2013 IAA Planetary Defense Conference

Conceptual Design of a Flight Validation Mission for a Hypervelocity Asteroid Intercept Vehicle

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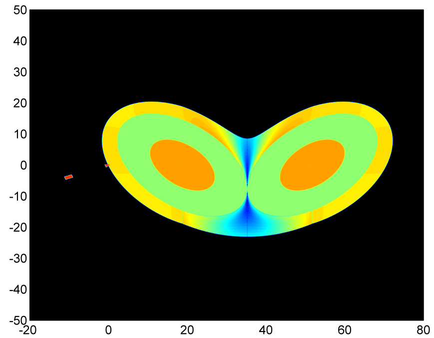
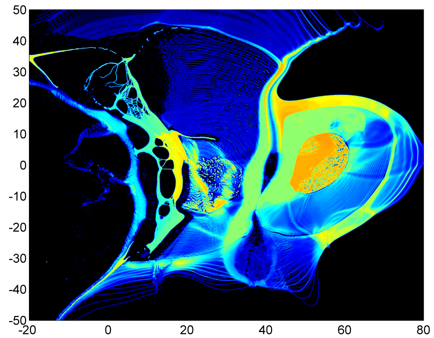
Introduction

- Earth has been struck, and continues to be struck, by near-Earth objects (NEOs).
- Very small NEOs tend to explode very high in the atmosphere, but moderately small ones can penetrate far enough into our atmosphere to cause damage and injuries.
- Large NEOs deliver massive amounts of energy to Earth, but smaller (< 100 m in size) NEOs are far, far more numerous.
- While a number of spacecraft missions have studied asteroids and comets scientifically, to date no NEO mitigation flight demonstrations have been performed.
- Recent events on February 15th, 2013 (Chelyabinsk, 2012 DA_{14}) are a stark reminder of the NEO threat.
- *We cannot rely upon any proposed NEO mitigation system until it has been thoroughly proven with flight demonstrations.*

Background

- The Hypervelocity Asteroid Intercept Vehicle (HAIV) system and mission architecture were initially developed during a NIAC Phase 1 research study.
- HAIV combines a kinetic impactor with a Nuclear Explosive Device (NED) delivery system.
  - The leading kinetic impactor portion of the HAIV create a shallow crater.
  - The following NED carrier portion of the HAIV flies into the crater and detonates.
- Subsurface detonation is $\sim$ 20 times more effective at NEO disruption.
- Enhanced effectiveness reduces required NED yield (mass).
- Hypervelocity intercept & reduced NED mass enable short warning time ($<$ 10 years) response.
- We are continuing this research in a NIAC Phase 2 study (PI: Wie, Co-I: Barbee) entitled "An Innovative Solution to NASA's NEO Impact Threat Mitigation Grand Challenge and Flight Validation Mission Architecture Development"
- One of our first activities was a week-long intensive evaluation and development of the HAIV and its flight validation mission in NASA/GSFC's Mission Design Lab (MDL)



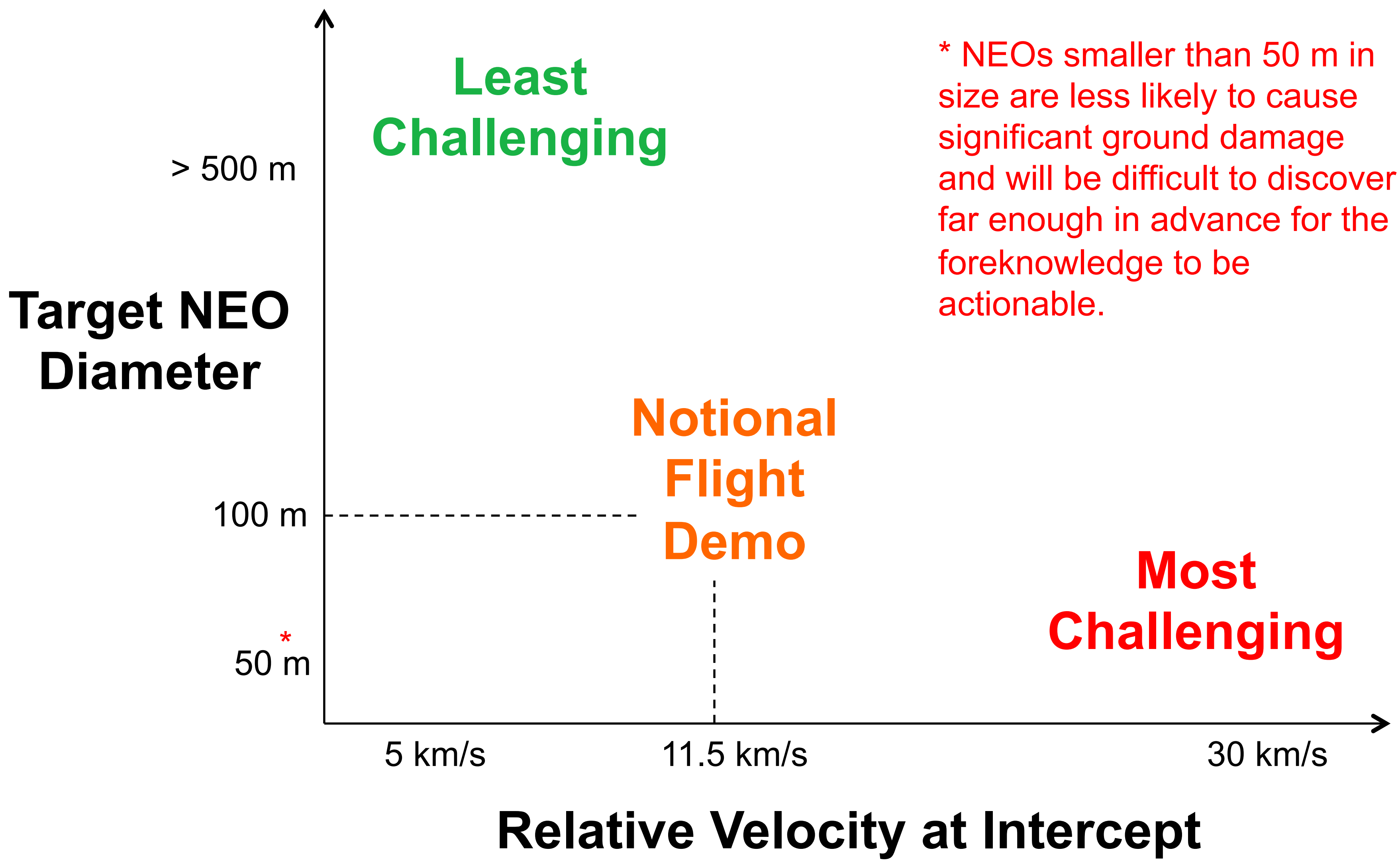


Simplified 2-D simulation of a penetrated, 70 kiloton nuclear explosion for a 70 m asymmetric reference target.

MDL Study Objectives

- Assess the technical feasibility of performing hypervelocity intercept of NEOs as small as 50 m in size, striking within 10 m of the NEO's center with 3σ confidence.
- Design a two-body Hypervelocity Asteroid Intercept Vehicle (HAIV) system capable of intercepting a 50 m size NEO at hypervelocity and performing a subsurface Nuclear Explosive Device (NED) detonation for NEO disruption.
- Design a notional flight demonstration mission that applies the HAIV design to a test case scenario involving a harmless 100 m size NEO.
  - The flight validation mission carries an inert mass as a proxy for the NED payload, modeled simply as a cylinder 1 m in length with a 0.5 m face diameter and a mass of 300 kg.
  - To minimize cost, no observer spacecraft is included in the design; the HAIV must have the necessary observational and communications capabilities to acquire and transmit sufficient data to verify the success of the experiment on the ground solely from HAIV telemetry.
  - Impact of the leading portion of the HAIV with the NEO must be detected onboard and the NED detonation signal must be generated accordingly.

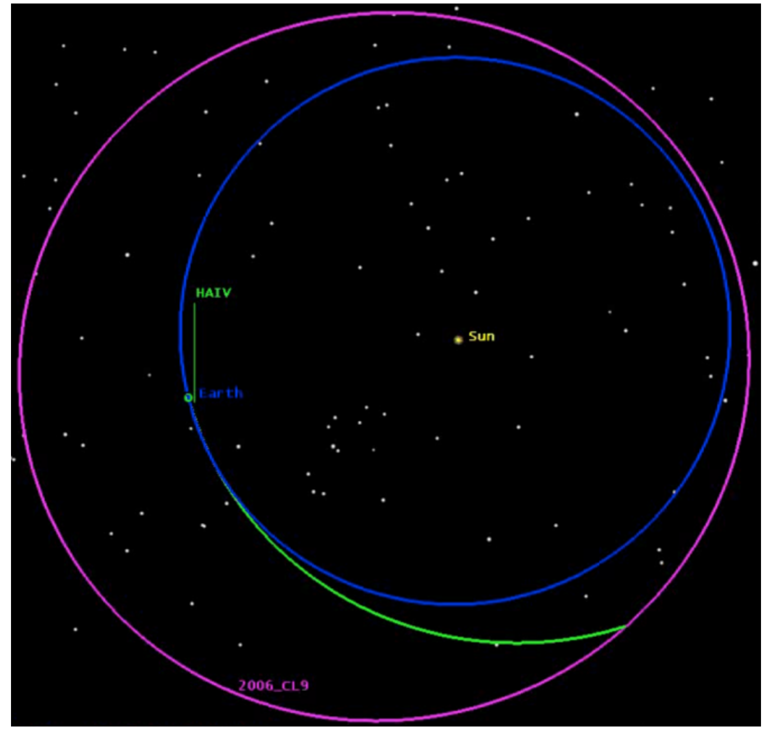
Notional Target Selection Rationale



* NEOs smaller than 50 m in size are less likely to cause significant ground damage and will be difficult to discover far enough in advance for the foreknowledge to be actionable.

Notional Target: 2006 CL_9

- Safety: only consider Amors and Atiras.
- OCC ≤ 5
- Estimated diameter around 100 m.
- Earth departure $C_3 \leq 12.5$ km^2/s^2
- Earth departure date between 2018 and 2020
- Sun-Spacecraft-Earth angle $> 3^\circ$ at intercept.
- Approach phase angle $\leq 90^\circ$ at intercept.
- Trajectory scans performed to optimally balance key parameters.



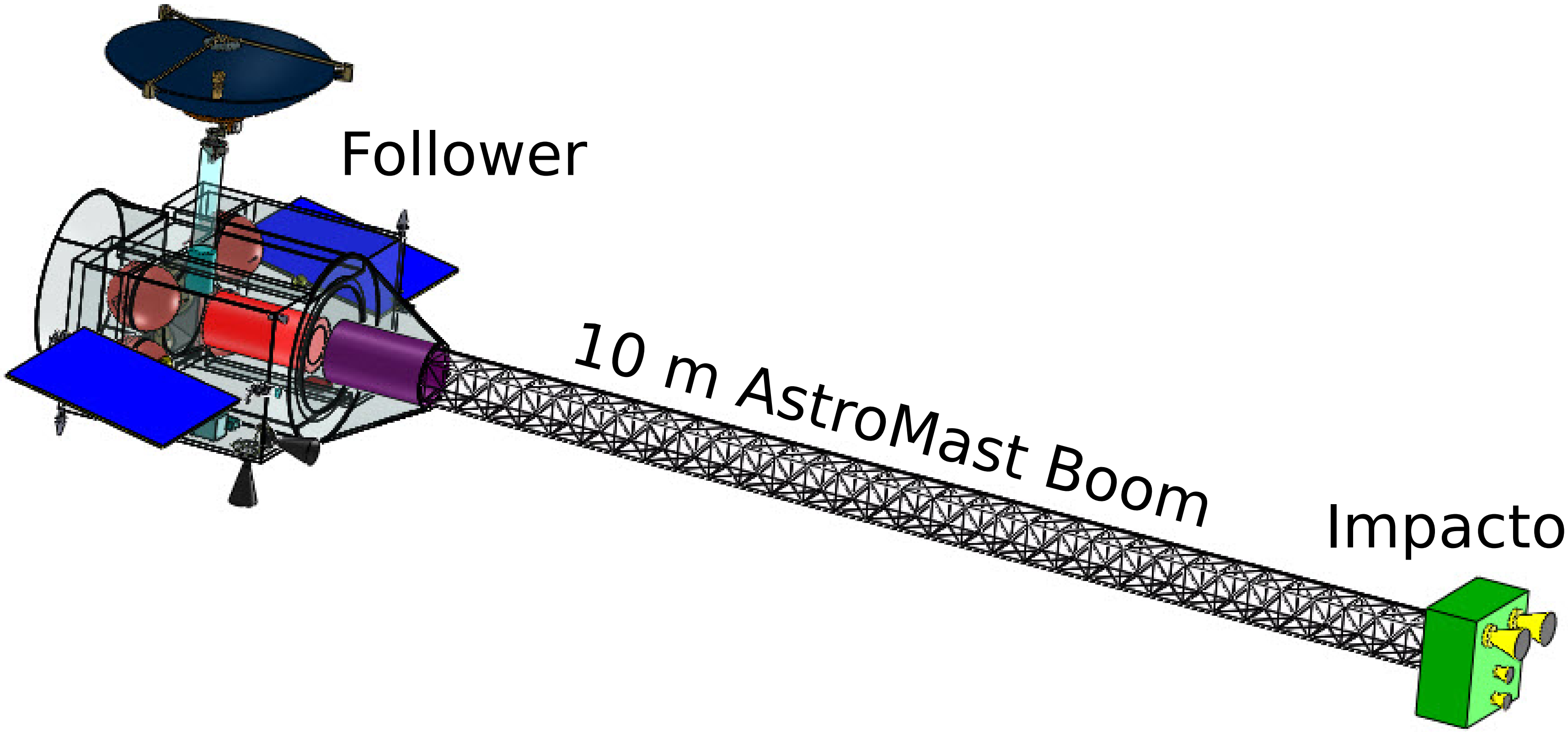
Physical and orbital properties of 2006 CL_9.

Absolute magnitude, H	22.73
Estimated diameter w/ $p = 0.13$	104 m
Estimated diameter w/ $p = 0.25$	75 m
Rotation period (hours)	0.145 $\pm$ 30%
Semi-major axis, a (AU)	1.34616
Eccentricity, e	0.23675
Inclination, i	2.93551°
Longitude of Ascending Node, Ω	139.313°
Argument of Perihelion, ω	9.94912°
Mean Anomaly at Epoch, M	209.664°
OCC	5
Earth MOID (AU)	0.03978

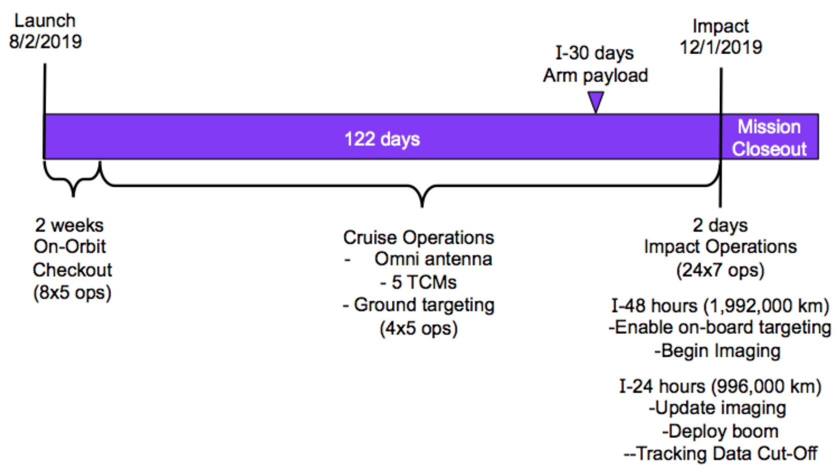
Nominal mission trajectory to 2006 CL_9.

Earth departure date	2019-08-02
Earth departure C_3	11.99 km^2/s^2
Flight time to intercept NEO	121.41 days
Relative velocity at intercept	11.5 km/s
Approach phase angle	3.04°
Max. distance from Earth	0.36 AU
Max. distance from Sun	1.28 AU

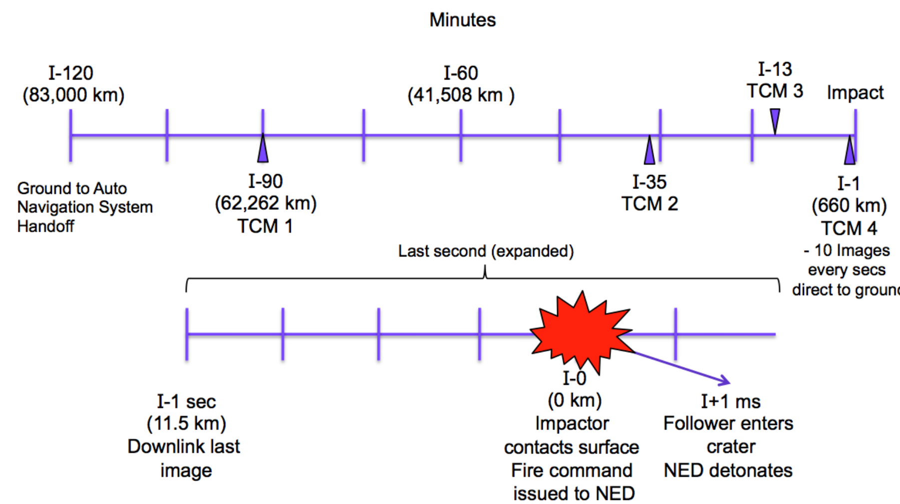
HAIV with Boom Extended



Mission Timeline



Overall mission timeline.



Mission timeline for the final 2 hours.

Flight Dynamics

- 5 Trajectory Correction Maneuvers (TCMs)
- 4 Terminal Guidance Maneuvers (TGMs)
- Total post-launch Δv is small ($\sim$ 37 m/s)

Maneuver schedule and Δv budget.

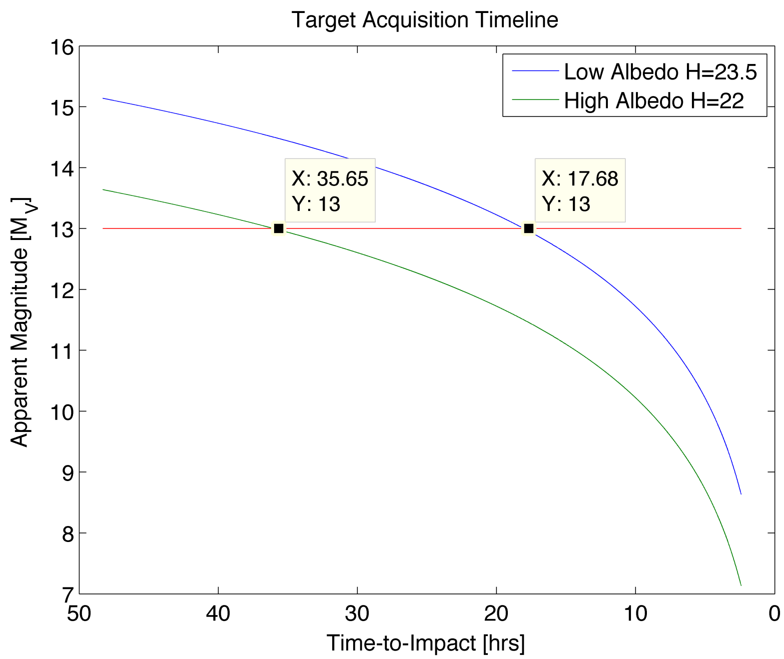
Maneuver	Δv (m/s)	Time	Correction	Δv Error (%)	Δv Error (m/s)
TCM 1	26.0	L + 01 days	Launch vehicle insertion (3σ)	10	2.6
TCM 2	2.8	L + 10 days	TCM 1 error	5	0.140
TCM 3	0.3	L + 30 days	TCM 2 error	5	0.015
TCM 4	0.2	L + 60 days	TCM 3 error	5	0.010
TCM 5	0.3	L + 90 days	TCM 4 error	0	0.000
TGM 1	3.1	I - 90 min	Nav and TCM 5 error	-	-
TGM 2	0.4	I - 35 min	Nav and TGM 1 error	-	-
TGM 3	0.5	I - 13 min	Nav and TGM 2 error	-	-
TGM 4	3.5	I - 60 secs	Nav and TGM 3 error	-	-
Total Δv	37.1				

Preliminary launch window.

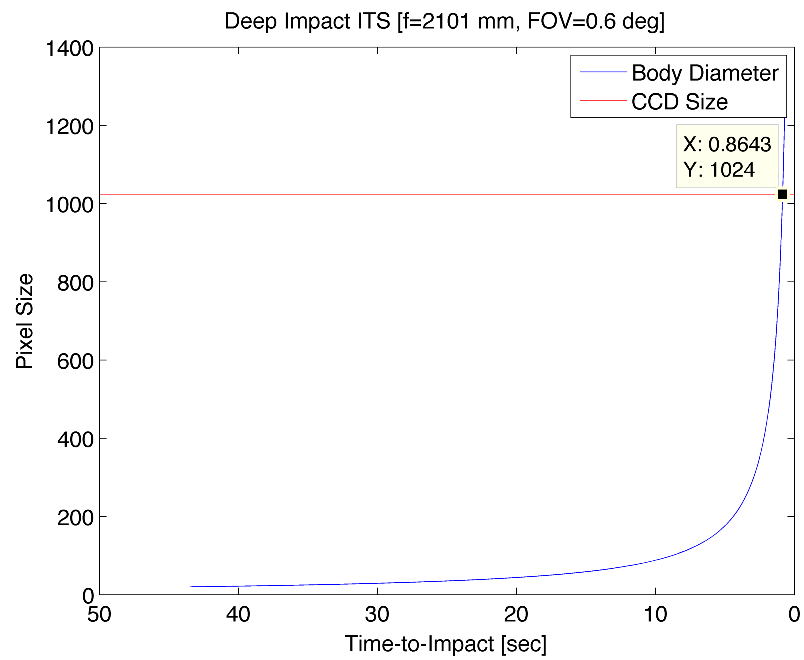
	Open	Middle	Close
Launch date	2019-07-21	2019-08-02	2019-08-12
Earth departure C_3 (km^2/s^2)	22.48	11.99	8.44
RLA	$58.6°$	$52.4°$	$38.9°$
DLA	$-3.1°$	$-12.0°$	$-20.8°$
Relative velocity at intercept (km/s)	13.4	11.5	10.0

Terminal Guidance - Acquisition

- Simulated optical navigation sensor is modeled after the Deep Impact mission's Impactor Targeting Sensor (ITS): 0.6° FOV, 2101 mm focal length, 1024 × 1024 resolution.
- Acquisition requirement: detect 13th magnitude object with SNR $\geq$ 10 within a 5 second exposure.

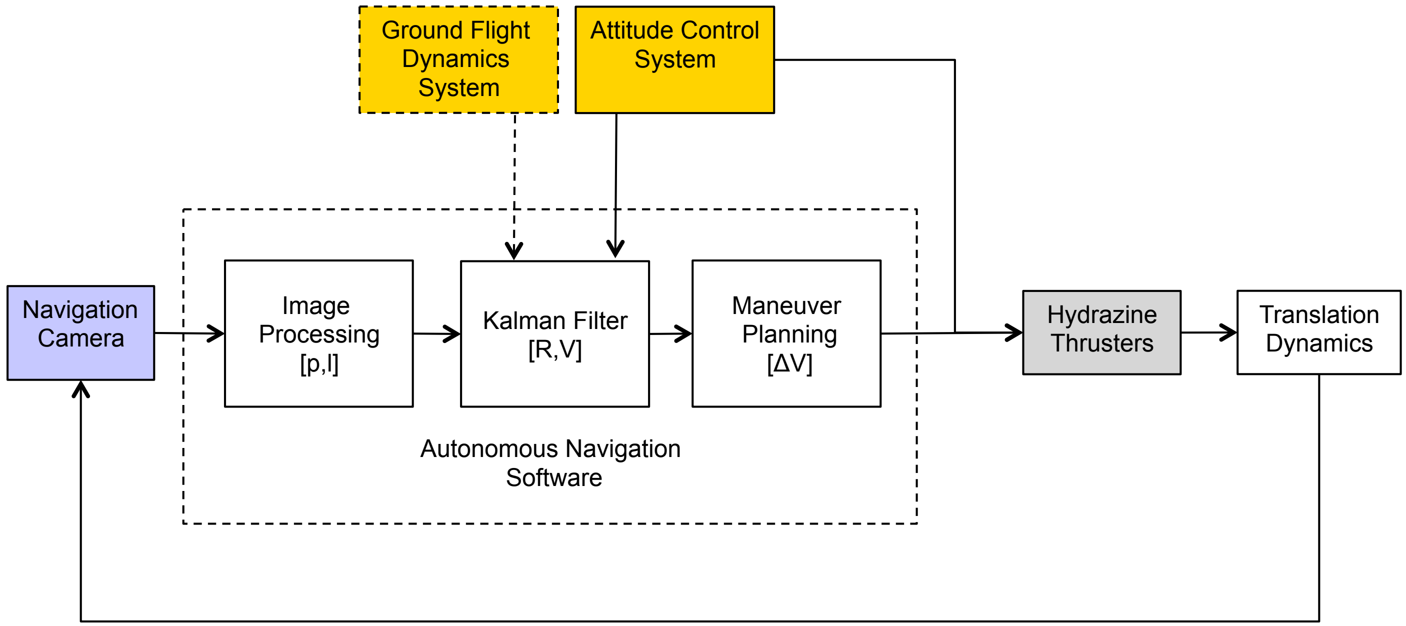


Optical acquisition time for low and high NEO albedo.



NEO size in ITS FOV as a function of time.

Autonomous Navigation System

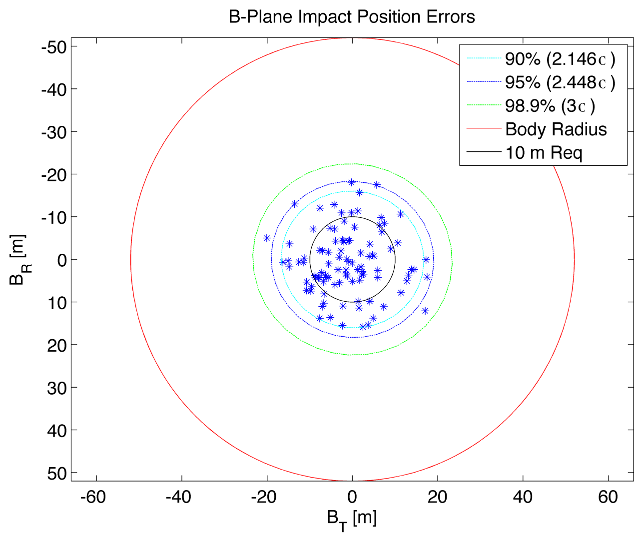


Block diagram of the Autonomous Navigation System (ANS) modeled in simulation.

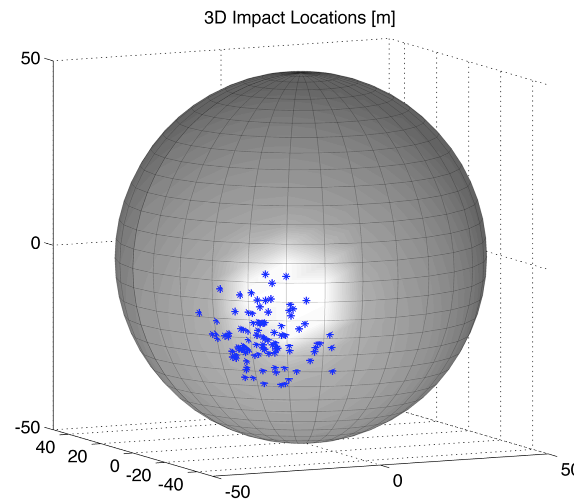
- Error sources (all 1σ) modeled in navigation simulation:
  - Spacecraft a priori state uncertainties of 5 km in position and 1 cm/s in velocity.
  - 3-axis spacecraft attitude uncertainty of 10 μrad.
  - Random centroid pixel noise of 0.05 pixels with a 0.1 pixel bias.
  - Proportional and fixed maneuver execution errors of 1% and 1 mm/s, respectively.

Terminal Guidance - Impact Locations

- 56% of cases in Monte Carlo analysis impact within 10 m of NEO center.



Simulated HAIV impact locations in the B-plane.

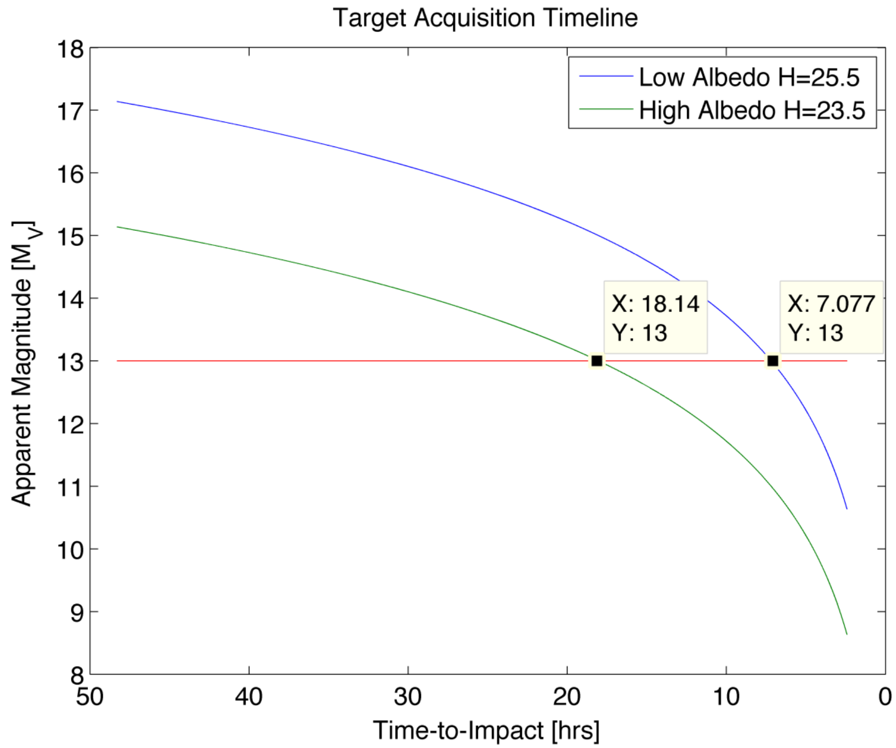


Simulated HAIV impact locations on the target NEO body.

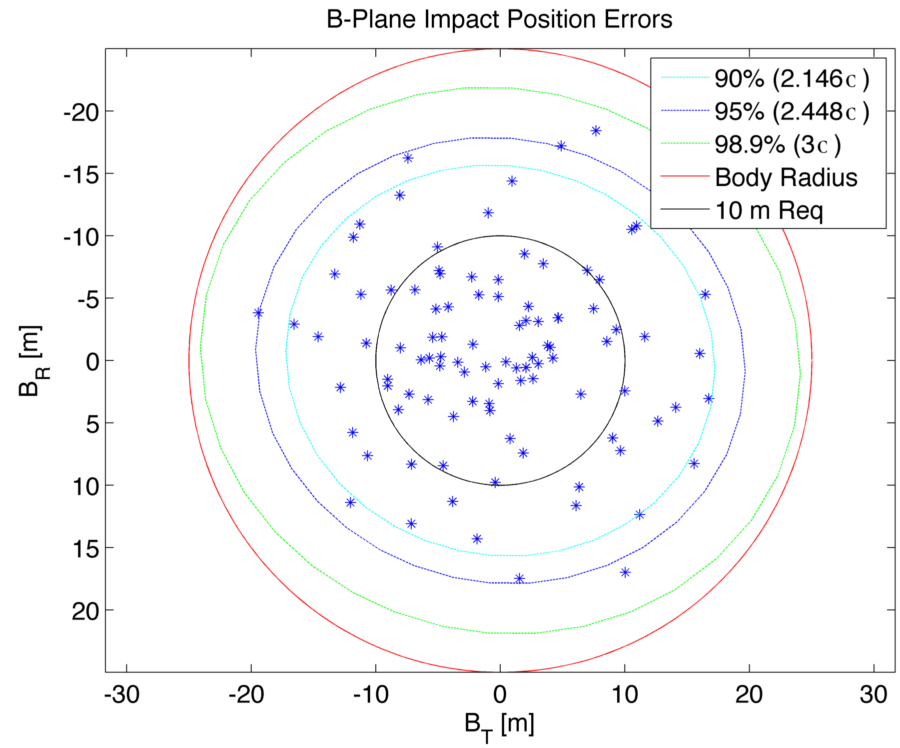
Terminal Guidance Maneuver (TGM) statistics.

Maneuver	Minimum (m/s)	Maximum (m/s)	Mean (m/s)	Mean + 3σ (m/s)
TGM 1 Δv	0.1557	2.9892	1.1705	3.0643
TGM 2 Δv	0.0127	0.4065	0.1451	0.3807
TGM 3 Δv	0.0120	0.5006	0.1812	0.4790
TGM 4 Δv	0.1689	3.4926	1.3377	3.5045
Total	-	-	2.8345	7.4285

Terminal Guidance - 50 m Size NEO

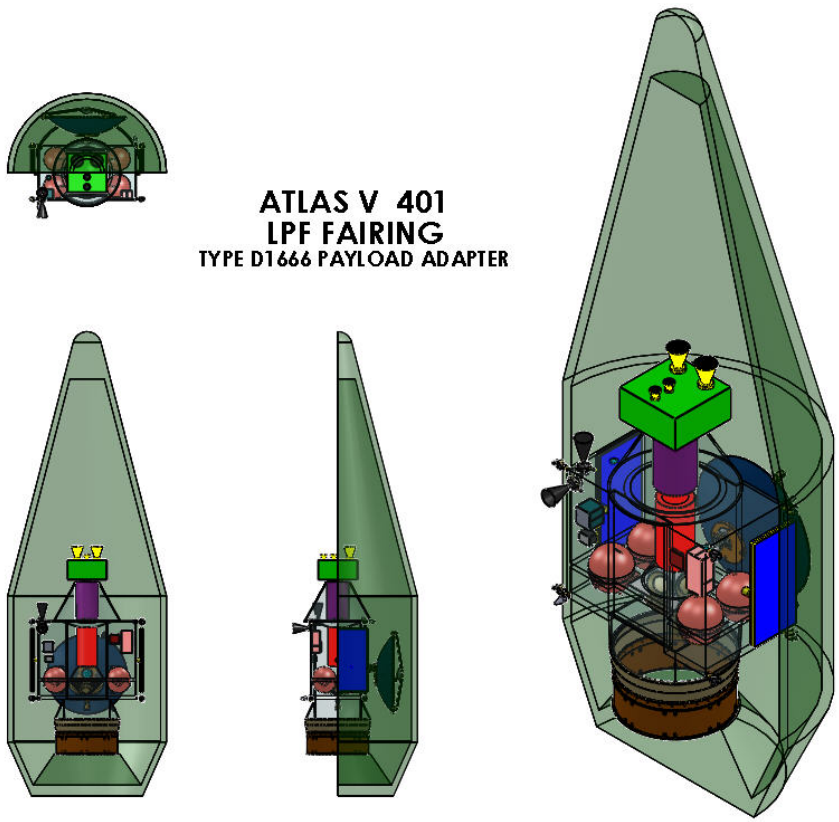


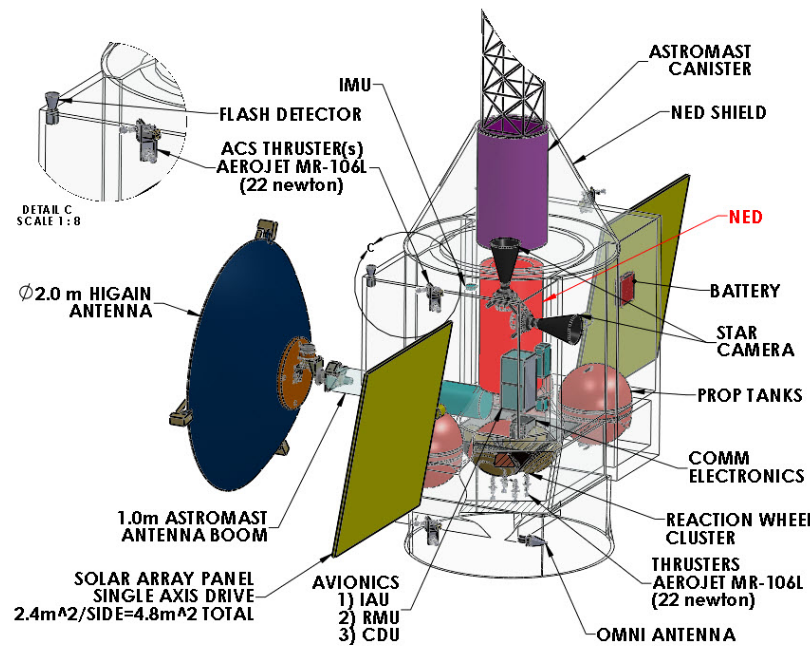
Optical acquisition time for low and high albedo for a 50 m NEO.



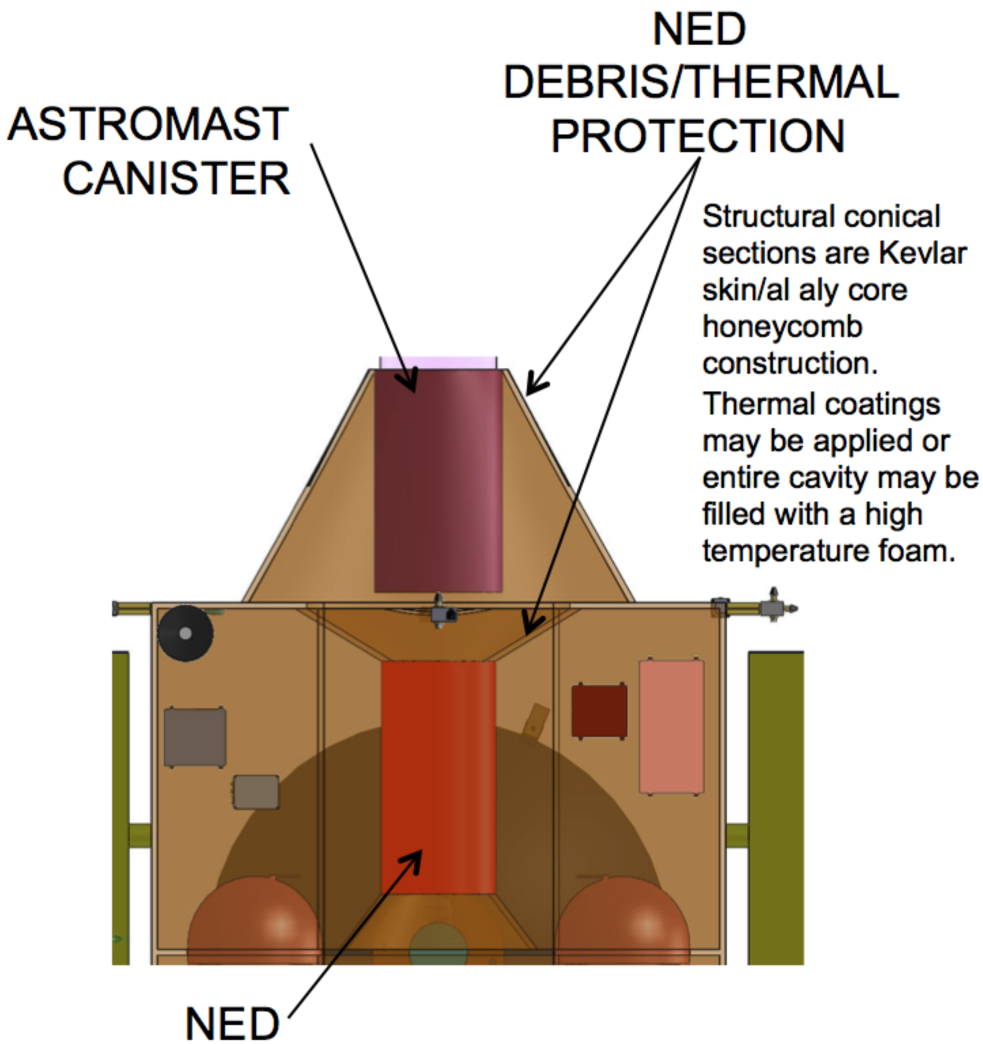
Simulated HAIV impact locations in the B-plane for a 50 m NEO.

Launch Configuration & Subsystems





NED Shielding



Configuration of NED shielding to protect against debris and thermal effects of kinetic impact.

Spacecraft Mass Summary

Spacecraft mass summary with minimum propellant load.

Payload Mass			
NED	CBE (kg)	Contingency (%)	MEV (kg)
Payload Dry Mass	300.0	0	300.0
Payload Wet Mass	0.0	0	0.0
Total Payload Mass	300.0	0	300.0
Impactor Bus Dry Mass			
	CBE (kg)	Contingency (%)	MEV (kg)
ACS-NAVCAM 1,2 ($\times$ 2)	10.0	0	10.0
ACS-IMPACTCAM 1,2 ($\times$ 2)	2.0	0	2.0
ACS-Impact Sensor	2.0	0	2.0
Mechanical Impactor	136.0	0	136.0
Power (2 Lithium-Ion Battaries, 12.33 kg)	12.3	0	12.3
Spacecraft Bus Dry Mass total	162.3	0	162.3
Follower Bus Dry Mass			
	CBE (kg)	Contingency (%)	MEV (kg)
Attitude Determination and Control	52.7	30	68.4
Mechanical	82.5	30	106.7
AstroMast Boom	38.3	30	49.7
Thermal	32.8	30	42.6
Propulsion	80.3	30	104.4
Power (SA, Battery, Harness, no PSE)	92.9	30	120.7
Avionics	59.2	30	77.0
Communications	80.8	30	105.0
Spacecraft Bus Dry Mass Total	681.2	23	836.8
Total Spacecraft Mass			
	CBE (kg)	Contingency (%)	MEV (kg)
Payload Total	300.0	0	300.0
Spacecraft Bus Dry Mass	681.2	23	836.9
Total Dry Mass	981.2	16	1136.9
Propellant (Hydrazine + Pressurant)	64.0	0	64.0
Spacecraft Wet Mass (Launch Mass)	1045.2	15	1200.9
Launch Vehicle Evaluation			
Launch Vehicle Capability (Atlas V 401) (kg)			2315
Launch Vehicle Throw Mass Margin (kg)			1114
Launch Vehicle Throw Mass Margin (%)			92.8
Margin Above 15%			77.8

Schedule & Cost

- The preliminary cost estimate for the flight validation mission is $530.4M, including launch vehicle.
  - Assuming approximate cost of $150M for the Atlas V 401 launch vehicle.
  - Includes design, construction, integration, and testing of spacecraft; launch vehicle integration and test; project management; mission operations; ground system; systems integration and test; education and public outreach; and project reserves.
- Project start for the specific notional flight validation mission described herein is May 1st, 2015.
- Project duration from start to mission closeout is approximately 4.5 years.

Project schedule summary.

Period 0	Project Start to End of Phase A	2015-05-01 – 2015-10-31
Period 1	Start of Phase B to End of Phase C	2015-10-31 – 2017-10-30
Period 2	End of Phase C to mid Phase D	2017-10-30 – 2019-06-05
Period 3	Mid Phase D to Launch - 1 month	2019-06-05 – 2019-07-03
Period 4	Launch - 1 month to Start of Nominal Operations	2019-07-03 – 2019-08-17
Period 5	Nominal Operations	2019-08-17 – 2019-12-02
Period 6	Mission Closeout	2019-12-02 – 2020-01-01

Key Research Topics from MDL Study

- Improve performance and robustness of the Autonomous Navigation System.
  - Improve impact accuracy.
  - Ensure no Terminal Guidance Maneuver requests more thrust than the propulsion system can provide.
  - Upgrade algorithms to process synthetic imagery.
  - Demonstrate robust performance for cases involving irregularly shaped and rotating NEOs of various sizes.
- Search for mission opportunities that include an observer spacecraft affordably.
- Perform trade studies to assess feasibility, advantages, and disadvantages of physically separated (free-flying) impactor and follower versus connected by a boom.
- Develop a parametric model for the final approach timeline as a function of key parameters such as NEO size, shape, albedo, approach angle, and relative velocity.
- Optimize the design of the onboard optical systems to ensure target NEO acquisition sufficiently far in advance of impact for the ANS to operate robustly and achieve a precise and accurate impact with high confidence.
- Assess minimum required impact velocity to ensure a sufficient crater depth on the target NEO as a function of NEO physical properties, e.g., density.
- Consider ground laboratory testing of hypervelocity impact with scale models.
  - Design and test candidate hypervelocity impact sensors (electromechanical, LIDAR/radar, visible flash, etc.).
  - Assess behavior of impactor/follower separation boom during hypervelocity impact.
  - Demonstrate NED shielding techniques.

Conclusions

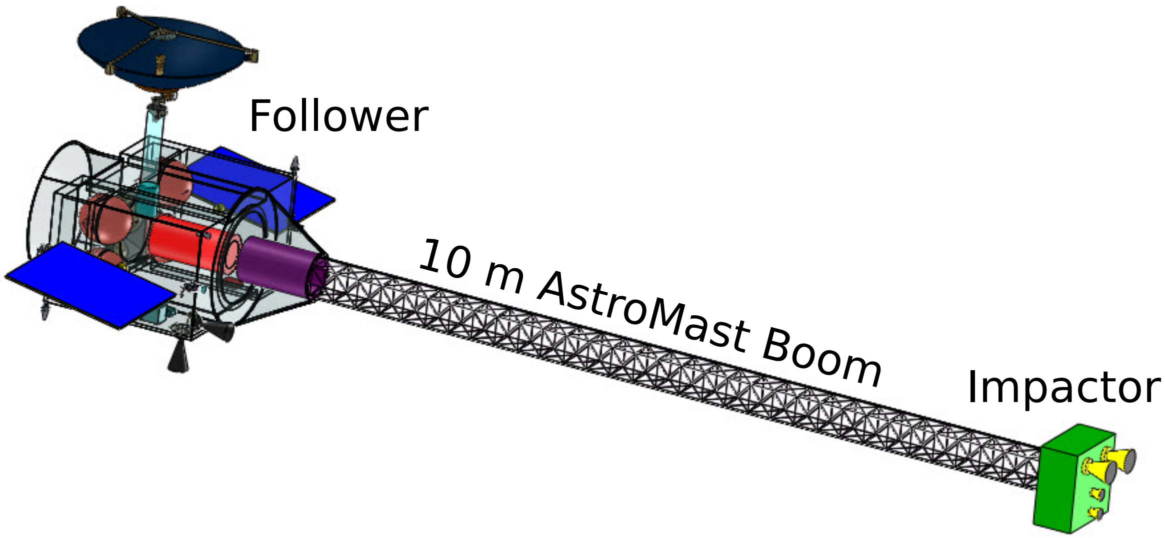
- NEOs pose a serious hazard to life on Earth.
- Small NEOs can be very damaging but difficult to detect in advance, and they are far more numerous than larger NEOs.
- The HAIV concept provides a NEO mitigation solution for both small and large NEOs.
- Hypervelocity intercept for a precisely timed kinetic impactor / NED delivery to a small irregularly shaped NEO requires advanced research in Guidance, Navigation, and Control (GNC), hypervelocity impact physics, robust hypervelocity detection instrumentation, and hypervelocity shielding systems (for NED protection).
- Our team is making steady progress in our NIAC Phase 2 research toward the first flight validation of a NEO mitigation system.

A NEO mitigation system cannot be relied upon until it has been thoroughly tested and proven with flight validation missions.

When a NEO on a collision course with Earth is discovered, we will only have one chance to deploy an effective, reliable defense.

Acknowledgments

This research has been supported by a NIAC (NASA Innovative Advanced Concepts) Phase 2 study grant. The authors would like to thank Dr. John (Jay) Falker, the NIAC Program Executive, for his support.



http://www.adrc.iastate.edu/

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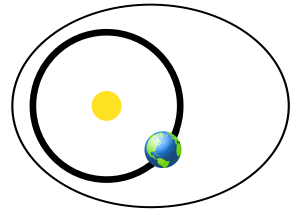
Appendices

NEA Groups According to Orbit Type

Amors

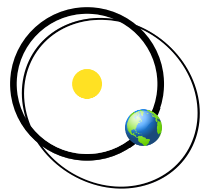
Earth-approaching NEAs with orbits exterior to Earth's but interior to Mars' (named after asteroid (1221) Amor)



$$a > 1.0 \text{ AU}$$
$$1.017 \text{ AU} < q < 1.3 \text{ AU}$$

Apollos

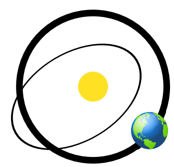
Earth-crossing NEAs with semi-major axes larger than Earth's (named after asteroid (1862) Apollo)



$$a > 1.0 \text{ AU}$$
$$q < 1.017 \text{ AU}$$

Atens

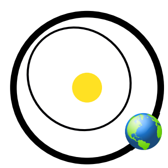
Earth-crossing NEAs with semi-major axes smaller than Earth's (named after asteroid (2062) Aten)



$$a < 1.0 \text{ AU}$$
$$Q > 0.983 \text{ AU}$$

Atiras

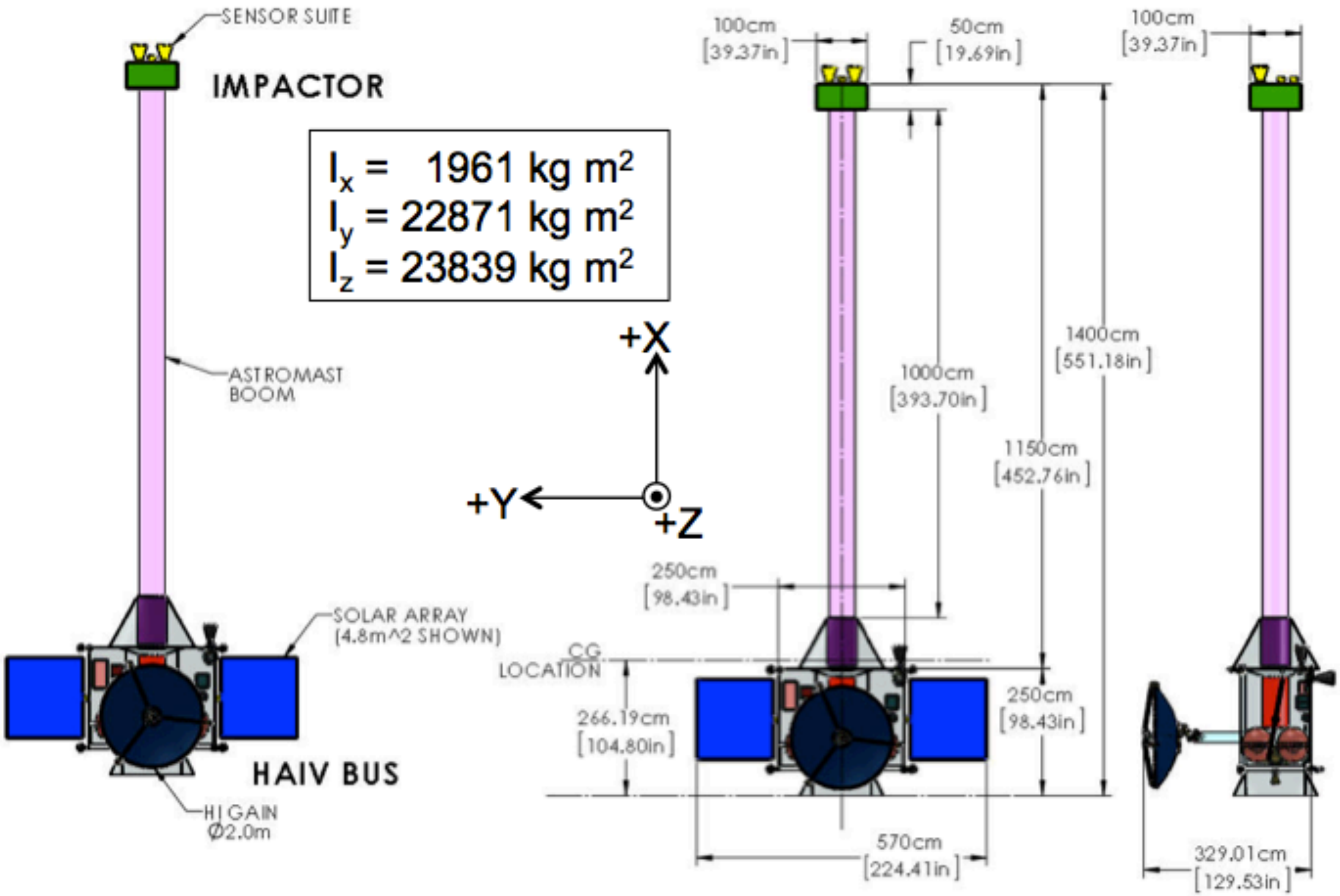
NEAs whose orbits are contained entirely within the orbit of the Earth (named after asteroid (163693) Atira)



$$a < 1.0 \text{ AU}$$
$$Q < 0.983 \text{ AU}$$

(q = perihelion distance, Q = aphelion distance, a = semi-major axis)

HAIV Dimensions and Mass Properties



Propulsion

- Monopropellant hydrazine operating in a blow-down mode.
- Four propellant tanks (total capacity of 360 kg).
- Twelve 22 N thrusters.
- Three-axis attitude control capability; supports momentum unloading.
- Δv along $+X$ (88 N thrust), $\pm Y$ (31–62 N thrust), and $\pm Z$ (31–62 N thrust) axes.

Maneuver	Δv (m/s)	ACS Tax	Effective Δv (m/s)	Effective I_{sp} (s)	HAIV Mass (kg)	Propellant Mass (kg)	Burn Time (s)
Checkout/Engineering Burns	2.3	0	2.30	229	2310.0	2.4	60.4
LV Dispersion, L + 1 day	26.0	50	39.00	229	2307.6	39.8	1014.2
Correction 2, L + 10 days	2.8	50	4.20	229	2267.9	4.2	108.2
Correction 3, L + 30 days	0.3	50	0.45	162	2263.6	0.6	32.1
Correction 4, L + 60 days	0.2	50	0.30	162	2263.0	0.4	21.4
Correction 5, L + 90 days	0.3	50	0.45	162	2262.6	0.6	32.1
TGM 1, I - 90 minutes	3.1	50	4.65	162	2261.9	6.6	330.8
TGM 2, I - 35 minutes	0.4	50	0.60	162	2255.3	0.9	42.6
TGM 3, I - 12 minutes	0.5	50	0.75	162	2254.5	1.1	53.2
TGM 4, I - 1 minutes	3.5	50	5.25	162	2256.4	7.4	372.0
Totals	39.4	-	57.95	-	2246.0 (final)	64.0	2066.8