Orbital Simulations on the Deflection of Near Earth Objects by Directed Energy

Qicheng Zhang\textsuperscript{1},
Kevin Walsh, Carl Melis, Gary Hughes, Philip Lubin

\textsuperscript{1}Dept of Physics / College of Creative Studies,
University of California, Santa Barbara

SPIE Optics + Photonics
San Diego, CA - August 10, 2015
The Problem(s)

- Near Earth Objects (NEO)
The Problem(s)

- Near Earth Objects (NEO)
  - most are not dangerous (only needs $q < 1.3$ au)
The Problem(s)

- Near Earth Objects (NEO)
  - most are not dangerous (only needs $q < 1.3 \text{ au}$)
  - few on collision course with Earth
The Problem(s)

- Near Earth Objects (NEO)
  - most are not dangerous (only needs $q < 1.3 \text{ au}$)
  - few on collision course with Earth
- Potentially Hazardous Asteroids (PHA) - NEO subgroup
  - MOID $< 0.05 \text{ au}$, diam $\gtrsim 140 \text{ m}$

Figure: Orbits of known PHA as of 2013. Credit: NASA/JPL-Caltech
The Problem(s)

- Near Earth Objects (NEO)
  - most are not dangerous (only needs $q < 1.3$ au)
  - few on collision course with Earth
- Potentially Hazardous Asteroids (PHA) - NEO subgroup
  - MOID < 0.05 au, diam $\geq 140$ m
  - smaller asteroids still dangerous – historically common
    - *Tunguska* (1908) - $\sim 80$ m
    - *Curuçá River* (1930) - $\sim 20$ m
    - *Chelyabinsk* (2013) - $\sim 20$ m

Figure: Orbits of known PHA as of 2013. *Credit: NASA/JPL-Caltech*
Figure: "Meteor Crater" in Arizona, formed by the impact (energy $\sim 10$ MT) of a 50 m iron-nickel asteroid 50,000 years ago. Credit: NASA Earth Observatory
Solution: Laser Ablation

Figure: A laser beam heats and vaporizes material off an asteroid into a plume, generating thrust in the opposite direction.
Effectiveness of Ablation

How much thrust do we get for a given power?
Effectiveness of Ablation

How much thrust do we get for a given power?

\[ \sim 100 \, \mu\text{N/W} \leftrightarrow 10 \, \text{kW/N} \]

(from theory + lab measurements)
Effectiveness of **Thrust**

How far is an asteroid deflected by a given thrust?
Effectiveness of **Thrust**

How far is an asteroid deflected by a given thrust?

*need orbital simulations*
Numerical Model

- simple three body Newtonian system:
  1. Sun
  2. Earth
  3. asteroid
Numerical Model

- simple three body Newtonian system:
  - Sun
  - Earth
  - asteroid

- assume asteroid density of 2 g/cm³
Numerical Model

- simple three body Newtonian system:
  1. Sun
  2. Earth
  3. asteroid

- assume asteroid density of 2 g/cm$^3$

- initial conditions generation:
  1. start with Earth, asteroid at same point in space
  2. select orbital elements for asteroid, then use two body solution to (slightly) move back in time, separating the Earth and asteroid
  3. numerically integrate in reverse to laser start time
Numerical Model

- simple three body Newtonian system:
  1. Sun
  2. Earth
  3. asteroid

- assume asteroid density of 2 g/cm³

- initial conditions generation:
  1. start with Earth, asteroid at same point in space
  2. select orbital elements for asteroid, then use two body solution to (slightly) move back in time, separating the Earth and asteroid
  3. numerically integrate in reverse to laser start time

Where is the laser?
Laser Systems

DE-STAR:
“Directed Energy System for Targeting of Asteroids and exploration”
Laser Systems

DE-STAR:

“Directed Energy System for Targeting of Asteroids and Exploration”

Two main categories:
Laser Systems

**DE-STAR:**

“Directed Energy System for Targeting of Asteroids and exploration”

Two main categories:

1. **stand-on** - laser delivered to the target asteroid
Laser Systems

DE-STAR:
“Directed Energy System for Targeting of Asteroids and exploration”

Two main categories:

1. **stand-on** - laser delivered to the target asteroid
2. **stand-off** - laser targets asteroid from Earth orbit
DE-STARLITE: A Stand-On System

- laser delivered to the target asteroid
DE-STARLITE: A Stand-On System

- laser delivered to the target asteroid
  - small: 1 MW (≈100 N) system fits in SLS Block 1
DE-STARLITE: A Stand-On System

- Laser delivered to the target asteroid
  - Small: 1 MW (≈100 N) system fits in SLS Block 1
  - Delay by transit to target – a few days to many years
DE-STARLITE: A Stand-On System

- laser delivered to the target asteroid
  - small: 1 MW (~100 N) system fits in SLS Block 1
  - delay by transit to target – a few days to many years
  - easily maneuvered relative to asteroid
    - thrust may be selected to be in any direction
Stand-\textbf{On} Numerical Setup
Stand-On Numerical Setup

- assume constant $100 \, \mu \text{N/W}$
Stand-On Numerical Setup

- assume constant 100 $\mu$N/W
- direction of thrust measured relative to velocity of asteroid
Stand-On Numerical Setup

- assume constant 100 $\mu$N/W
- direction of thrust measured relative to velocity of asteroid
Stand-On Numerical Setup

- Assume constant 100 $\mu$N/W
- Direction of thrust measured relative to velocity of asteroid
Stand-On Numerical Setup

- assume constant 100 $\mu$N/W
- direction of thrust measured relative to velocity of asteroid

- consider only constant $\alpha$, $\beta$
A Hazardous Asteroid

Consider asteroid similar to 99942 Apophis:

- Diameter: 325 m
- Mass: $3.6 \times 10^{10}$ kg
- Energy released if impact: $\sim 1$ GT
A Hazardous **Asteroid**

Consider asteroid similar to 99942 Apophis:

- 325 m diameter $\implies 3.6 \times 10^{10}$ kg
A Hazardous Asteroid

Consider asteroid similar to 99942 Apophis:

- 325 m diameter $\implies 3.6 \times 10^{10}$ kg
  - $\sim 1$ GT energy released if impact
A Hazardous Asteroid

Consider asteroid similar to 99942 Apophis:

- 325 m diameter $\implies 3.6 \times 10^{10}$ kg
  - $\sim 1$ GT energy released if impact

- Orbital parameters:
  - Semi-major axis: $a = 0.92$ au
  - Eccentricity: $e = 0.19$
  - Inclination: $i = 6^\circ$
Deflection of Asteroid Over 5 Years

325 m Asteroid ($\alpha = \beta = 0^\circ$)

- Earth
- No force (Impact)
- 100 N / 1 MW (12.5 $R_\oplus$)

Time: 5,000 yr
Deflection with 100 N / 1 MW

How much time to deflect 325 m asteroid by 2 Earth radii?
Deflection with 100 N / 1 MW

How much time to deflect 325 m asteroid by 2 Earth radii?
Which direction should the thrust be in?
Deflection with **100 N / 1 MW**

How much time to deflect 325 m asteroid by 2 Earth radii? Which direction should the thrust be in?

For $\beta = 0^\circ$:
- $\alpha = 0^\circ$: 2.5 years
How much time to deflect 325 m asteroid by 2 Earth radii? Which direction should the thrust be in?

For $\beta = 0^\circ$: 
- $\alpha = 0^\circ$: 2.5 years 
- $\alpha = 45^\circ$: 3.1 years
Deflection with \textbf{100 N / 1 MW}

How much time to deflect 325 m asteroid by 2 Earth radii? Which direction should the thrust be in?

For $\beta = 0^\circ$:

- $\alpha = 0^\circ$: 2.5 years
- $\alpha = 45^\circ$: 3.1 years
- $\alpha = 90^\circ$: ?? years
Deflection with 100 N / 1 MW

How much time to deflect 325 m asteroid by 2 Earth radii? Which direction should the thrust be in?

For $\beta = 0^\circ$:

- $\alpha = 0^\circ$: 2.5 years
- $\alpha = 45^\circ$: 3.1 years
- $\alpha = 90^\circ$: ?? years
- $\alpha = 135^\circ$: 3.0 years
Deflection with 100 N / 1 MW

How much time to deflect 325 m asteroid by 2 Earth radii?
Which direction should the thrust be in?

For $\beta = 0^\circ$:
- $\alpha = 0^\circ$: 2.5 years
- $\alpha = 45^\circ$: 3.1 years
- $\alpha = 90^\circ$: ?? years
- $\alpha = 135^\circ$: 3.0 years
Deflection with 100 N / 1 MW

How much time to deflect 325 m asteroid by 2 Earth radii? Which direction should the thrust be in?

For $\beta = 0^\circ$:
- $\alpha = 0^\circ$: 2.5 years
- $\alpha = 45^\circ$: 3.1 years
- $\alpha = 90^\circ$: ?? years
- $\alpha = 135^\circ$: 3.0 years

For $\alpha = 0^\circ$:
- $\beta = 0^\circ$: 2.5 years
How much time to deflect 325 m asteroid by 2 Earth radii? Which direction should the thrust be in?

For $\beta = 0^\circ$:
- $\alpha = 0^\circ$: 2.5 years
- $\alpha = 45^\circ$: 3.1 years
- $\alpha = 90^\circ$: ?? years
- $\alpha = 135^\circ$: 3.0 years

For $\alpha = 0^\circ$:
- $\beta = 0^\circ$: 2.5 years
- $\beta = 45^\circ$: 3.0 years
Deflection with 100 N / 1 MW

How much time to deflect 325 m asteroid by 2 Earth radii? Which direction should the thrust be in?

For $\beta = 0^\circ$:
- $\alpha = 0^\circ$: 2.5 years
- $\alpha = 45^\circ$: 3.1 years
- $\alpha = 90^\circ$: ?? years
- $\alpha = 135^\circ$: 3.0 years

For $\alpha = 0^\circ$:
- $\beta = 0^\circ$: 2.5 years
- $\beta = 45^\circ$: 3.0 years
- $\beta = 90^\circ$: ?? years
How much time to deflect 325 m asteroid by 2 Earth radii? Which direction should the thrust be in?

For $\beta = 0^\circ$:
- $\alpha = 0^\circ$: 2.5 years
- $\alpha = 45^\circ$: 3.1 years
- $\alpha = 90^\circ$: ?? years
- $\alpha = 135^\circ$: 3.0 years

For $\alpha = 0^\circ$:
- $\beta = 0^\circ$: 2.5 years
- $\beta = 45^\circ$: 3.0 years
- $\beta = 90^\circ$: ?? years
Deflection with **Smaller Lasers** and **More Time**

What if we had more time? How big of a laser do we need then?

\[100 \mu N/W \leftrightarrow 10 \text{ kW/N}\]
Deflection with **Smaller Lasers** and **More Time**

What if we had more time? How big of a laser do we need then?

\(100 \, \mu\text{N/W} \leftrightarrow 10 \, \text{kW/N}\)

Using \(\alpha = \beta = 0^\circ\):

- \(\Delta t = 5\) years:
  - need 26 N / 260 kW
What if we had more time? How big of a laser do we need then?

\[(100 \, \mu\text{N/W} \leftrightarrow 10 \, \text{kW/N})\]

Using \(\alpha = \beta = 0^\circ\):
- \(\Delta t = 5\) years:
  need 26 N / 260 kW
- \(\Delta t = 10\) years:
  need 6 N / 60 kW
Deflection with **Smaller Lasers and More Time**

What if we had more time? How big of a laser do we need then?  
\[(100 \ \mu N/W \leftrightarrow 10 \ \text{kHz/N})\]

Using \( \alpha = \beta = 0^\circ \):

- \( \Delta t = 5 \ \text{years} \):
  - need 26 N / 260 kW

- \( \Delta t = 10 \ \text{years} \):
  - need 6 N / 60 kW

- \( \Delta t = 15 \ \text{years} \):
  - need 2 N / 20 kW
Consider a Tunguska-class asteroid:
Consider a Tunguska-class asteroid:

- 80 m diameter $\implies 5.4 \times 10^8$ kg
Consider a Tunguska-class asteroid:

- 80 m diameter $\implies 5.4 \times 10^8$ kg
- $\sim 15$ MT energy released if impact
Small Asteroid

Consider a Tunguska-class asteroid:

- 80 m diameter $\implies 5.4 \times 10^8$ kg
  - $\sim 15$ MT energy released if impact
- use Apophis-like orbital parameters as before
Small Asteroid Deflection with 100 N / 1 MW

How much time to deflect 80 m asteroid by 2 Earth radii? Which direction should the thrust be in?
Small Asteroid Deflection with 100 N / 1 MW

How much time to deflect 80 m asteroid by 2 Earth radii? Which direction should the thrust be in?

For $\beta = 0^\circ$:
- $\alpha = 0^\circ$: 0.45 years
Small Asteroid Deflection with 100 N / 1 MW

How much time to deflect 80 m asteroid by 2 Earth radii? Which direction should the thrust be in?

For $\beta = 0^\circ$:
- $\alpha = 0^\circ$: 0.45 years
- $\alpha = 45^\circ$: 0.57 years
Small Asteroid Deflection with **100 N / 1 MW**

How much time to deflect 80 m asteroid by 2 Earth radii? Which direction should the thrust be in?

For $\beta = 0^\circ$:
- $\alpha = 0^\circ$: 0.45 years
- $\alpha = 45^\circ$: 0.57 years
- $\alpha = 90^\circ$: 0.45 years
Small Asteroid Deflection with 100 N / 1 MW

How much time to deflect 80 m asteroid by 2 Earth radii? Which direction should the thrust be in?

For $\beta = 0^\circ$:

- $\alpha = 0^\circ$: 0.45 years
- $\alpha = 45^\circ$: 0.57 years
- $\alpha = 90^\circ$: 0.45 years
- $\alpha = 135^\circ$: 0.4 years
How much time to deflect 80 m asteroid by 2 Earth radii?
Which direction should the thrust be in?

For $\beta = 0^\circ$:
- $\alpha = 0^\circ$: 0.45 years
- $\alpha = 45^\circ$: 0.57 years
- $\alpha = 90^\circ$: 0.45 years
- $\alpha = 135^\circ$: 0.4 years
Small Asteroid Deflection with **100 N / 1 MW**

How much time to deflect 80 m asteroid by 2 Earth radii? Which direction should the thrust be in?

For $\beta = 0^\circ$:
- $\alpha = 0^\circ$: 0.45 years
- $\alpha = 45^\circ$: 0.57 years
- $\alpha = 90^\circ$: 0.45 years
- $\alpha = 135^\circ$: 0.4 years

For $\alpha = 0^\circ$:
- $\beta = 0^\circ$: 0.45 years
Small Asteroid Deflection with 100 N / 1 MW

How much time to deflect 80 m asteroid by 2 Earth radii? Which direction should the thrust be in?

For $\beta = 0^\circ$:
- $\alpha = 0^\circ$: 0.45 years
- $\alpha = 45^\circ$: 0.57 years
- $\alpha = 90^\circ$: 0.45 years
- $\alpha = 135^\circ$: 0.4 years

For $\alpha = 0^\circ$:
- $\beta = 0^\circ$: 0.45 years
- $\beta = 45^\circ$: 0.47 years
Small Asteroid Deflection with 100 N / 1 MW

How much time to deflect 80 m asteroid by 2 Earth radii?  
Which direction should the thrust be in?

For $\beta = 0^\circ$:
- $\alpha = 0^\circ$: 0.45 years
- $\alpha = 45^\circ$: 0.57 years
- $\alpha = 90^\circ$: 0.45 years
- $\alpha = 135^\circ$: 0.4 years

For $\alpha = 0^\circ$:
- $\beta = 0^\circ$: 0.45 years
- $\beta = 45^\circ$: 0.47 years
- $\beta = 90^\circ$: ?? years
Small Asteroid Deflection with **100 N / 1 MW**

How much time to deflect 80 m asteroid by 2 Earth radii? Which direction should the thrust be in?

For $\beta = 0^\circ$:
- $\alpha = 0^\circ$: 0.45 years
- $\alpha = 45^\circ$: 0.57 years
- $\alpha = 90^\circ$: 0.45 years
- $\alpha = 135^\circ$: 0.4 years

For $\alpha = 0^\circ$:
- $\beta = 0^\circ$: 0.45 years
- $\beta = 45^\circ$: 0.47 years
- $\beta = 90^\circ$: ?? years
Optimal Thrust Direction

How does optimal thrust direction change?
Optimal Thrust Direction

How does optimal thrust direction change?

For $\beta = 0^\circ$:
- $\Delta t = 0.3$ years: optimal $\alpha = 100^\circ$
Optimal Thrust Direction

How does optimal thrust direction change?

For $\beta = 0^\circ$:

- $\Delta t = 0.3$ years: optimal $\alpha = 100^\circ$
- $\Delta t = 0.5$ years: optimal $\alpha = 140^\circ$
Optimal Thrust Direction

How does optimal thrust direction change?

For $\beta = 0^\circ$:

- $\Delta t = 0.3$ years: optimal $\alpha = 100^\circ$
- $\Delta t = 0.5$ years: optimal $\alpha = 140^\circ$
- $\Delta t = 0.7$ years: optimal $\alpha = 160^\circ$
Optimal Thrust Direction

How does optimal thrust direction change?

For $\beta = 0^\circ$:
- $\Delta t = 0.3$ years: optimal $\alpha = 100^\circ$
- $\Delta t = 0.5$ years: optimal $\alpha = 140^\circ$
- $\Delta t = 0.7$ years: optimal $\alpha = 160^\circ$
- $\Delta t = 0.9$ years: optimal $\alpha = 170^\circ$
How does optimal thrust direction change?

For \( \alpha = 0^\circ \):

- \( \Delta t = 0.3 \) years:
  - optimal \( \beta = 65^\circ \)
Optimal Thrust Direction

How does optimal thrust direction change?

For $\alpha = 0^\circ$:

- $\Delta t = 0.3$ years: optimal $\beta = 65^\circ$
- $\Delta t = 0.5$ years: optimal $\beta = 5^\circ$
Optimal Thrust Direction

How does optimal thrust direction change?

For $\alpha = 0^\circ$:
- $\Delta t = 0.3$ years: optimal $\beta = 65^\circ$
- $\Delta t = 0.5$ years: optimal $\beta = 5^\circ$
- $\Delta t = 0.7$ years: optimal $\beta \approx 0^\circ$
Optimal Thrust Direction

How does optimal thrust direction change?

For $\alpha = 0^\circ$:

- $\Delta t = 0.3$ years: optimal $\beta = 65^\circ$
- $\Delta t = 0.5$ years: optimal $\beta = 5^\circ$
- $\Delta t = 0.7$ years: optimal $\beta \approx 0^\circ$
- $\Delta t = 0.9$ years: optimal $\beta \approx 0^\circ$
How about with other orbits?
Effects of Eccentricity

How does *eccentricity* affect deflection? \((\alpha = \beta = 0^\circ)\)
Effects of Eccentricity

How does *eccentricity* affect deflection? \((\alpha = \beta = 0^\circ)\)
Effects of Eccentricity

How does *eccentricity* affect deflection? \((\alpha = \beta = 0^\circ)\)

![Graph showing the effects of eccentricity on miss distance](image)
Effects of Eccentricity

How does eccentricity affect deflection? ($\alpha = \beta = 0^\circ$)

![Graph showing the effects of eccentricity on deflection](image-url)
How does *eccentricity* affect deflection? \( (\alpha = \beta = 0^\circ) \)
Effects of Eccentricity

How does eccentricity affect deflection? ($\alpha = \beta = 0^\circ$)

- 50% drop in effectiveness from $e = 0.2$ to $e = 0.11$
Effects of Eccentricity

How does eccentricity affect deflection? \((\alpha = \beta = 0^\circ)\)

- 50% drop in effectiveness from \(e = 0.2\) to \(e = 0.11\)
- Slower decay in effectiveness for \(e > 0.25\)
Effects of Inclination

How does inclination affect deflection? \((\alpha = \beta = 0^\circ)\)
How does \textit{inclination} affect deflection? \((\alpha = \beta = 0^\circ)\)

80 m Asteroid, 100 N Thrust - 0° Thrust

\begin{itemize}
  \item Miss Distance (Earth radii)
  \item Inclination (°)
\end{itemize}
How does *inclination* affect deflection? ($\alpha = \beta = 0^\circ$)
Effects of Inclination

How does inclination affect deflection? \( (\alpha = \beta = 0^\circ) \)

80 m Asteroid, 100 N Thrust - 0° Thrust

- 0.45 yr active
- 0.55 yr active
- 0.6 yr active

Miss Distance (Earth radii) vs Inclination (°)

Graph showing the effect of inclination on miss distance for different active periods with an asteroid of 80 m radius, thrust of 100 N and initial inclination of 0°. The graph illustrates how the miss distance changes with increasing inclination for three different active periods.
Effects of Inclination

How does inclination affect deflection? ($\alpha = \beta = 0^\circ$)

![Graph showing miss distance as a function of inclination for different time periods with 80 m asteroid and 100 N thrust]
Effects of Inclination

How does \textit{inclination} affect deflection? ($\alpha = \beta = 0^\circ$)

- some decay for $i < 30^\circ$ and $i > 40^\circ$
Effects of **Inclination**

How does *inclination* affect deflection? \( \alpha = \beta = 0^\circ \)

- some decay for \( i < 30^\circ \) and \( i > 40^\circ \)
- dependence weaker than with eccentricity
low eccentricity, low inclination *preferred*
low eccentricity, low inclination *preferred* (low $\Delta v$ for stand-on laser to reach target)
low eccentricity, low inclination preferred
(low $\Delta v$ for stand-on laser to reach target)

reminder: orbit generally not a choice
DE-STAR Stand-Off System

- Laser targets asteroid from Earth orbit.
DE-STAR Stand-Off System

- laser targets asteroid from Earth orbit
  - immediate response to threat
DE-STAR Stand-Off System

- Laser targets asteroid from Earth orbit
  - Immediate response to threat
  - Can target objects in any orbit
DE-STAR Stand-Off System

- laser targets asteroid from Earth orbit
  - immediate response to threat
  - can target objects in any orbit
  - no control over thrust direction
DE-STAR Stand-Off System

- laser targets asteroid from Earth orbit
  - immediate response to threat
  - can target objects in any orbit
  - no control over thrust direction
  - far from target: beam diverges $\implies$ flux decreases
Stand-Off Range

Range is limited by flux density after beam divergence.
Stand-Off Range

Range is limited by flux density after beam divergence. (need $\sim 10^7$ W/m$^2$ to ablate most rock)

Flux from Laser Arrays at 50% Efficiency

- Rock Vaporization
**Stand-Off Range**

Range is limited by flux density after beam divergence. (need $\sim 10^7$ W/m$^2$ to ablate most rock)

Ablation range:
- 500 m array:
  - 0.008 au ($\sim 3$ LD)
Stand-Off Range

Range is limited by flux density after beam divergence.
(need $\sim 10^7$ W/m$^2$ to ablate most rock)

Ablation range:
- 500 m array: 0.008 au (≈ 3 LD)
- 1 km array: 0.03 au (≈ 12 LD)
Stand-Off Range

Range is limited by flux density after beam divergence. (need $\sim 10^7$ W/m$^2$ to ablate most rock)

Ablation range:
- 500 m array: $0.008$ au ($\sim 3$ LD)
- 1 km array: $0.03$ au ($\sim 12$ LD)
- 2 km array: $0.1$ au ($\sim 40$ LD)
Stand-Off Range

Range is limited by flux density after beam divergence. (need $\sim 10^7 \text{ W/m}^2$ to ablate most rock)

Ablation range:
- 500 m array: 0.008 au ($\sim 3 \text{ LD}$)
- 1 km array: 0.03 au ($\sim 12 \text{ LD}$)
- 2 km array: 0.1 au ($\sim 40 \text{ LD}$)

BIG array needed
Stand-Off Numerical Setup

- square solar array, same width $D$ as laser array
Stand-Off Numerical Setup

- square solar array, same width $D$ as laser array
  - 1360 W/m$^2$ in Earth orbit
  - 50% efficiency: solar $\rightarrow$ laser
Stand-Off Numerical Setup

- square solar array, same width $D$ as laser array
  - 1360 W/m$^2$ in Earth orbit
  - 50% efficiency: solar $\rightarrow$ laser
- beam divergence half angle $\lambda/D$
  - circular spot with uniform illumination
Stand-Off Numerical Setup

- square solar array, same width $D$ as laser array
  - 1360 W/m$^2$ in Earth orbit
  - 50% efficiency: solar $\rightarrow$ laser
- beam divergence half angle $\lambda/D$
  - circular spot with uniform illumination
- thrust on asteroid directed away from Earth
**Stand-Off Numerical Setup**

- square solar array, same width $D$ as laser array
  - 1360 W/m$^2$ in Earth orbit
  - 50% efficiency: solar $\rightarrow$ laser
- beam divergence half angle $\lambda/D$
  - circular spot with uniform illumination
- thrust on asteroid directed away from Earth
  - no thrust when out of range
Stand-Off Numerical Setup

- Square solar array, same width $D$ as laser array
  - 1360 W/m² in Earth orbit
  - 50% efficiency: solar $\rightarrow$ laser
- Beam divergence half angle $\lambda/D$
  - Circular spot with uniform illumination
- Thrust on asteroid directed away from Earth
  - No thrust when out of range
  - Reduced thrust when spot is bigger than target
Stand-Off Numerical Setup

- square solar array, same width $D$ as laser array
  - 1360 W/m² in Earth orbit
  - 50% efficiency: solar $\rightarrow$ laser
- beam divergence half angle $\lambda/D$
  - circular spot with uniform illumination
- thrust on asteroid directed away from Earth
  - no thrust when out of range
  - reduced thrust when spot is bigger than target
  - only turn on if Earth is ahead or behind the target
Stand-Off Modes

(a) Earth behind
Stand-Off Modes

(a) Earth behind
(b) Earth ahead
Stand-Off Effectiveness

How big of an asteroid can we deflect by 2 Earth radii?
Stand-Off Effectiveness

How big of an asteroid can we deflect by 2 Earth radii?

- 400 m array: none
How big of an asteroid can we deflect by 2 Earth radii?

- 400 m array: none
- 600 m array: 15 m
Stand-Off Effectiveness

How big of an asteroid can we deflect by 2 Earth radii?

- 400 m array: none
- 600 m array: 15 m
- 800 m array: 30 m
Stand-Off Effectiveness

How big of an asteroid can we deflect by 2 Earth radii?

- 400 m array: none
- 600 m array: 15 m
- 800 m array: 30 m
- 1.2 km array: 100 m
How big of an asteroid can we deflect by 2 Earth radii?

- 400 m array: none
- 600 m array: 15 m
- 800 m array: 30 m
- 1.2 km array: 100 m
- 1.6 km array: 250 m
Stand-Off Effectiveness

How big of an asteroid can we deflect by 2 Earth radii?

- 400 m array: none
- 600 m array: 15 m
- 800 m array: 30 m
- 1.2 km array: 100 m
- 1.6 km array: 250 m
- 2 km array: 1 km
*reminder*: simulation assumes **constant mass**
*reminder:* simulation assumes **constant mass**

(not accurate for very small asteroids)
A Typical Comet

- high eccentricity, high inclination orbit
  - consider $e = 0.98$, $i = 130^\circ$, $q = 0.8$ au
A Typical **Comet**

- high eccentricity, high inclination orbit
  - consider $e = 0.98$, $i = 130^\circ$, $q = 0.8$ au
  - typically $\Delta v \sim 70$ km/s from Earth to comet
  - stand-on mission *not* practical
A Typical Comet

- high eccentricity, high inclination orbit
  - consider $e = 0.98$, $i = 130^\circ$, $q = 0.8$ au
  - typically $\Delta v \sim 70$ km/s from Earth to comet
  - stand-on mission not practical
- large fraction ($\sim 50\%$) water ice
  - low vaporization flux $\sim 300$ W/m$^2$
Stand-Off Range for Comets

Need flux density $\sim 300$ W/m$^2$ to ablate water ice.
Stand-Off Range for Comets

Need flux density $\sim 300 \text{ W/m}^2$ to ablate water ice.

Ablation range:
- 500 m array: 1 au
- 1 km array: 5 au
- 2 km array: 20 au
Stand-Off Range for Comets

Need flux density $\sim 300 \text{ W/m}^2$ to ablate water ice.

Ablation range:
- 500 m array: 1 au
- 1 km array: 5 au
- 2 km array: 20 au
- Sun: 2 au
Stand-Off Range for Comets

Need flux density $\sim 300 \text{ W/m}^2$ to ablate water ice.

Ablation range:
- 500 m array: 1 au
- 1 km array: 5 au
- 2 km array: 20 au
- Sun: 2 au
farther for other volatiles
Comet Deflection in Action

Deflection of Comet Over 2 Years

500 m Comet (Stand-Off)

Earth
No force (Impact)
1 km array (32.9 R_e)

Time: T-2,000 yr
Comet Deflection Effectiveness

How big of a comet can we deflect by 5 Earth radii?
Comet Deflection Effectiveness

How big of a comet can we deflect by 5 Earth radii?

- 200 m array: none
Comet Deflection Effectiveness

How big of a comet can we deflect by 5 Earth radii?

- 200 m array: none
- 400 m array: 80 m
How big of a comet can we deflect by 5 Earth radii?

- 200 m array: none
- 400 m array: 80 m
- 600 m array: 450 m
Comet Deflection Effectiveness

How big of a comet can we deflect by 5 Earth radii?

- 200 m array: none
- 400 m array: 80 m
- 600 m array: 450 m
- 800 m array: 1.4 km
Comet Deflection Effectiveness

How big of a comet can we deflect by 5 Earth radii?

- 200 m array: none
- 400 m array: 80 m
- 600 m array: 450 m
- 800 m array: 1.4 km
- 1 km array: 2 km
Stand-On vs. Stand-Off

...
Stand-On vs. Stand-Off

- near future: stand-on
Stand-On vs. Stand-Off

- Near future: stand-on
  - Small - single launch possible
Stand-On vs. Stand-Off

- near future: stand-on
  - small - single launch possible
  - handles all asteroidal threats given sufficient time
Stand-On vs. Stand-Off

- near future: stand-on
  - small - single launch possible
  - handles all asteroidal threats given sufficient time
- in a while: stand-off
Stand-On vs. Stand-Off

- **near future:** stand-on
  - small - single launch possible
  - handles all asteroidal threats given sufficient time
- **in a while:** stand-off
  - must be **BIG** to be of use in deflection
Stand-On vs. Stand-Off

- near future: stand-on
  - small - single launch possible
  - handles all asteroidal threats given sufficient time
- in a while: stand-off
  - must be BIG to be of use in deflection
  - operates on short timescales
Stand-On vs. Stand-Off

- near future: stand-on
  - small - single launch possible
  - handles all asteroidal threats given sufficient time

- in a while: stand-off
  - must be BIG to be of use in deflection
  - operates on short timescales
  - necessary for deflecting long period comets
Keys to Success

Early detection / threat confirmation

Prepare system in advance

Otherwise, much more powerful lasers (expensive)
Keys to Success

- Early detection / threat confirmation
Keys to Success

- Early detection / threat confirmation
- Prepare system in advance
Keys to Success

- Early detection / threat confirmation
- Prepare system in advance
- Otherwise, much more powerful lasers (expensive)
Acknowledgements

- Kevin Walsh
- Carl Melis
- Gary Hughes
- Philip Lubin

- Duncan, Levison, Lee - *Symplectic Massive Body Algorithm* (SyMBA)
- NASA Space Grant: NASA NNX10AT93H
Acknowledgements

- Kevin Walsh
- Carl Melis
- Gary Hughes
- Philip Lubin

- Duncan, Levison, Lee - Symplectic Massive Body Algorithm (SyMBA)
- NASA Space Grant: NASA NNX10AT93H

Code: http://github.com/ucsbdeepspace

UCSB Experimental Cosmology Group
deespace.ucsb.edu