Mission Opportunities for the Flight Validation of the Kinetic Impactor Concept for Asteroid Deflection

Presented to the 2013 IAA Planetary Defense Conference

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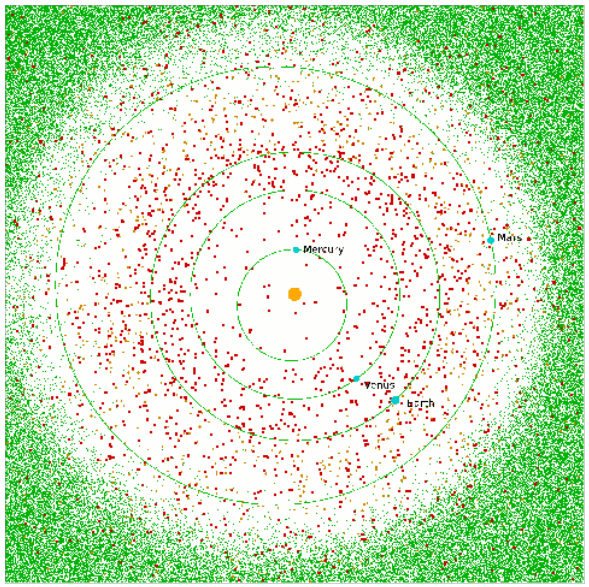
April 16th, 2013

Motivation and Objective

- Our planet has been struck with devastating force by asteroids and **will be hit again**.
- Collisions are aperiodic and can happen at any time.
- **Deflection techniques** have been proposed to defend our planet from impact.
  - Types:
    1. Kinetic Impactor
    2. Gravity Tractor
    3. Nuclear Detonation
  - None of these techniques have been tested!
- NEA mitigation technologies must be thoroughly **tested** before they can be considered reliable.

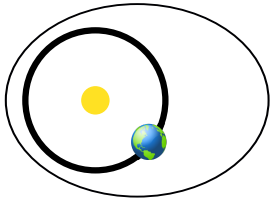
We propose a campaign of **asteroid deflection technology test missions** deployed to harmless asteroids in order to safely test, measure, and refine the **Kinetic Impactor** deflection technique.

Classification of NEAs



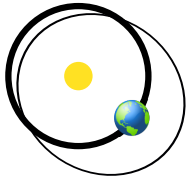
Amors

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



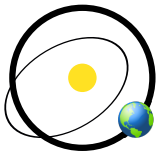
Apollos

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



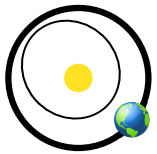
Atens

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



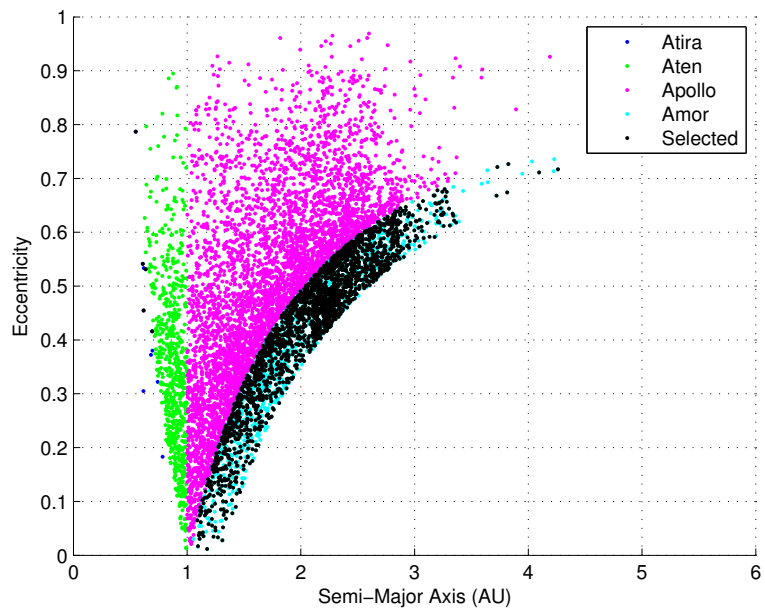
Atiras

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



Identifying Possible Candidates

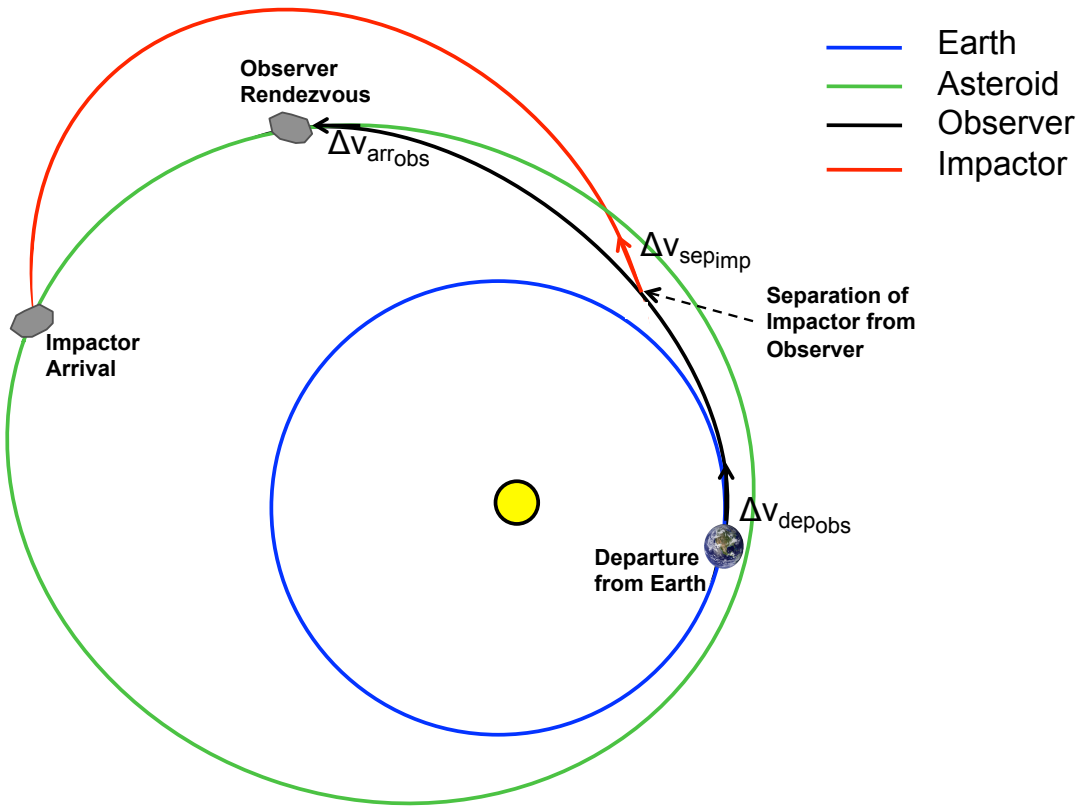
- Safe experiments which pose no risk to Earth: **Atiras and Amors**
- NEAs with orbit inclination less than 20 degrees
- NEAs with diameter of at least 95 m and OCC ≤ 2



- Using a single launch vehicle (**Atlas V 551**) helps make the mission affordable
- **Observer** and **impactor** spacecraft launch together but separate after; observer rendezvouses with NEA 3 months to 3 years prior to impact
- **Impactor** must create a measurable and meaningful deflection

Trajectory Design

- Single Launch using Atlas V 551 for Impactor and Observer
- Developed a grid search algorithm to check for all trajectory possibilities
- Trajectory design utilized two-body dynamics and patched conics for the spacecraft, and high-fidelity ephemeris for Earth and NEAs



- Impactor and Observer Constraints:

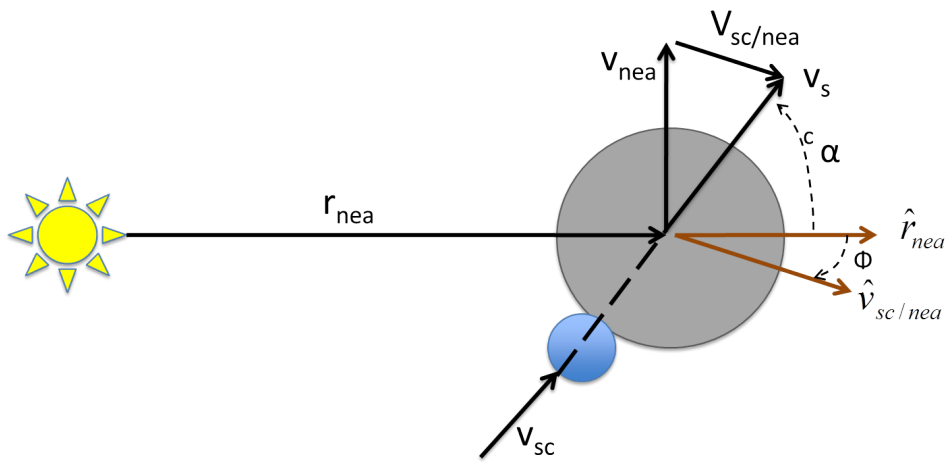
	Observer
Dep. Date Year	2018 - 2022
TOF (days)	≤ 1000
m_{dry} (kg)	≥ 500

	Impactor
Arr. Date	$t_{arr_{imp}} - 3$ yr. $\leq t_{arr_{obs}}$ $t_{arr_{obs}} \leq t_{arr_{imp}} - 3$ mon.
Separation Date from Observer	$t_{sep} \geq 1$mon. from departure date $t_{sep} \leq 1$ mon. before observer arrival
TOF (days)	≤ 1000
Approach Angle (^{o})	≤ 90
Deflection (km) after 2 years	≥ 100

Impactor Approach Angle

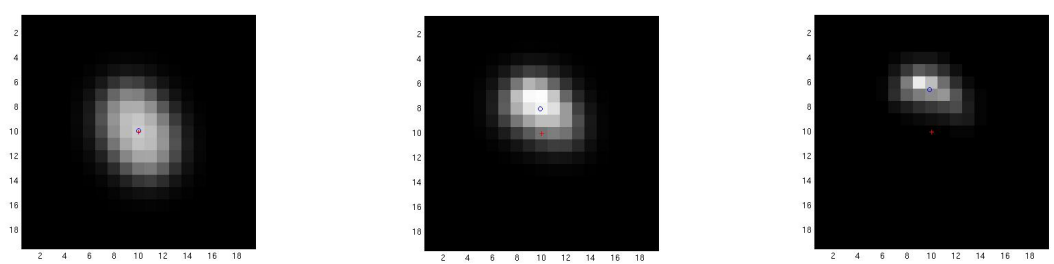
- The impactor spacecraft approach phase angle with respect to the asteroid needs to be taken into account
- Small approach phase angle to facilitate optical acquisition of the NEA by the spacecraft's onboard sensors during terminal guidance
- The approach angle is computed as

$$\phi = \cos^{-1}\left(\hat{\mathbf{v}}_{sc/nea} \cdot \hat{\mathbf{r}}_{nea}\right) \leq 90^o$$



- Example to show why low approach angle is important

$\phi = 5^o$ $\phi = 80^o$ $\phi = 140^o$



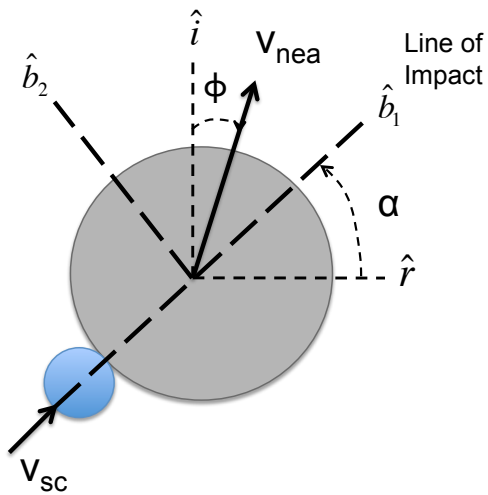
Kinetic Impactor Model

1. Computing $\mathbf{\Delta v}$

   - Plastic collision: $v_{nea}^{+} = v_{sc}^{+}$
   - Conservation of LM for the NEA-spacecraft system:

$$m v_{sc}^{-} + M v_{nea}^{-} = (m + M) v_{nea}^{+}$$

   - $\boxed{\mathbf{\Delta v} = \Delta v_r \hat{\mathbf{r}} + \Delta v_i \hat{\mathbf{i}} + \Delta v_c \hat{\mathbf{c}}}$
     where $\mathbf{\Delta v} = f(\beta, M, m)$.



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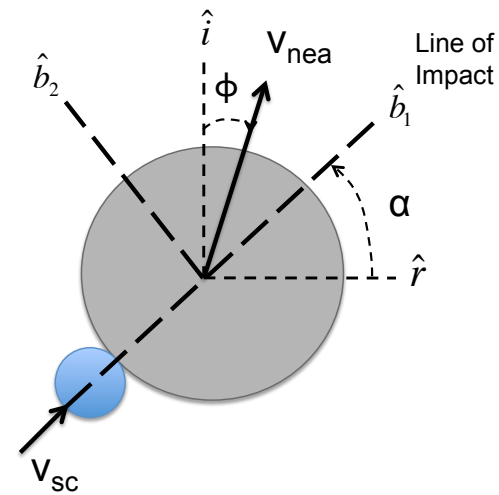
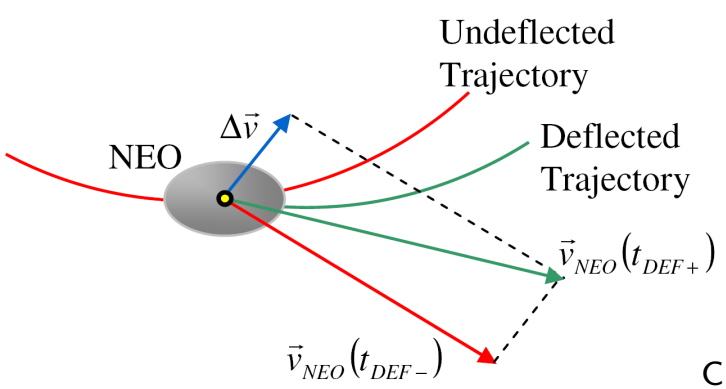


2. Computing Δr: Use **Lagrange planetary equations as an approximation.**



$$\Delta a = \frac{2}{\sqrt{1-e^2}} \sqrt{\frac{a^3}{\mu}} \left[e \sin\nu \Delta v_{\hat{r}} + (1 + e\cos\nu) \Delta v_{\hat{i}} \right]$$

$$\Delta r = 1.5 \frac{\Delta t}{T} \frac{\Delta a}{a} C$$

C is approximate NEA orbit circumference

Candidates that Meet Requirements

- We run grid search algorithm with ALL NEAs to find ALL possible trajectory solutions
- Three NEAs were found to meet all the requirements
  1. 1998 KG_3
  2. 2003 SM_{84}
  3. 2004 EO_{20}
- Each one offers many feasible trajectory solutions
- The solution shown here is the one with the **lowest approach angle** at impact

	NEA	D (m)	OCC	Type	Earth Dep. Date	C_3 (km^2/s^2)	ΔV_{arr} (km/s)	Separation Date	ΔV_{sep} (km/s)	TOF (days)	TBI (days)	m_{final} (kg)	Δr (km)	Approach Angle (^{o})
1	1998 KG_3	123	0	Obs Imp	4-16-2018	16.12	3.04 2.84	10-3-2018	0.9	354 454	270	500 2,280	101.35	11.28
2	2003 SM_{84}	97	1	Obs Imp	3-27-2021	33.69	1.60 8.11	11-22-2021	8.34	294 874	820	500 132	103.21	30.85
3	2004 EO_{20}	137	2	Obs Imp	9-22-2019	10.74	3.15 7.68	3-10-2020	6.67	327 997	840	500 367	138.89	36.23

- **1998 KG_3** was chosen for further mission analysis because of its **low** v_∞ at impactor arrival and **low** approach angle ϕ, it offer a good option as a **first test mission**.
- The other two candidates offer more challenging missions, which will be great opportunities for future test missions!

1998 KG_3: Mission Opportunities

	NEA	D (m)	OCC	Type	Earth Dep. Date	C_3 (km^2/s^2)	ΔV_{arr} (km/s)	Separation Date	ΔV_{sep} (km/s)	TOF (days)	TBI (days)	m_{final} (kg)	Δr (km)	Approach Angle (^{o})
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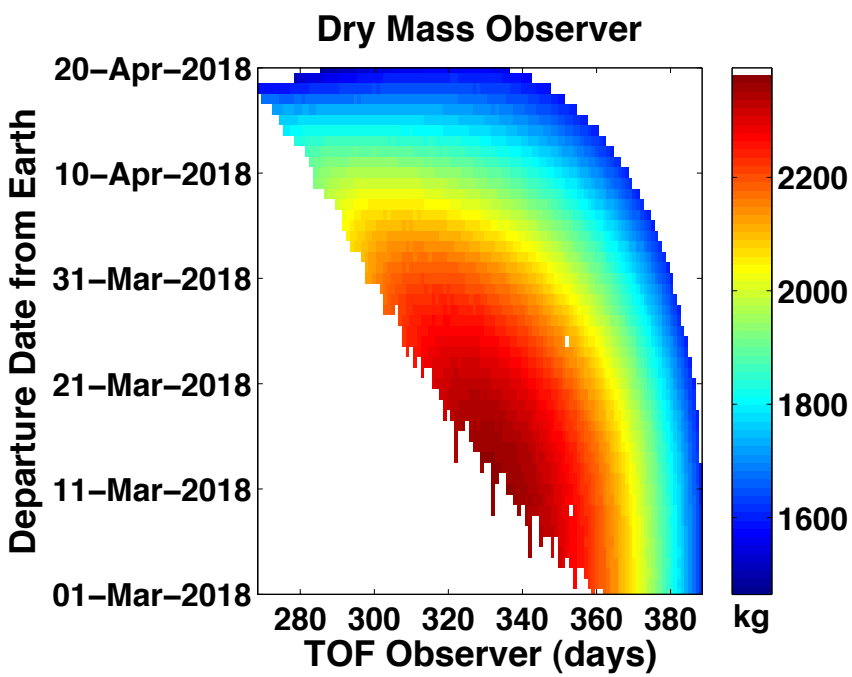

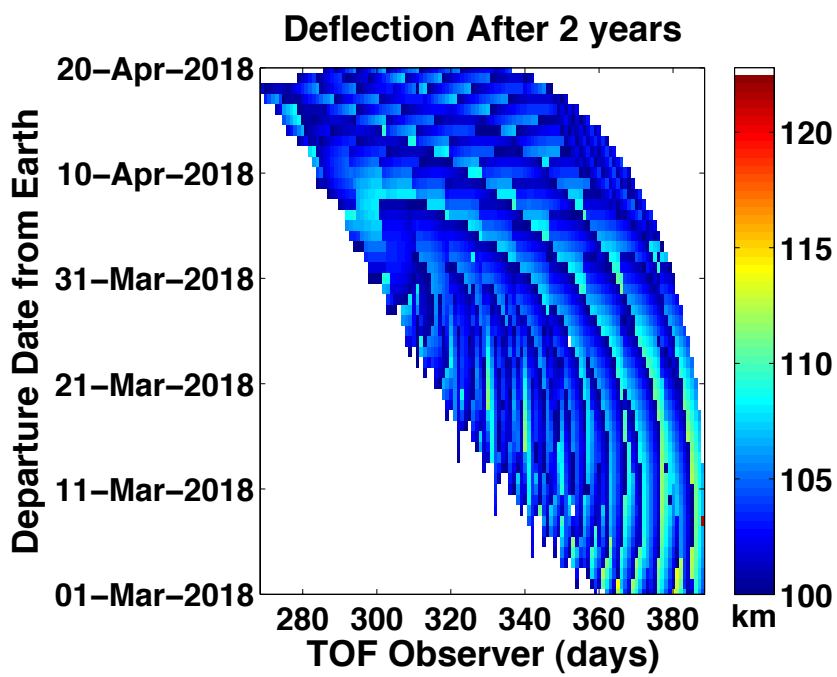

1998 KG_3: Trajectory Solution

	NEA	D (m)	OCC	Type	Earth Dep. Date	C_3 (km^2/s^2)	ΔV_{arr} (km/s)	Separation Date	ΔV_{sep} (km/s)	TOF (days)	TBI (days)	m_{final} (kg)	Δr (km)	Approach Angle (^{o})
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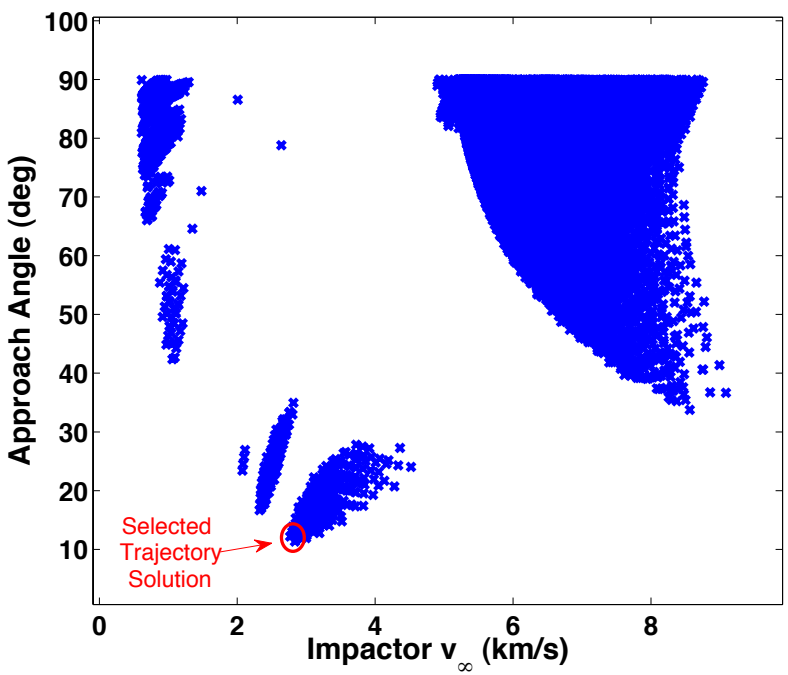
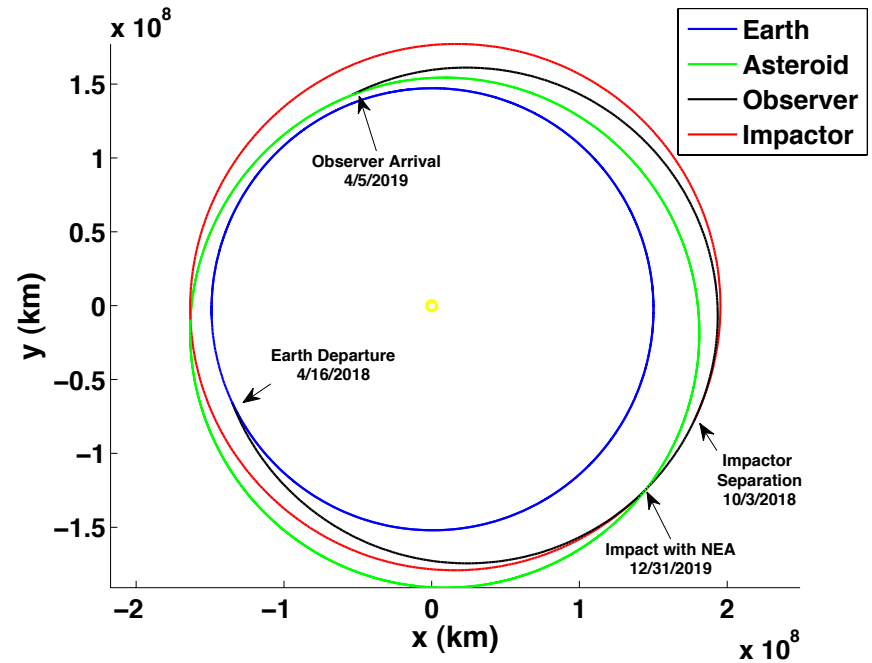
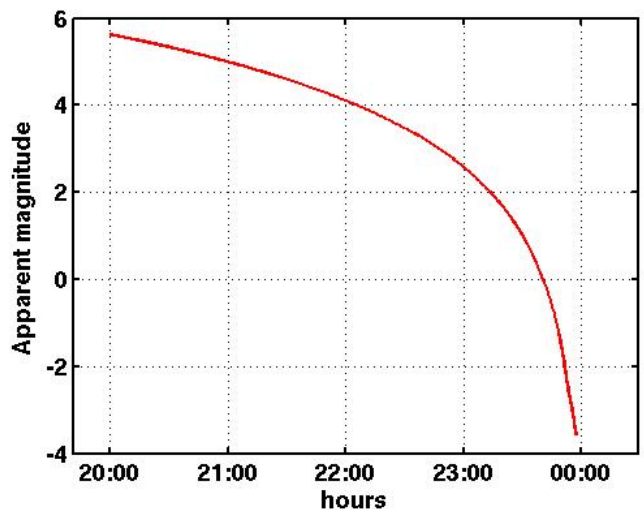
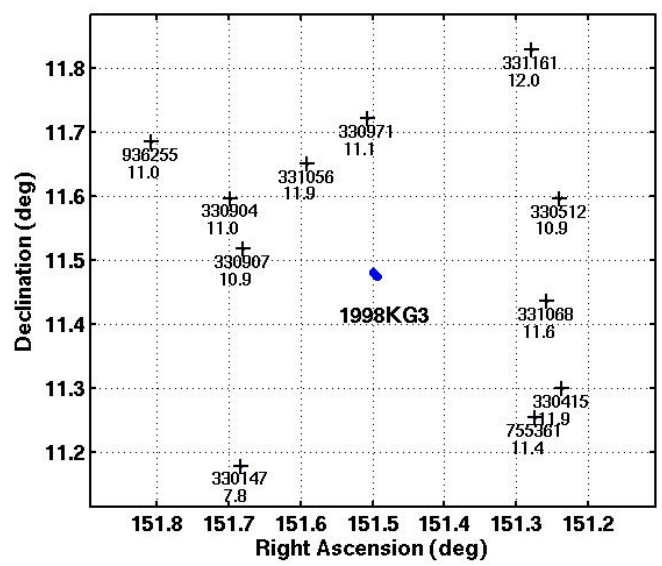




1998 KG_3: Terminal Guidance Analysis

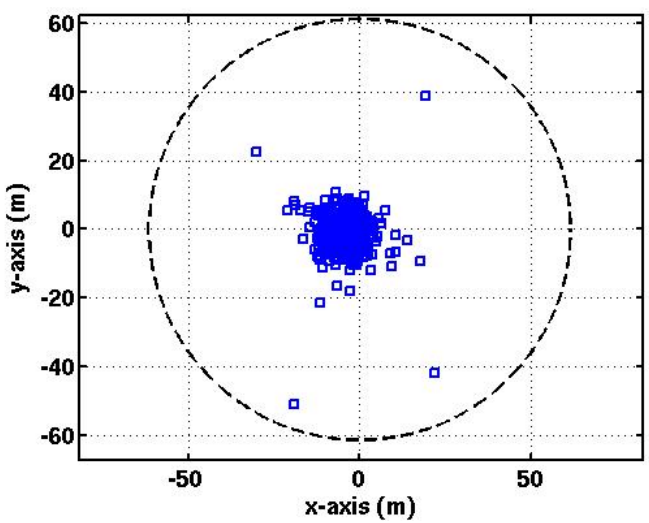
- Terminal guidance simulation utilizes **JPL AutoNav** software, which has extensive heritage (e.g., Deep Impact, Stardust)
- In this study we model the Deep Impact Medium Resolution Imager (MRI) camera (focal length = 2100 mm, 1024 square pixel CCD array, 0.6 degree FOV, 10 microradian IFOV)
- The MRI resolves 1998 KG3 72 hours prior to impact
- Lack of sufficiently bright background stars in the FOV centered on 1998 KG3 leads to the **use of an IMU** for spacecraft attitude
- Terminal guidance phase begins **4 hours before impact** (ensures asteroid will be in camera FOV at start of AutoNav in spite of orbit knowledge uncertainties); 3 terminal guidance maneuvers are performed

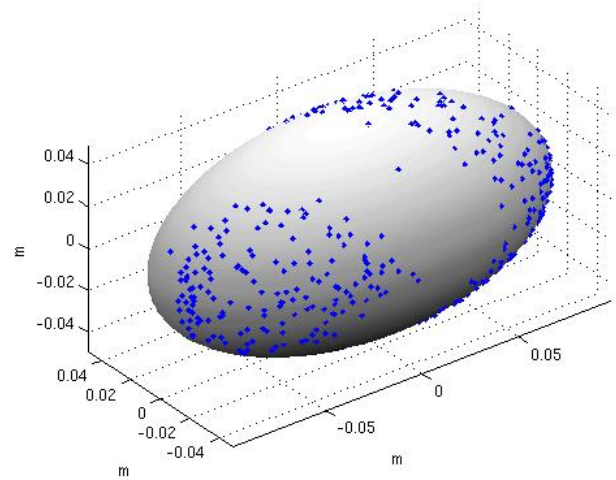




1998 KG_3: Terminal Guidance Analysis

- We model the nominal asteroid diameter of 123 m as a 2:1 ellipsoid with dimensions 196 x 98 x 98 m
- Asteroid pole orientation is sampled from a uniform distribution
- 497 out of 500 Monte Carlo runs show successful asteroid impact; the majority of impact locations are within 25 m of the asteroid center





Conclusion

- It is imperative that we begin **testing** candidate NEA deflection systems, such as the **kinetic impactor on harmless NEAs**
- We provide a set of targets that offer safe and **affordable** mission scenarios
- Kinetic impactor must be measured by an observer spacecraft that has previously rendezvoused
- **Impactor** and **Observer** launch together on a single launch vehicle
- Key filters are NEA diameter, OCC, approach phase angle, relative velocity at intercept, and amount of deflection
- Full mission analysis is performed on **1998 KG**$_3$
- Future Work
  - Only accept Earth departure asymptote declinations that are within a specified range given by the launch vehicle
  - Do not let magnitude of Δv maneuvers exceed a specified value
  - Muti-revolution Lambert targeter and incorporate gravity assists
  - Apply optimization algorithm

Appendix

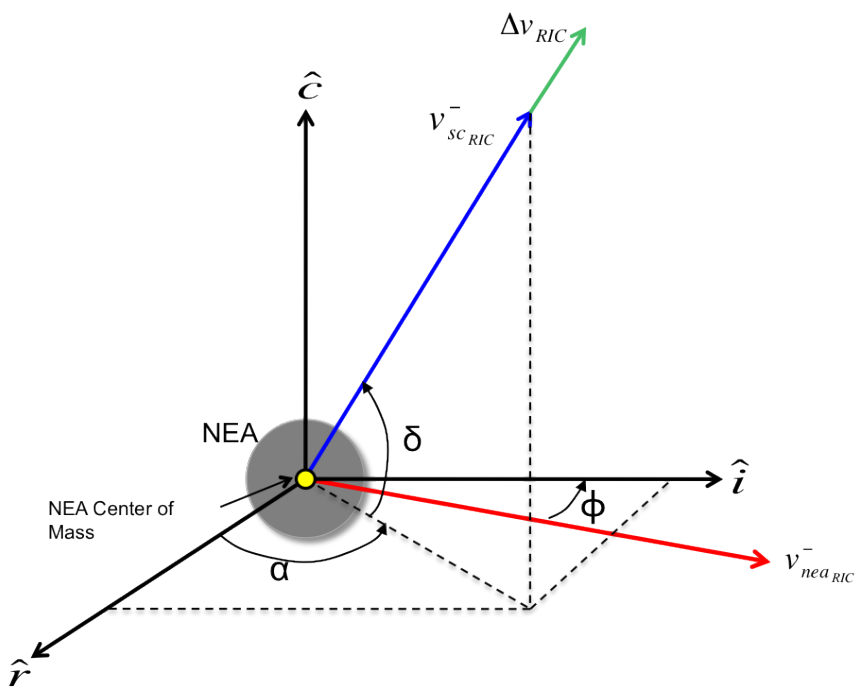
Kinetic Impactor Model

Applies an impulsive velocity change to the NEA by colliding a spacecraft with the asteroid.

1. Compute $\mathbf{\Delta V}$ imparted to a NEA
2. Compute deflection Δr

The Radial, In-Track, Cross-Track (RIC) Frame

$$\hat{\mathbf{r}} = \frac{\mathbf{r}_{nea}}{\|\mathbf{r}_{nea}\|} \qquad \hat{\mathbf{c}} = \frac{\mathbf{r}_{nea} \times \mathbf{v}_{\overline{nea}}}{\|\mathbf{r}_{nea} \times \mathbf{v}_{\overline{nea}}\|} \qquad \hat{\mathbf{i}} = \hat{\mathbf{c}} \times \hat{\mathbf{r}}$$



$$\mathbf{v}_{\overline{nea}_{RIC}} = v_{\overline{nea}} \begin{pmatrix} \sin\phi \\ \cos\phi \\ 0 \end{pmatrix}.$$

$$\mathbf{v}_{\overline{sc}_{RIC}} = v_{\overline{sc}} \begin{pmatrix} \cos\alpha\cos\delta \\ \sin\alpha\cos\delta \\ \sin\delta \end{pmatrix}$$