An Optimal Mitigation Strategy Against the Asteroid Impact Threat with Short Warning Time

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NIAC Study Objective (2011 – 2014)

To develop an innovative yet practically implementable mitigation technique for the most probable impact threat of an asteroid or comet with short warning time (i.e., when we don’t have sufficient warning times for a deflection mission)
NIAC Phase 1 Proposal (2011)

- Late intercept missions, with short warning time < 1 yr, will result in a hypervelocity arrival closing (relative) velocity of 5 to 30 km/s.
- $\Delta V = 10 \text{ km/s}$ requires a 96% propellant mass (300-s Isp)
- $\Delta V = 30 \text{ km/s}$ requires a 99.99% propellant mass ratio
- Impact velocity of nuclear explosive devices (NEDs) is limited as 300 m/s max (2005 NRC Report on NEPWs)
**Precision Terminal Intercept Guidence**

**Terminal Guidance Begins**
Impact - 2 hrs for 50- to 150-m target

- Target Acquisition
  - Cameras identify target NEO

- Deployment of 10-m boom with contact fuzes and sensors

- Leader S/C separates from Follower S/C

- Sensors on boom detect NEO surface and Leader S/C sends a signal to initiate detonation sequence of NED

- Leader S/C impacts and creates a shallow crater allowing more surface area to be exposed to NED

- Cameras, LIDAR and deployable boom with contact fuzes

- Stowed Boom (Optional)

- Thermal Shield

- NED Nuclear Explosive Device (NED)

- Follower S/C with NED enters crater and detonates resulting in optimal disruption of target NEO

**Launch Vehicles**

- **Delta IV Heavy**
  - 1500 kg NED
  - ($\approx$ 2 Mt yield)

- **Delta IV M+**
  - 1000 kg NED
  - ($\approx$ 1 Mt yield)

- **Delta II Class**
  - 300 kg NED
  - ($\approx$ 300 kt yield)
Asteroid Deflection Research Center

NASA Innovative Advanced Concepts

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2006 NEO Report by NASA
2010 NEO Report by NRC

Graph showing the relationship between diameter (m) and warning time (years) for asteroid deflection strategies. The graph is divided into three sections:

- **Ready to Launch**
- **Build and Launch**

The strategies are categorized as follows:

- **Nuclear**
- **Kinetic**
- **Tractor**
- **Civil Defense**

The graph highlights the 2006 and 2010 NEO Reports by NASA and NRC.
NIAC Project Outcomes (1/2)

- The Hypervelocity Asteroid Intercept Vehicle (HAIV) mission concept of blending a kinetic impactor with nuclear subsurface explosion
- 7 journal articles + 30 plus technical papers
- 3 Ph.D. (graduated) + 3 MS (graduated) + 3 Ph.D. (current)
- The HAIV mission concept should further exploit the ATLAS last alert system for active last-minute planetary defense (1 week – 3 weeks)
ATLAS Last Alert System
(Asteroid Terrestrial-Impact Last Alert System)

- A $5M project started in 2013 (due to the Chelyabinsk event)
- The ATLAS is currently scanning the sky with a prototype camera and telescope, and will be fully operational in 2015-2016.
- So far, only for civil defense (evacuation)
- One-day alert for a 8-m, 30-kt “town killer”
- One-week alert for a 45-m, 5-Mt “city killer”
- Three-week alert for a 140-m “county killer”
• If a HAIV/IPBM system ($\approx$ $200M - $500M) becomes ready to launch at anytime in the future,

✓ Given one-week warning from the ATLAS, an asteroid (> 45 m) can be intercepted/fragmented far outside the orbit of moon.

✓ Given three-week warning from the ATLAS, an asteroid (> 140 m) can be intercepted/fragmented far outside Earth’s gravitational field.

• Note that ALL other “non-nuclear deflection” options will require much earlier warning of at least 10 to 20 years.
Suborbital Nuclear Intercept/Pulverization Mission Scenario

Minuteman III
6.6 km/s

20 min
2,500 km

4 min

Asteroid

SM-3 IIA

AAS-2014-281
AIAA-2014-4460
PDC 2015
HAIV Design by NASA GSFC for a Flight Validation Mission ($500M)

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HAIV Design by the Mission Design Lab (MDL) of NASA Goddard Space Flight Center

Acta Astronautica
Vol. 106, 2015, pp.139-159

Spacecraft Bus with NED Payload

10-m AstroMast Deployable Boom

Kinetic Impactor

GNC Sensors
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Approach Phase

The approach phase extends from 60 days before to five days before encounter. Sixty days out roughly coincides with the earliest time that the team expects the spacecraft to be able to detect comet Tempel 1 in its high-resolution camera. This milestone marks the beginning of an intensive period of observations to refine knowledge of the comet's orbit. Regular scientific observations will be used to study the comet's rotation, activity and dust environment.

Comet Encounter

The encounter phase begins five days before and ends one day after the impact with comet Tempel 1. This brief but very intense period includes two final targeting maneuvers, leading up to release of the impactor and its dramatic collision with the comet's nucleus. After releasing the impactor, the flyby spacecraft will execute a deflection maneuver so that it does not also collide with the comet; the maneuver will also slow it down enough to make observations after the impact and before flying past the nucleus.

Launch

Jan. 8, 2005

Spacecraft

Earth

orbit

Earth at
encounter

Tempel 1

Impact

July 4, 2005

Sun

Earth orbit

2005 Deep Impact Mission Trajectory

HAIIV Flight Validation Mission Trajectory

Table 5. Preliminary launch window.

<table>
<thead>
<tr>
<th>Launch Date</th>
<th>Earth Departure</th>
<th>Relative Velocity at Intercept (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2019-07-21</td>
<td>22.48</td>
<td>13.4</td>
</tr>
<tr>
<td>2019-08-02</td>
<td>11.99</td>
<td>11.5</td>
</tr>
<tr>
<td>2019-08-12</td>
<td>8.44</td>
<td>10.0</td>
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</tbody>
</table>

Table 6. Maneuver schedule and v budget.

<table>
<thead>
<tr>
<th>Maneuver</th>
<th>Δv (m/s)</th>
<th>Time Correction</th>
<th>Δv Error (%)</th>
<th>Δv Error (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCM 1</td>
<td>26.0</td>
<td>L + 01 days</td>
<td>10</td>
<td>2.6</td>
</tr>
<tr>
<td>TCM 2</td>
<td>2.8</td>
<td>L + 10 days</td>
<td>5</td>
<td>0.140</td>
</tr>
<tr>
<td>TCM 3</td>
<td>0.3</td>
<td>L + 30 days</td>
<td>5</td>
<td>0.015</td>
</tr>
<tr>
<td>TCM 4</td>
<td>0.2</td>
<td>L + 60 days</td>
<td>5</td>
<td>0.010</td>
</tr>
<tr>
<td>TCM 5</td>
<td>0.3</td>
<td>L + 90 days</td>
<td>0</td>
<td>0.000</td>
</tr>
<tr>
<td>TGM 1</td>
<td>3.1</td>
<td>I - 90 min</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TGM 2</td>
<td>0.4</td>
<td>I - 35 min</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TGM 3</td>
<td>0.5</td>
<td>I - 13 min</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TGM 4</td>
<td>3.5</td>
<td>I - 60 secs</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Total Δv = 37.1 m/s

American Institute of Aeronautics and Astronautics

2005 Deep Impact Mission Trajectory
Hypervelocity Asteroid Intercept Vehicle (HAIV) Interplanetary Ballistic Missile (IPBM) Concept
Pulverization and Dispersion of a 300-m Asteroid with a 30-day Warning Time

Educational Use Only

Apophis

Earth

14 Mar 2036 01:00:00.000  Time Step: 3600.00 sec
ATLAS Last Alert

ATLAS project head Dr. John Tonry with a conceptual drawing for an ATLAS telescope. The project would use two of these 20-inch telescopes. Credit: UH/IfA

**NIAC Study Summary**

**Early Warning (> 10 yrs)**
- “Build and Launch” (Deflection)

**> 2 yrs**
- “Build and Launch” (Deflection vs. Disruption)

**< 1 yr**
- “Ready to Launch” (Disruption)

**ATLAS Last Alert**

- 3-week (> 140 m) “Ready to Launch” (Interplanetary)
- 1-week (> 45 m)
- 1 day – 1 wk “Ready to Launch” (inside/outside lunar orbit)

**IPBM/HAIV**
$200M - $500M
Thank You!