid intercept with short warning times (1 to 24 hrs), and iv) precision ascent guidance and terminal intercept guidance.

CONCLUSIONS

A suborbital intercept of a small (50 - 150 m) asteroid with a very short warning time has been examined. The ideal optimal trajectory calculation presented in this paper can serve as a simple open-loop trajectory model for an asteroid intercept mission design study. Current silo launched booster vehicles have sufficient burn-out velocities to deliver payloads on interception trajectories and could achieve a successful and useful intercept. The performance of a modified ICBM could easily be improved by carrying a smaller payload than the large warhead it was designed to carry. Such a system could serve as a last-minute defense tier. It is again emphasized that if an earlier alert (e.g., $>$ 1 week) can be assured, then an interplanetary intercept/fragmentation becomes feasible, which will require an interplanetary launch vehicle. While this paper is limited in scope and is in an early study phase, it has paved the way for a further research and development. Most importantly, this paper has shown that planetary defense cost need not be prohibitively expensive. The need for planetary defense will grow stronger in coming years as we learn more about our dangerous cosmic neighborhood.

REFERENCES

[1] Chesley, S., Chodas, P., and Yeomans, D., "Asteroid 2008 TC3 Strikes Earth: Predictions and Observations Agree," NASA Near Earth Object Program, Nov. 4, 2008.

[2] Wie, B., "Hypervelocity Nuclear Interceptors for Asteroid Disruption," *Acta Astronautica*, 90, 2013, pp. 146-155.

[3] Kaplinger, B., Wie, B., and Dearborn, D. "Nuclear Fragmentation/Dispersion Modeling and Simulation of Hazardous Near-Earh Objects," *Acta Astronautica*, 90, 2013, pp. 156-164.

[4] Ptiz, A., Kaplinger, B., Vardaxis, G., Winkler, T., and Wie, B., "Conceptual Design of a Hypervelocity Asteroid Intercept Vehicle (HAIV) and its Flight Validation Mission," *Acta Astronautica*, 94, 2014, pp. 42-56.

[5] Barbee, B., Wie, B., Mark, S., and Getzandanner, K., "Conceptual Design of HAIV Flight Demo Mission," IAA-PDC13-04-07, 2013 IAA Planetary Defense Conference, April 15-19, 2013, Flagstaff, AZ.

[6] Melamed, N., McVey, J.P., Mayberry, J.P., "Expeditious Response to a Short Warning NEO Impact Threat," Presented at 2013 IAA Planetary Defense Conference, April 15-19, 2013, Flagstaff, AZ.

[7] Bate, R., Mueller, D., and White, J., *Fundamentals of Astrodynamics*, Dover Publications, 1971.

[8] Hanson, J. M., Shrader, M.,W., and Cruze, C. A., "Ascent Guidance Comparisons," *The Journal of the Astronautical Sciences,* Vol. 43, No. 3, 1995, pp.'307-326. Also, NASA-TM-112493.

[9] Dukeman, G. A., "Atmospheric Ascent Guidance for Rocket-Powered Launch Vehicles," AIAA 2002-4559, August 2002.

[10] Picka, B. A. and Glenn, C. B., "Space Shuttle Ascent Flight Design Process Evolution and Lessons Learned," AIAA 2011-7243, 2011.

[11] Lu, P., Griffin, B., Dukeman, G., and Chavez, F., "Rapid Optimal Multiburn Ascent Planning and Guidance," *Journal of Guidance, Control, and Dynamics*, Vol. 31, No. 6, 2008, pp. 1656-1664.

[12] Chavez, F. and Lu, P., "Rapid Ascent Trajectory Planning and Closed-Loop Guidance for Responsive Launch," RS7-2009-1004, *7th Responsive Space Conference*, April 27-30, 2009, Los Angeles, CA.

[13] http://en.wikipedia.org/wiki/Asteroid_Terrestrial-impact_Last_Alert_System