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

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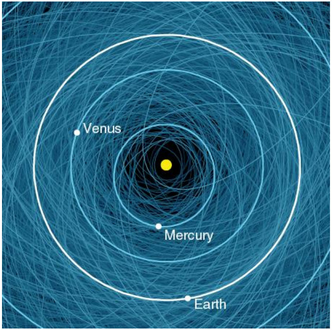

Figure: Orbits of known PHA as of 2013. *Credit: NASA/JPL-Caltech*

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  - 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 $\gtrsim 140$ m
  - smaller asteroids still dangerous – historically common
    - *Tunguska* (1908) - ~ 80 m
    - *Curuçá River* (1930) - ~ 20 m
    - *Chelyabinsk* (2013) - ~ 20 m

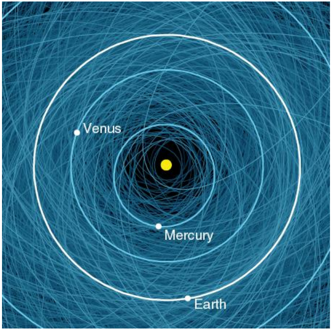

Figure: Orbits of known PHA as of 2013. *Credit: NASA/JPL-Caltech*

Barringer Crater

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.

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How much thrust do we get for a given power?

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$$\sim 100\ \mu\text{N/W} \leftrightarrow 10\ \text{kW/N}$$

(from theory + lab measurements)

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How far is an asteroid deflected by a given thrust?

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need orbital simulations

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Where is the laser?

Laser Systems

DE-STAR:
"**D**irected **E**nergy **S**ystem for **T**argeting of **A**steroids and exploRation"

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1. stand-**on** - laser delivered to the target asteroid
2. stand-**off** - laser targets asteroid from Earth orbit

DE-STARLITE: A Stand-**On** System

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  - small: 1 MW ($\sim$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

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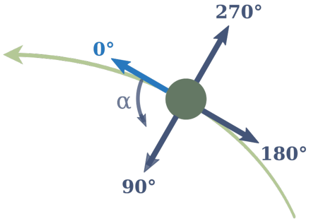

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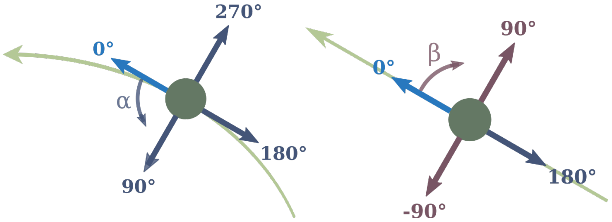

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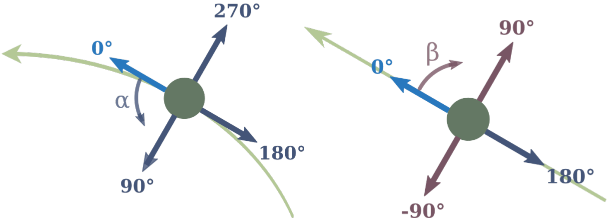

- consider only constant α, β

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Consider asteroid similar to 99942 Apophis:

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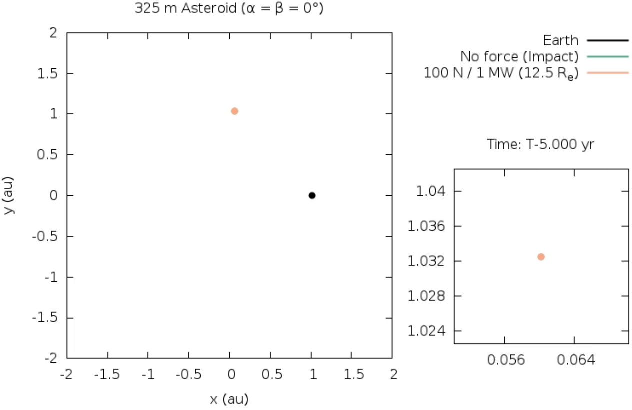
- 325 m diameter $\implies 3.6 \times 10^{10}$ kg
  - ~ 1 GT energy released if impact
- orbital parameters:
  - semi-major axis: $a = 0.92$ au
  - eccentricity: $e = 0.19$
  - inclination: $i = 6^\circ$

Stand-**On** System in Action

Deflection of Asteroid Over 5 Years



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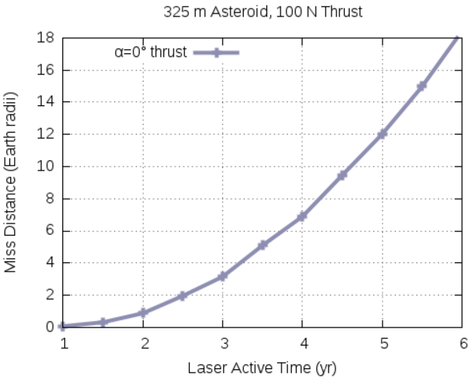

For $\beta = 0°$:

- $\alpha = 0°$: 2.5 years

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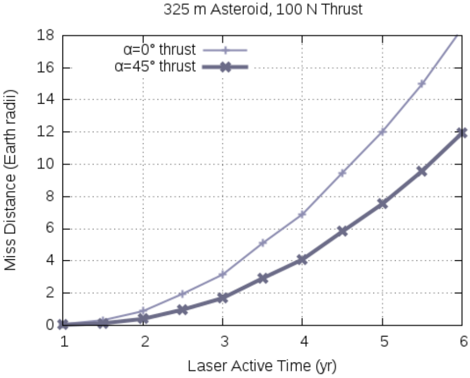

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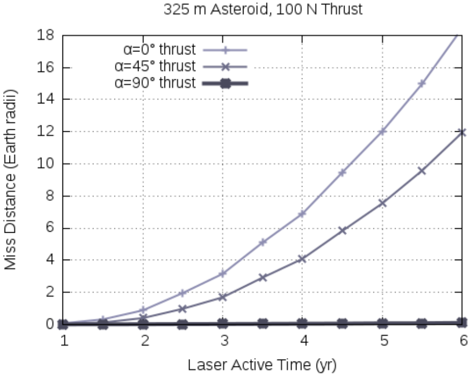

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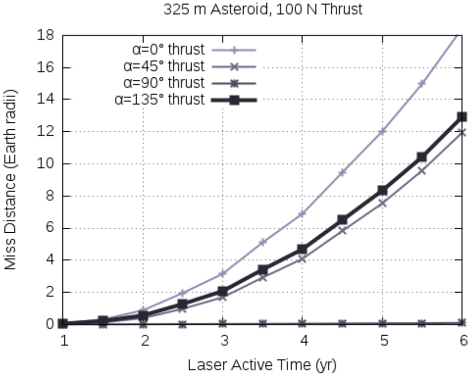

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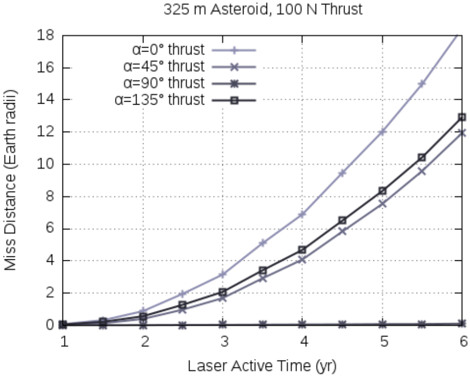

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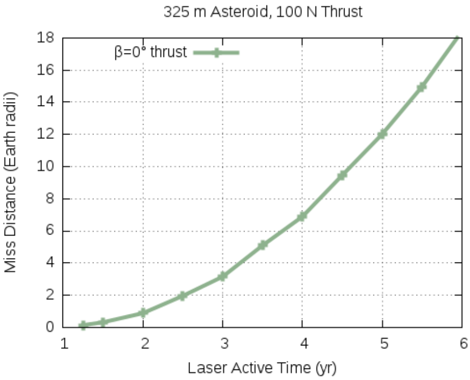

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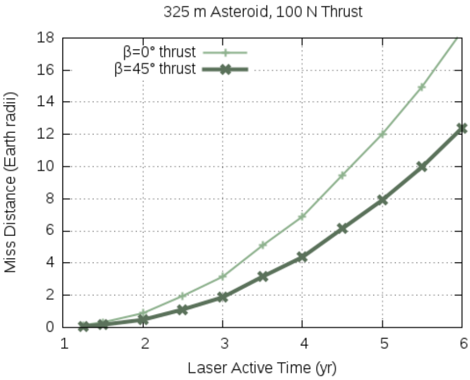

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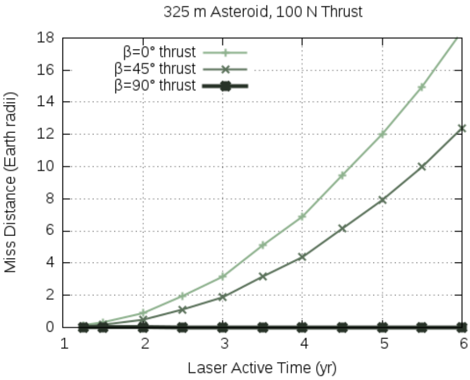

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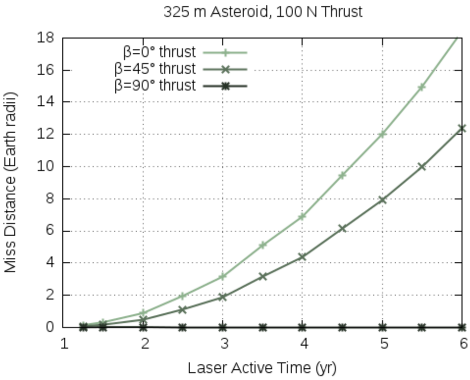

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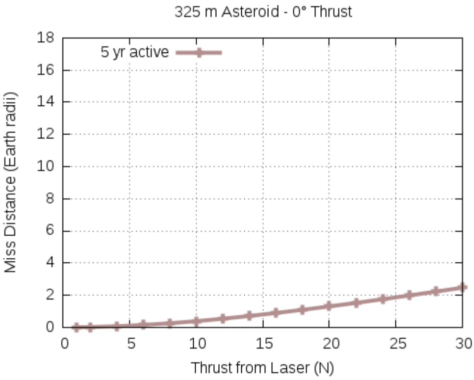

Using $\alpha = \beta = 0°$:

- $\Delta t = 5$ years:
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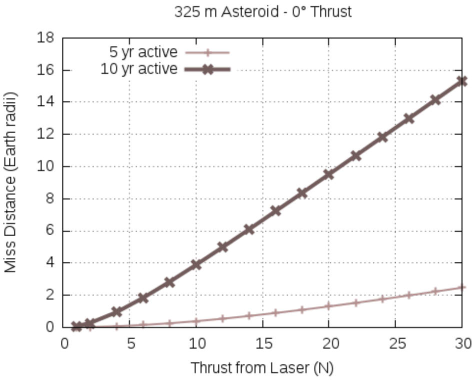

Using $\alpha = \beta = 0°$:

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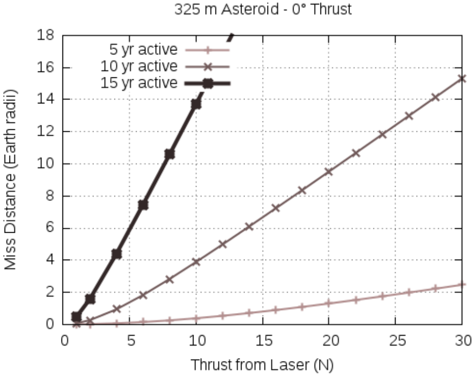

Using $\alpha = \beta = 0°$:

- $\Delta t = 5$ years: need 26 N / 260 kW
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- $\Delta t = 15$ years: need 2 N / 20 kW

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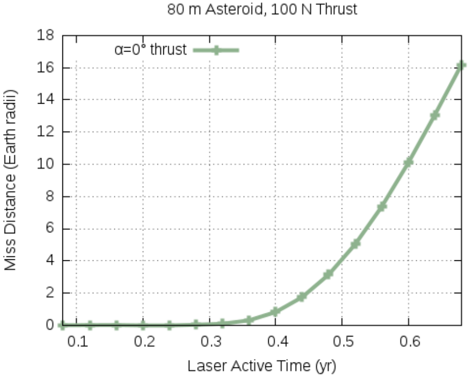

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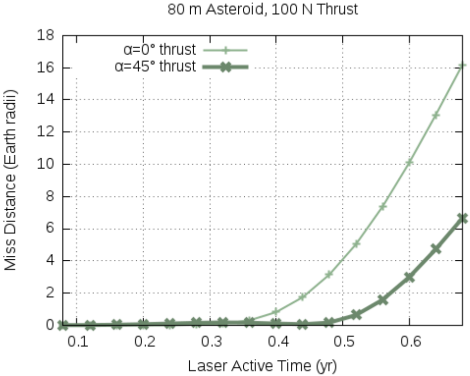

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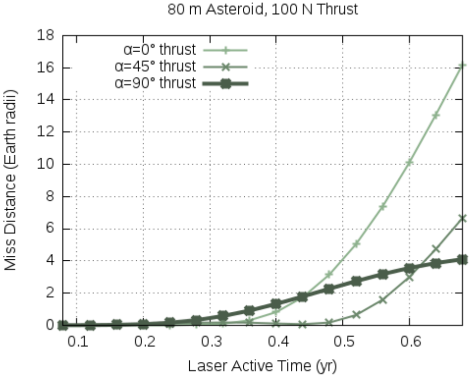

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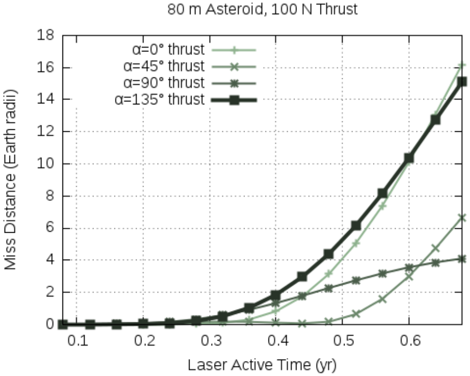

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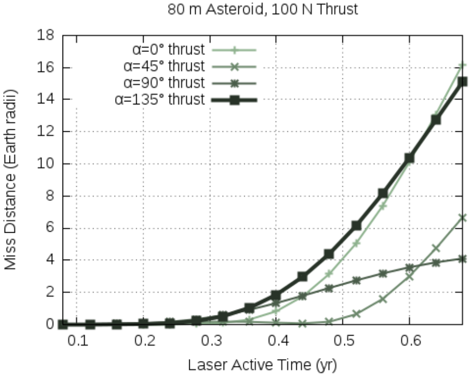

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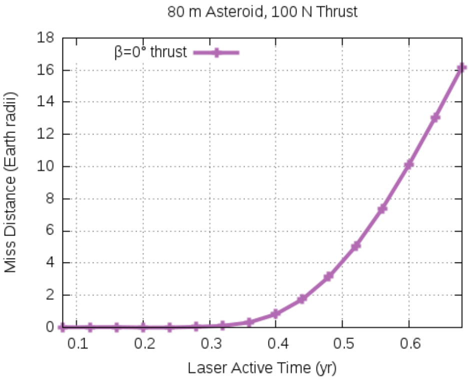

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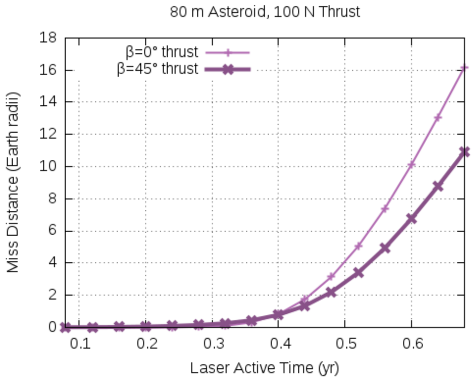

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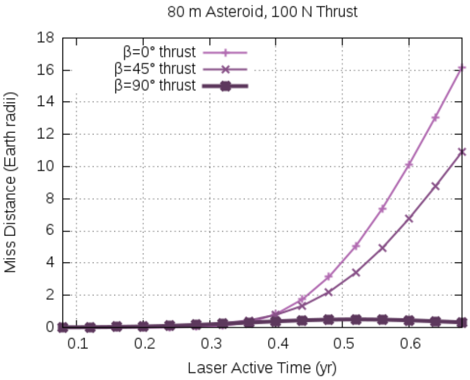

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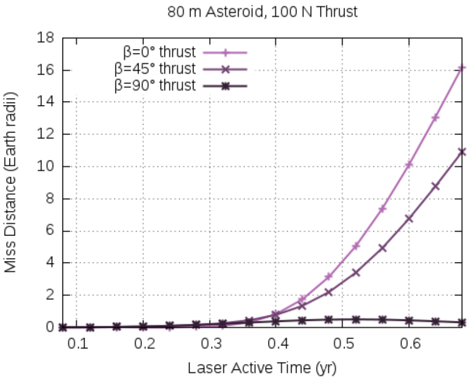

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Optimal Thrust Direction

How does optimal thrust direction change?

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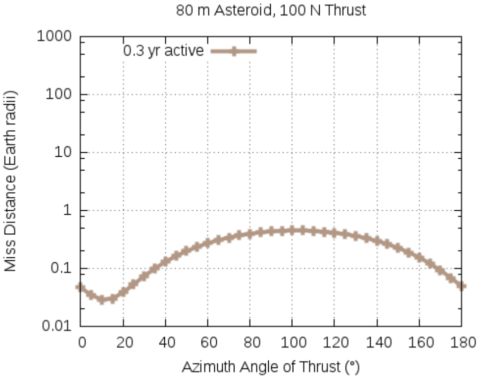

For $\beta = 0°$:

- $\Delta t = 0.3$ years: optimal $\alpha = 100°$

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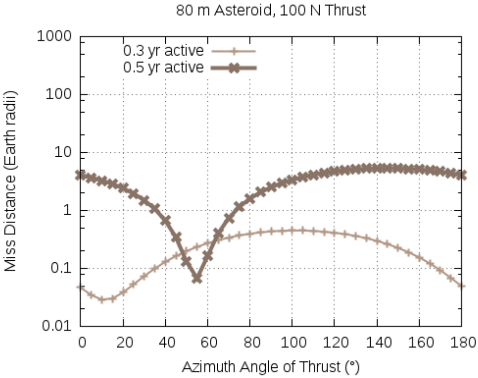

For $\beta = 0^\circ$:

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

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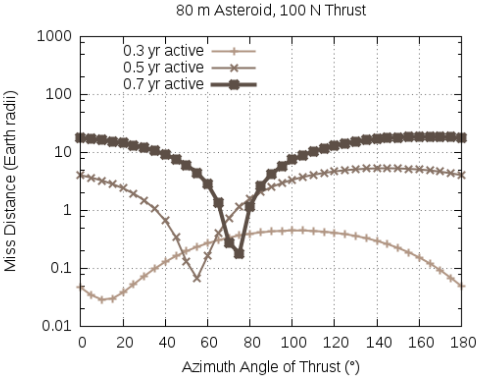

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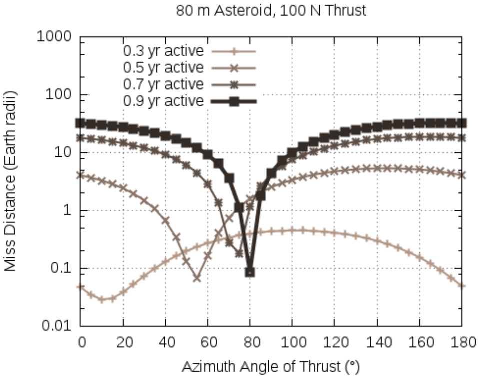

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- $\Delta t = 0.9$ years: optimal $\alpha = 170^\circ$

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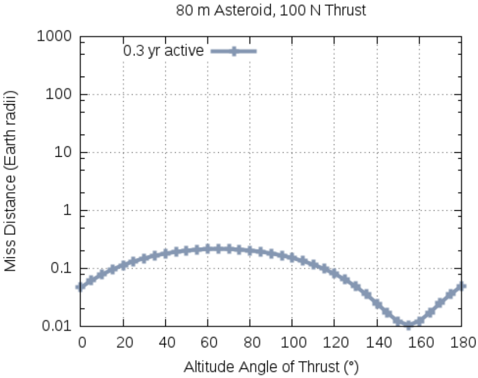
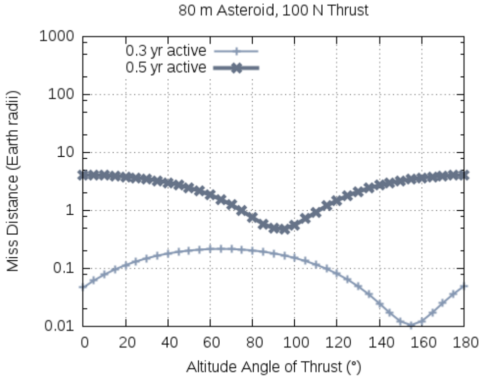


For $\alpha = 0°$:

- $\Delta t = 0.3$ years: optimal $\beta = 65°$

Optimal Thrust Direction

How does optimal thrust direction change?



For $\alpha = 0°$:

- $\Delta t = 0.3$ years: optimal $\beta = 65°$
- $\Delta t = 0.5$ years: optimal $\beta = 5°$

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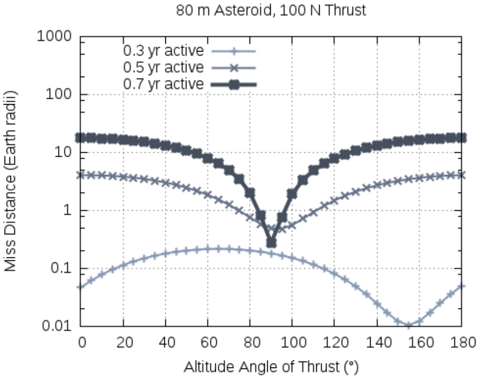

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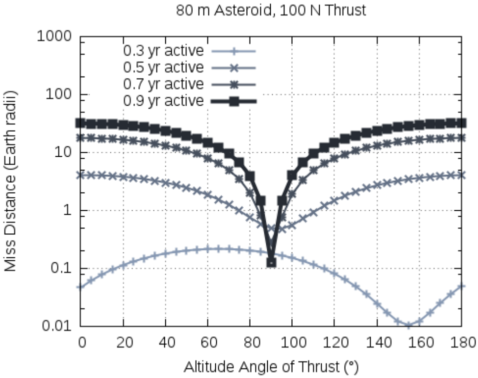

For $\alpha = 0^\circ$:

- $\Delta t = 0.3$ years: optimal $\beta = 65^\circ$
- $\Delta t = 0.5$ years: optimal $\beta = 5^\circ$
- $\Delta t = 0.7$ years: optimal $\beta =\sim 0^\circ$
- $\Delta t = 0.9$ years: optimal $\beta =\sim 0^\circ$

How about with other orbits?

Effects of **Eccentricity**

How does *eccentricity* affect deflection? $(\alpha = \beta = 0°)$

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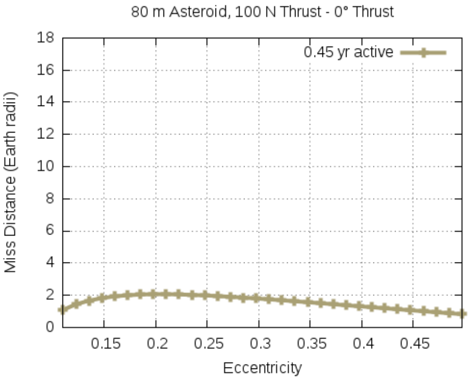

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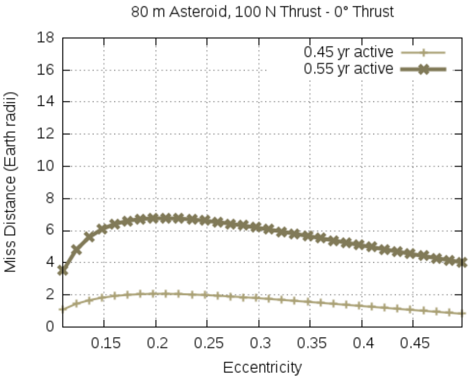

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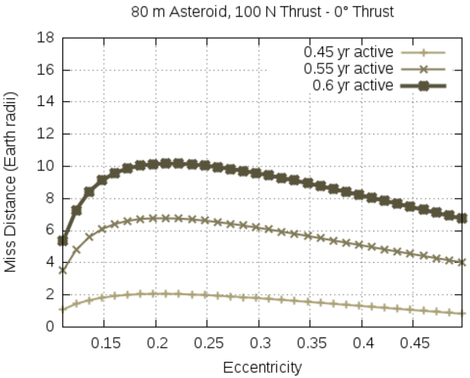

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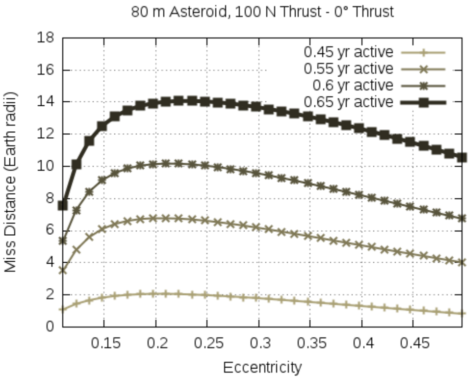

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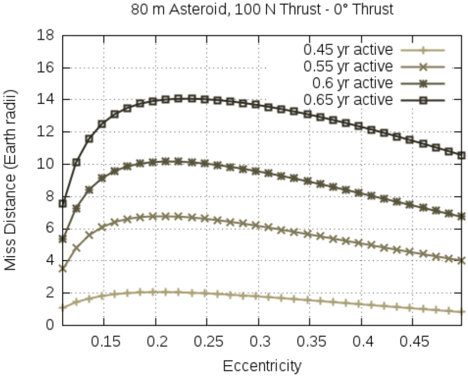

- 50% drop in effectiveness from $e = 0.2$ to $e = 0.11$

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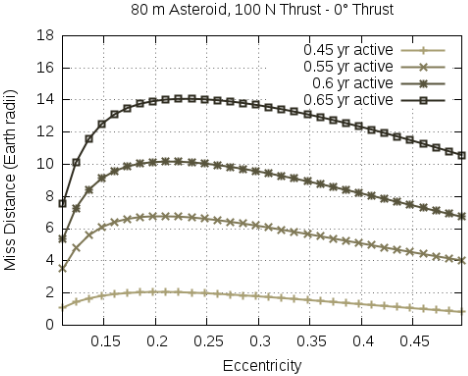

- 50% drop in effectiveness from $e = 0.2$ to $e = 0.11$
- slower decay in effectiveness for $e > 0.25$

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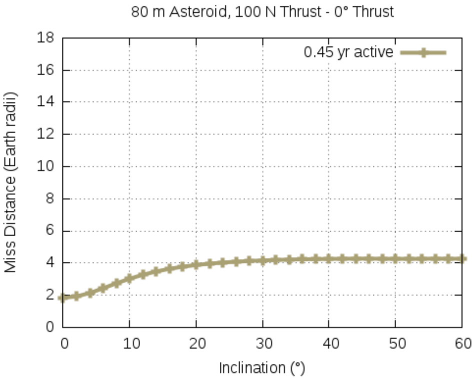

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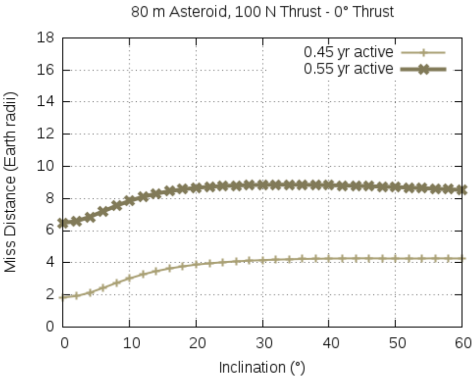

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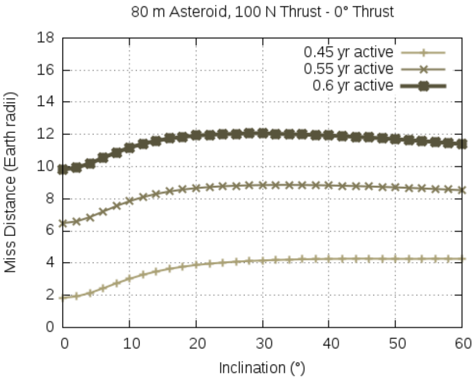

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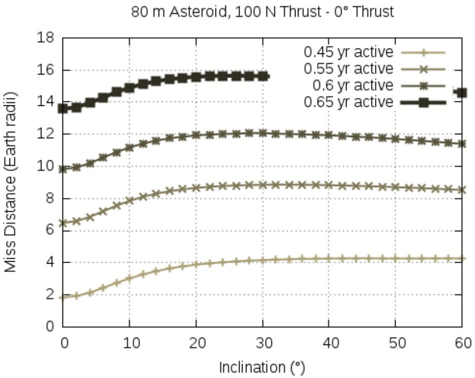

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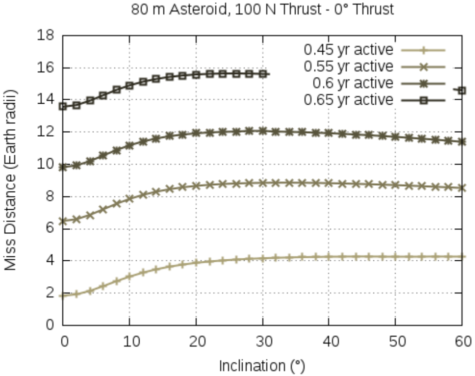

- some decay for $i < 30°$ and $i > 40°$

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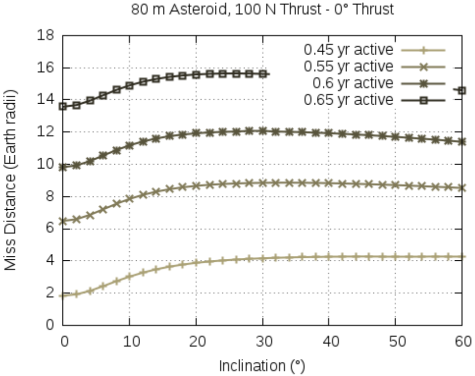

- some decay for $i < 30^\circ$ and $i > 40^\circ$
- dependence weaker than with eccentricity

low eccentricity, low inclination *preferred*

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reminder: orbit generally not a choice

DE-STAR Stand-**Off** System

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Range is limited by flux density after beam divergence.

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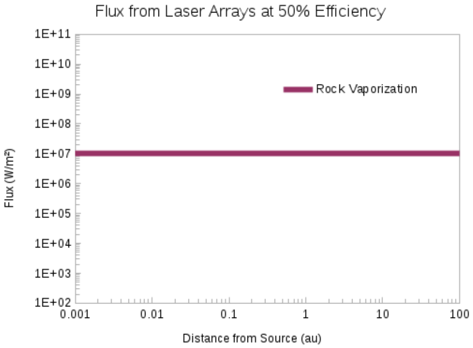
(need $\sim 10^7$ W/m^2 to ablate most rock)



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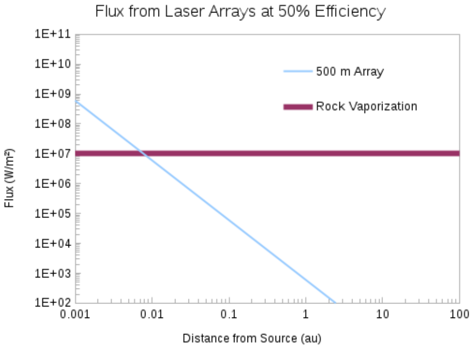

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- 500 m array:
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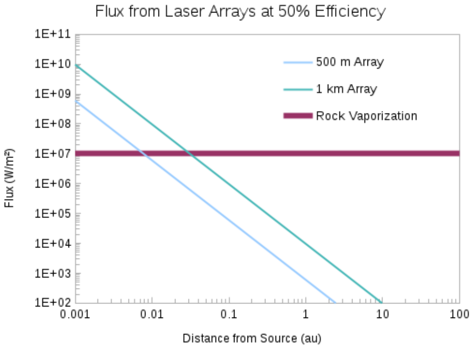

Ablation range:

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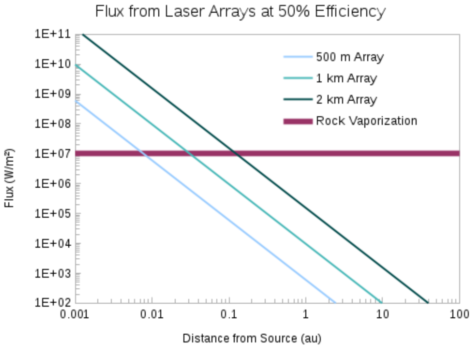

Ablation range:

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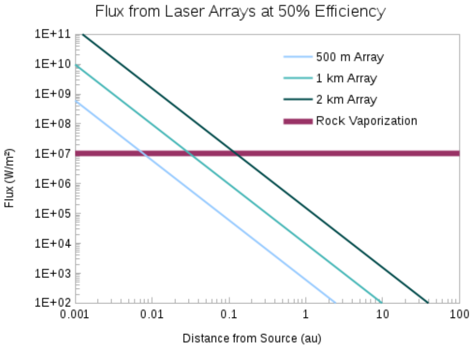

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BIG array needed

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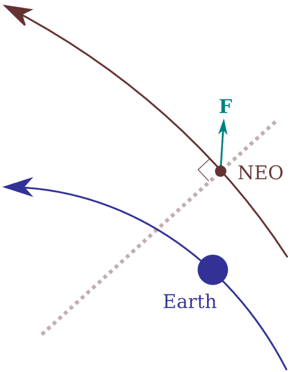
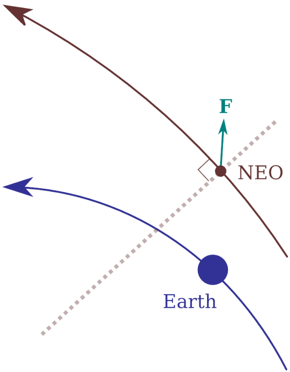
  - reduced thrust when spot is bigger than target
  - only turn on if Earth is ahead or behind the target

Stand-**Off** Modes



(a) Earth behind

Stand-**Off** Modes



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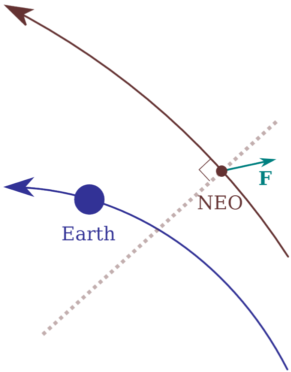

(b) Earth ahead

Stand-**Off** Effectiveness

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

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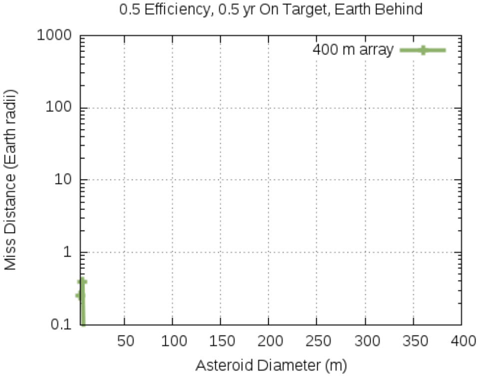

- 400 m array: none

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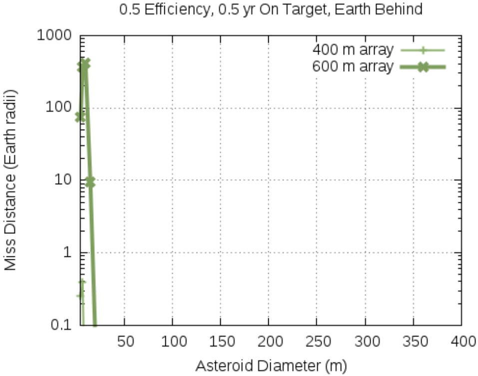

- 400 m array: none
- 600 m array: 15 m

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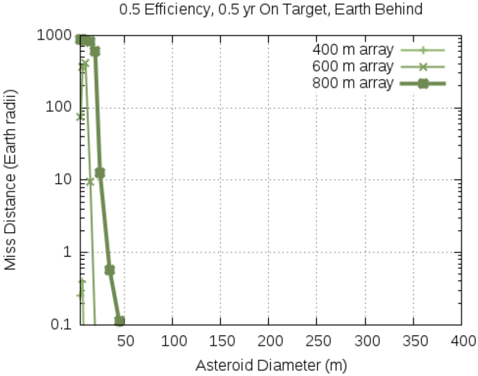

- 400 m array: none
- 600 m array: 15 m
- 800 m array: 30 m

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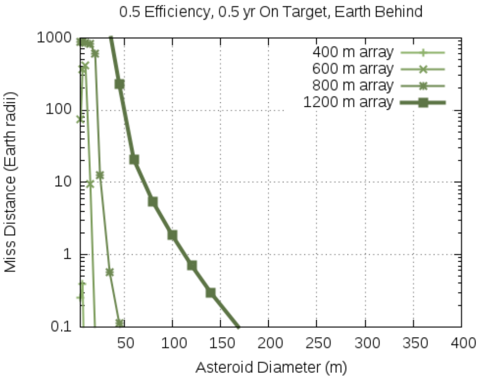

- 400 m array: none
- 600 m array: 15 m
- 800 m array: 30 m
- 1.2 km array: 100 m

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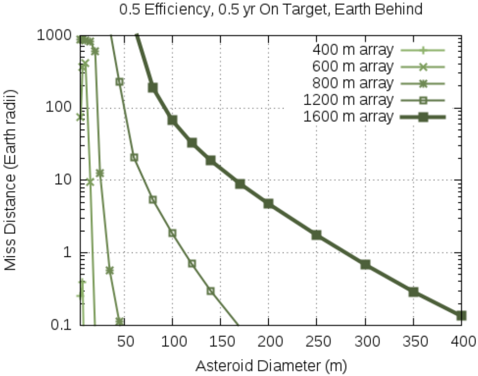

- 400 m array: none
- 600 m array: 15 m
- 800 m array: 30 m
- 1.2 km array: 100 m
- 1.6 km array: 250 m

Stand-**Off** Effectiveness

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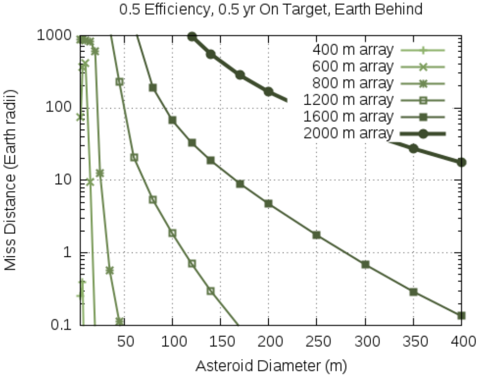

- 400 m array: none
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- 1.2 km array: 100 m
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- 2 km array: 1 km

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

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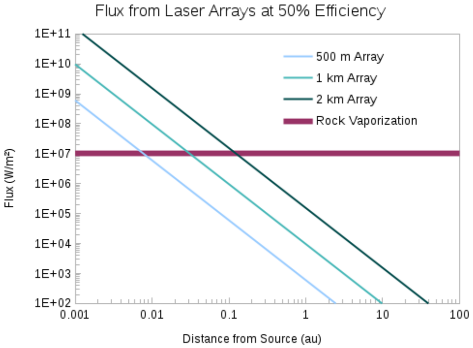
  - stand-**on** mission *not* practical
- large fraction ($\sim 50\%$) water ice
  - low vaporization flux ~ 300 W/m^2

Stand-**Off** Range for **Comets**

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



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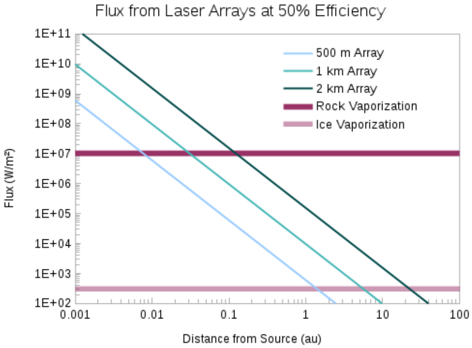

Ablation range:

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- 1 km array: 5 au
- 2 km array: 20 au

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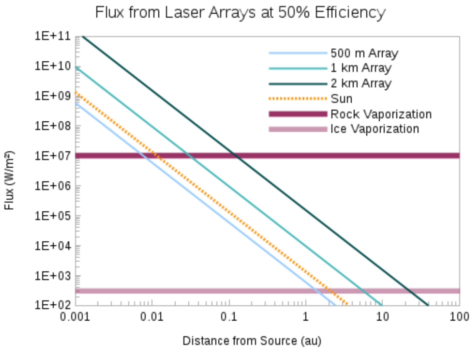

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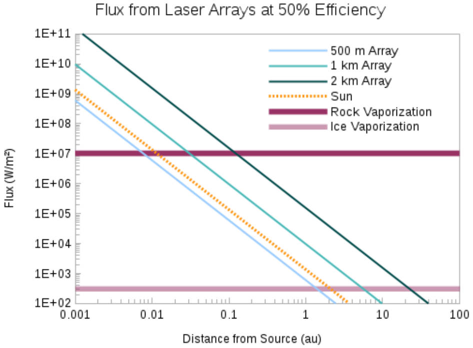

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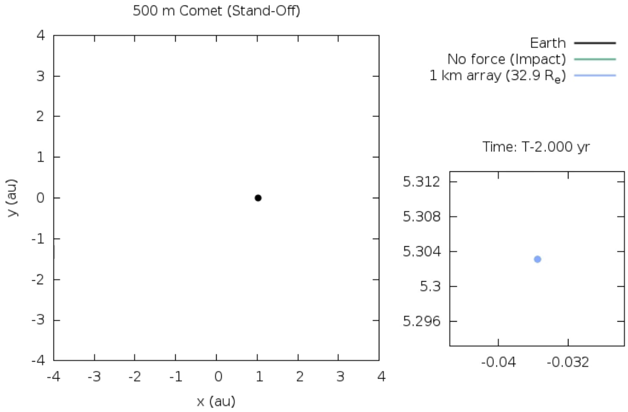
farther for other volatiles

Comet Deflection in Action

Deflection of Comet Over 2 Years



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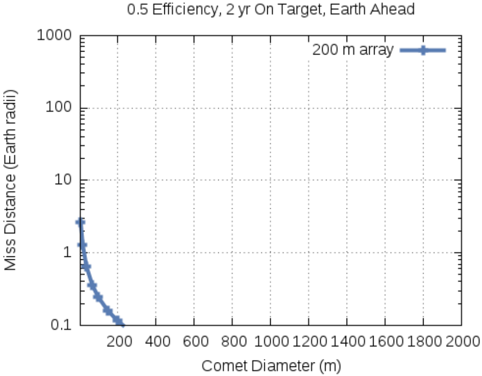

- 200 m array: none

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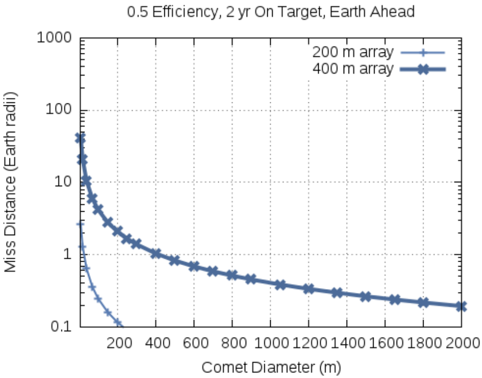

- 200 m array: none
- 400 m array: 80 m

Comet Deflection Effectiveness

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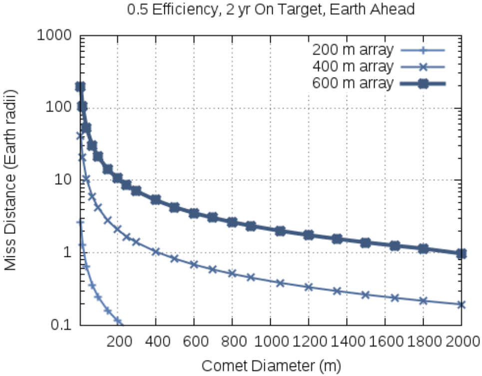

- 200 m array: none
- 400 m array: 80 m
- 600 m array: 450 m

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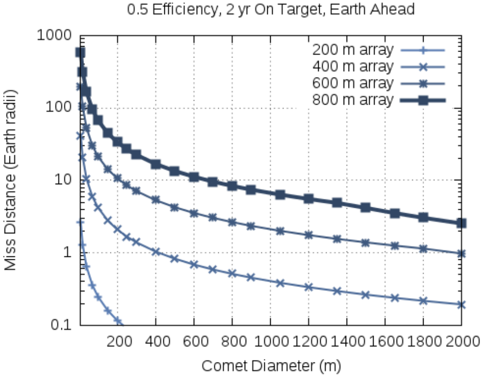

- 200 m array: none
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- 600 m array: 450 m
- 800 m array: 1.4 km

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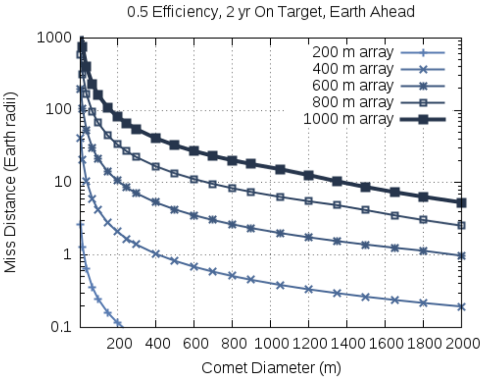

- 200 m array: none
- 400 m array: 80 m
- 600 m array: 450 m
- 800 m array: 1.4 km
- 1 km array: 2 km

Stand-**On** vs. Stand-**Off**

Stand-**On** vs. Stand-**Off**

- near future: stand-**on**

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  - handles all asteroidal threats given sufficient time
- in a while: stand-**off**
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  - operates on short timescales
  - necessary for deflecting long period comets

Keys to Success

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- Early detection / threat confirmation

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- Prepare system in advance

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- Otherwise, much more powerful lasers (expensive)

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Code: `http://github.com/ucsbdeepspace`

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deepspace.ucsb.edu