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# Orbital Simulations for Directed Energy Deflection of Near-Earth Asteroids

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**Abstract**

Directed energy laser ablation at the surface of an asteroid or comet produces an ejection plume that will impart a thrust on the asteroid. This thrust can mitigate a threatened collision with the Earth. This technique uses the asteroid itself as the deflection propellant. The DE-STAR laser system is designed to produce a sufficiently intense spot on the surface of an asteroid to accomplish this in one of two operational modes. One is a complete "stand-off" mode where a large space based phased-array laser directed energy system can interdict asteroids at large distances allowing sufficient time to mitigate nearly all known threats. A much smaller version of the same system, called DE-STARLITE, can be used in a "stand-on" mode by taking a much smaller laser to the asteroid and slowly deflecting it over a sufficiently long period of time. Here we present orbital simulations for a range of near-Earth asteroid impact scenarios for both the stand-off and stand-on systems. Simulated orbital parameters include asteroid radius and composition, initial engagement time, total laser-on time and total energy delivered to target. The orbital simulations indicate that, for exposures that are less than an orbital time, the thrust required to divert an asteroid is generally inversely proportional to laser-on time, proportional to target mass and proportional to the desired miss distance. We present a detailed stand-on scenario, consistent with current dedicated mission capabilities, to show the potential for laser ablation to allow significant deflection of targets with small systems. As one example we analyze a DE-STARLITE mission scenario that is in the same mass and launch envelope as the proposed Asteroid Redirect Mission (ARM) but using a multi kilowatt class laser array capable of deflecting a 325 m diameter asteroid with 2N of thrust for 15 years in a small fraction of even the smallest SLS block 1 launch vehicle configuration.



*Keywords*: Asteroid deflection, Asteroid hazard mitigation, Laser ablation, Near-Earth asteroid

**Nomenclature**

| | |
|---|---|
| $F$ | magnitude of thrust (N) |
| $m$ | mass of the asteroid (kg) |
| $\Delta t$ | length of time of laser activity (yr) |
| $\mathbf{r}$ | heliocentric position of the Asteroid |
| $\mathbf{v}$ | heliocentric velocity of the Asteroid |
| $\mathbf{r}_e$ | heliocentric position of Earth |
| $\mathbf{v}_e$ | heliocentric velocity of Earth |

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## 1. Introduction

A wide array of concepts for asteroid deflection has been proposed. Several detailed surveys of threat mitigation strategies are available, including [1], [2], [3], [4], and [5]. Currently proposed diversion strategies can be broadly grouped into six categories.

(1) Kinetic impactors, with or without explosive charges. An expendable spacecraft would be sent to intercept the threatening object. Direct impact would modify the object's orbit through momentum transfer. Enhanced momentum transfer can occur using an explosive charge, such as a nuclear weapon, e.g. [6], [7], [8], [9].

(2) Gradual orbit deflection by surface albedo alteration. The albedo of an object could be changed using paint [10], mirrors [11], sails [12], etc. As the albedo is altered, a change in the object's Yarkovsky thermal drag would gradually shift the object's orbit.

(3) Direct motive force, such as by mounting a thruster directly to the object. Thrusters could include chemical propellants, solar or nuclear powered electric drives, or ion engines [13].

(4) Indirect orbit alteration, such as gravity tractors. A spacecraft with sufficient mass would be positioned near the object, and maintain a fixed station with respect to the object using onboard propulsion. Gravitational attraction would tug the object toward the spacecraft, and gradually modify the object's orbit [14], [15].

(5) Expulsion of surface material such as by robotic mining. A robot on the surface of an asteroid would repeatedly eject material from the asteroid. The reaction force when material is ejected affects the object's trajectory [16].

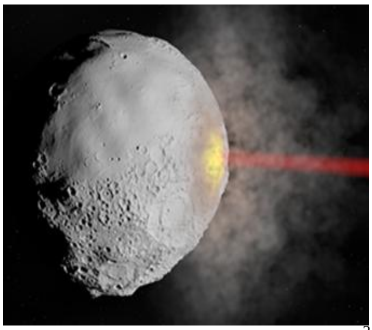
(6) Vaporization of surface material. Like robotic mining, vaporization on the surface of an object continually ejects the vaporized material, creating a reactionary force that pushes the object into a new path. Vaporization can be accomplished by solar concentrators [17] or lasers [18] deployed on spacecraft stationed near the asteroid. One study ([19]) envisioned a single large reflector mounted on a spacecraft traveling alongside an asteroid. The idea was expanded to a formation of spacecraft orbiting in the vicinity of the asteroid, each equipped with a smaller concentrator assembly capable of focusing solar power onto an asteroid at distances near ~1 km [20]. Efficiency of a laser system for surface ablation can be enhanced using an array of phase-locked lasers [21], allowing more photonic flux to be delivered to the asteroid and at greater distances. Envisioning ever larger arrays of phase-locked lasers allows contemplation of stand-off systems that could deliver sufficient flux to the surface of a distant asteroid from Earth orbit [22].

The purpose of this work is to demonstrate alternative asteroid deflection and hazard mitigation techniques based on long-term thrust drive by laser ablation, as proposed in [21] and [22]. We will briefly describe the laser technology, the spot and temperatures produced on an asteroid, and how that creates thrusts of different magnitudes. We have explored multiple scenarios for Earth-laser-asteroid configurations and will describe the "stand-on" and "standoff" modes of thrusting. The larger "stand-off" system is called DE-STAR for **Directed Energy System for Targeting of Asteroids and exploRation.** The much smaller ("lite" version) "stand-on" system is DE-STARLITE. Both are CW solid state laser arrays and are designed to run continuously, though pulsed operation is an option if needed. This technology is described in much greater detail in a series of papers from our group including [21], [22] and [28]. The effects of asteroid rotation for directed energy systems are discussed in [26] and the optical modeling is discussed in [27] and [29]. Finally we will show the results of numerous orbital simulations where we vary the time of interaction with the asteroid, the size of the asteroid and the configuration of the deflection system. Generally, we will describe multiple ways to use Laser ablation technology to mitigate impact threats from Asteroids – these techniques all rely on space-born Lasers that utilize the targeted asteroid's surface as the fuel to generate thrust and change the target's orbit.

### *1.1. Laser Ablation of an Asteroid Surface by DE-STAR and DE-STARLITE*

In a stand-on system, proposed as DE-STARLITE in [21], photovoltaic arrays are used to obtain ~100 kW electrical power. The objective of the laser directed energy system is to project a large enough flux onto the surface of the asteroid to heat the surface to a temperature that exceeds the vaporization point of constituent materials, typically around 2,000-3,000 K, or a flux in excess of $10^7$ W/m$^2$. A reactionary thrust due to mass ejection will divert the asteroid's trajectory. To produce sufficient flux, the system must have both adequate beam convergence and sufficient power. Optical aperture size, pointing control and jitter, and efficacy of adaptive optics techniques are several critical factors that affect beam convergence. The optical power output of DE-STARLITE can be varied depending on the target size and warning time and is typically between 1 and 1000 kW. The current laser "wallplug efficiency" baselined for DE-STAR and LITE are nearing 50%. Even higher efficiency allows for more thrust on the target for a given electrical input as well as for smaller radiators and hence lower mission mass. From a distance of 10 km, DE-STARLITE is capable of projecting a spot size on the asteroid of 10 cm, providing enough flux to vaporize (sublimate) rock [21]. Evaporation at the spot produces a vaporization plume thrust [N] that can be used to change the asteroid's orbit and effectively deflect asteroids from colliding with Earth.

4D (3D space + time) simulations are given in our papers [22], [26] and [28]. We simulate the high temperature materials expected in rocky target that require the highest flux while low temperature volatiles in comets can also be deflected and are much easier as they require much less flux. Targeting, optics and ranging are discussed in [21], [22], [28] and [29].



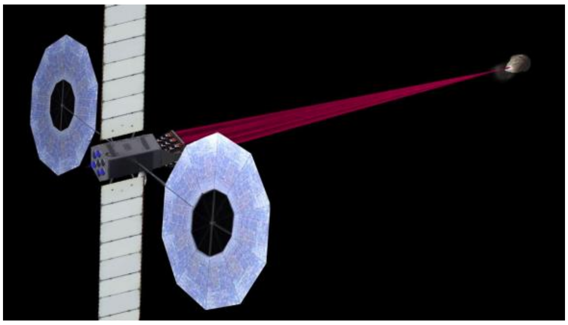


**Figure 1**. **LEFT**: Simulation of asteroid laser ablation.[2] **RIGHT**: Artistic rendering of a deployed DE-STARLITE spacecraft deflecting an asteroid. The spacecraft is outfitted with two 15 m diameter MegaFlex PV Arrays, a z-folded radiator deployed up and down, a laser array mounted on a gimbal at the front, and ion engines at the back. From Kosmo et al 2014 [21] and Lubin et al 2014 [22].

A miss distance of at least two Earth radii (12,742 km) is required to eliminate the threat of collision. The orbital deflection depends on the duration, magnitude, and direction of the applied thrust. Simulations of the thrust produced by laser ablation have been described in [21], [22], [26] and [28]. Such a system is illustrated in Figure 1. DE-STARLITE can be designed for a variety of power levels, depending on the target's needs, which range typically from 1-1000 kW with thrust of approximately $10^{-4}$ N/watt (optical). As mentioned a large asteroid with sufficient warning, such as Apophis which is about 325 m in diameter, can be deflected by a few newtons of laser induced thrust when applied for about a decade. This type of system would be relatively modest, needing less than 40 kW of laser power. Smaller and larger asteroid or comets with less or greater warning time can used DE-STARLITE systems that are simply scaled. This paper uses estimated thrust levels expected from simulation and measurement for DE-STAR and DE-STARLITE as input for orbital simulations of asteroid deflection scenarios.

### *1.2. Stand-on and Stand-off Modes for deflection*

In this model, we deal with a 3-body problem involving the Sun, Earth and asteroid with all three modeled as gravitational point sources. The Moon is not included as a separate body, although its mass is contained in that of the Earth's. We refer to the resulting "Earth-Moon point mass" simply as the Earth. The acceleration of the asteroid being numerically integrated is

$$\mathbf{a} = \mathbf{a_g} + \mathbf{a_l}$$

where the first component, $\mathbf{a_g}$, is the net gravitational acceleration by the Sun and Earth. The second component, $\mathbf{a_l}$, is the acceleration from the laser's thrust and varies depending on which method of applying thrust we choose.

In the "stand-on" thrust case, we envision a spacecraft-borne laser system that is present at or near the targeted asteroid, typically standing off by many km to avoid plume contamination. Thus, we are free to orient the laser and thus apply thrust in any direction. Our model focuses on two directions in particular:

1. Parallel to the asteroid's velocity, with the laser positioned behind the asteroid (the $0^\circ$ direction). The anti-parallel case ($180^\circ$ direction) yields a symmetrical deflection as the $0^\circ$ case.
2. Perpendicular to the asteroid's velocity, within the orbital plane, pointing to the inside of the orbit (the $90^\circ$ direction)

Let the asteroid's position be $\mathbf{r}$, velocity $\mathbf{v}$ and the magnitude of thrust from the laser be $F$. For the first case where the thrust is parallel to velocity, the acceleration due to thrust is

$$\mathbf{a_l} = \frac{F}{m} \cdot \frac{\mathbf{v}}{\|\mathbf{v}\|}$$

For the second case, the thrust is in a direction $90^\circ$ from the velocity directed into the orbit. The vector $(\mathbf{r} \times \mathbf{v}) \times \mathbf{v}$ points in this direction. Thus, the acceleration from the $90^\circ$ thrust is

$$\mathbf{a}_\mathbf{l} = \frac{F}{m} \cdot \frac{(\mathbf{r} \times \mathbf{v}) \times \mathbf{v}}{\|\mathbf{r}\|\|\mathbf{v}\|^2}$$

In the “stand-off” case, the laser orbits the Earth, which is at the position $\mathbf{r}_\mathbf{e}$. The only option for the thrust is to be in the direction of the asteroid’s geocentric position vector:

$$\mathbf{a}_\mathbf{l} = \frac{F}{m} \cdot \frac{\mathbf{r} - \mathbf{r}_e}{\|\mathbf{r} - \mathbf{r}_e\|}$$

To prevent cancellation of thrust over time, we enable the thrust either when the Earth is behind the asteroid or when the Earth is in front of the asteroid. Whether the Earth is in front or behind the asteroid is determined by the sign of the vector $(\mathbf{r} - \mathbf{r}_\mathbf{e}) \cdot \mathbf{v}$ – the Earth is in front of the asteroid when negative and behind when positive.

Thus, the acceleration by the laser at any time is actually

$$\mathbf{a}_\mathbf{l} = H\left(\pm(\mathbf{r} - \mathbf{r}_\mathbf{e}) \cdot \mathbf{v}\right) \cdot \frac{F}{m} \cdot \frac{\mathbf{r} - \mathbf{r}_\mathbf{e}}{\|\mathbf{r} - \mathbf{r}_e\|}$$

for a consistent choice of sign, where $H$ is the Heaviside step function.

### *1.3. Orbital Simulations*

Both the “stand-on” and “stand-off” modes were included in a standard Solar System *N*-body integrator package - SyMBA [23]. Each simulation allowed either stand-on or stand-off mode, with a selection of generated thrust and minimum and maximum distances for the laser to be generating thrust. The standard integrator used by SyMBA is the mixed variable symplectic mapping (MVS), and it recursively divides the time-step for two bodies suffering close approaches with each other.

The initial conditions were generated alternately through direct forward integration of a few hundred test particles, or the backward integration of a test particle in contact with the Earth. Each technique provided state vectors for Earth and the asteroid for any number of years or days ahead of impact.

## 2. Deflection Simulation Results

We have focused this work on studying asteroid deflection in two different modes of laser operation, a range of laser-produced thrust on the asteroid and a range of asteroid sizes.

To compute the miss distance of the asteroid to the Earth given a set of thrust parameters noted above, we first integrate with SyMBA from $t = 0$ through $t = \Delta t$. In addition to increasing the miss distance from impact, the thrust may also advance or delay the time of closest approach. Therefore, if $r - r_e$ is still decreasing at $t = \Delta t$, we continue integrating until it begins to increase again to ensure we integrate over the point of closest approach. Next, we have a set of discrete times $t_i$ and their associated Earth-asteroid distances. Beginning at the very last step, we move in reverse until we reach the first local minimum in distance. We define this local minimum step to be step $k$ occurring at time $t_k$. To refine the miss distance, we continue back one more step to time $t_{k-1}$. We then use $r(t_{k-1}), v(t_{k-1})$ and $r_e(t_{k-1}), v_e(t_{k-1})$ as the new initial state vectors for the asteroid and Earth respectively and perform integration with the classical $4^{\text{th}}$ order Runge-Kutta method (RK4) with the same acceleration functions as with SymBA but with a smaller time step, continuing through the point of minimum Earth-to-asteroid distance. We take the step with the smallest distance as the point of close approach and its distance as the miss distance.

### *2.1 Analytical Estimates*

The numerical results were compared with the Earth-asteroid miss distance estimate $d$ derived from the $\Delta v$ generated by a thrust $F$ over time $\Delta t$ in a simplified linear model (blue-green, in figures below).

$$\Delta v(t) = \int_{t_0}^{t} \frac{F}{m} dt = \frac{F}{m}(t - t_0)$$

$$d = \int_{t_0}^{t_f} \Delta v(t) dt = \frac{F}{2m} \Delta t^2$$

In addition, an adaptation of the linear model for circular orbits, which more closely approximate the elliptical orbits analyzed, gives a separation of $3d$ which is also computed for comparison (blue, in figures below).[25]

### *2.2 Numerical Results*

The asteroid 99942 Apophis is a well-known case of a relatively large Potentially Hazardous Object. It has a diameter of approximately 325 m with an orbital eccentricity of about 0.2. This is an ideal test case to exercise our model, and for these simulations, we assume the asteroid to be a sphere with a mean density of 2000 kg/m$^3$. With these parameters and considering scenarios starting 1 year and 15 years before impact, we obtain a generally linear relation between miss distance and thrust (Figure 2) as expected from our $\Delta v$ estimate above.

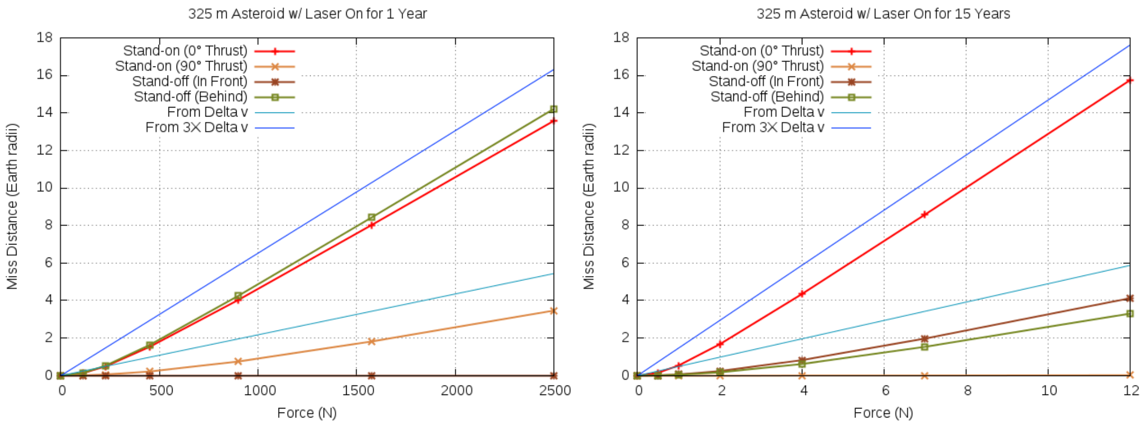



**Figure 2**: Miss distance of a 325 m asteroid to Earth as a function of thrust applied over 1 (left) and 15 years (right). The orbit of the asteroid has an eccentricity of 0.2 with an inclination of 0 degrees and a semi-major axis of 1.1 au.

For stand-on cases, 0 degree thrust (red) is in the direction of the asteroid's velocity and 90 degree thrust (orange) is orthogonal to the velocity in the orbital plane toward the inside of the orbit. For stand-off cases, "in front" (brown) and "behind" (green) refer to the position of the Earth (and thus laser) relative to the asteroid. The laser is only active for the "in front" case when the Earth is within 90 degrees of its velocity vector and for the "behind" case only when it is not. **Note that due to orbital geometry, the stand-off "in front" mode shown for this particular case is never active for the 1 year scenario (left). Under our initial conditions, at no point in the year before collision is the Earth (and thus the laser) ever positioned in front of the asteroid, and as a result, no deflection is produced. Instead, the Earth and laser remain behind the asteroid for the entire year and so laser activity only occurs here under the stand-off "behind" mode.**

In the second scenario where the mitigation target was discovered much earlier at 15 years before impact, we substantially lower the force needed to maintain the same level of deflections. One striking difference of the 15 year case is the relative drop of effectiveness for the stand-off case with thrust from behind (green) and the similar increase for stand-off thrust from in front (brown). Plots of miss distance as a function of time like those in Figure 3 show this effect more clearly.

The linear and circular deflection equations estimate a quadratic relationship between miss distance and the amount of the time the laser is active. Indeed, the stand-on thrust in the direction of the asteroid's velocity (red) follows this estimate relatively closely. Over short timescales, the stand-off "behind" case follows a similar quadratic increase. However, starting the laser earlier introduces less favorable Earth-asteroid geometry to a thrust from behind, leading to a negative deviation from the estimate. Meanwhile, the stand-off "in front" case remains completely inactive for timescales of less than a few years as the orbits of the Earth and asteroid never place the Earth in front of the asteroid over this span of time. If we look back sufficiently far back before impact however, we will find a similar span of time where the Earth is in front of the asteroid, over which only the "in front" mode will be active and thus gains effectiveness. Even longer timescales yield repeated switching off of relative effectiveness of the two methods as further changes in the orbit geometry favor one or the other.

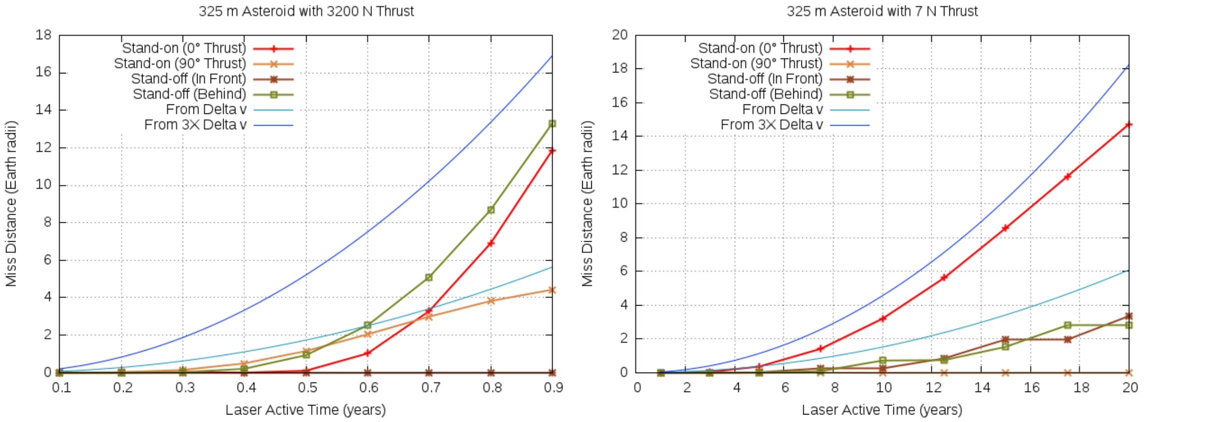



**Figure 3**: Miss distance of a 325 m asteroid to Earth as a function of time for which a thrust of 3200 N (left) and 7 N (right) are applied. As in Figure 2 (left), the stand-off (in front) case is never active over the range of times covered by the 3200 N case (left) due to orbital geometry which places the Earth behind the asteroid throughout the interval. Orbital elements, color scheme and labeling are also identical to those in Figure 2.

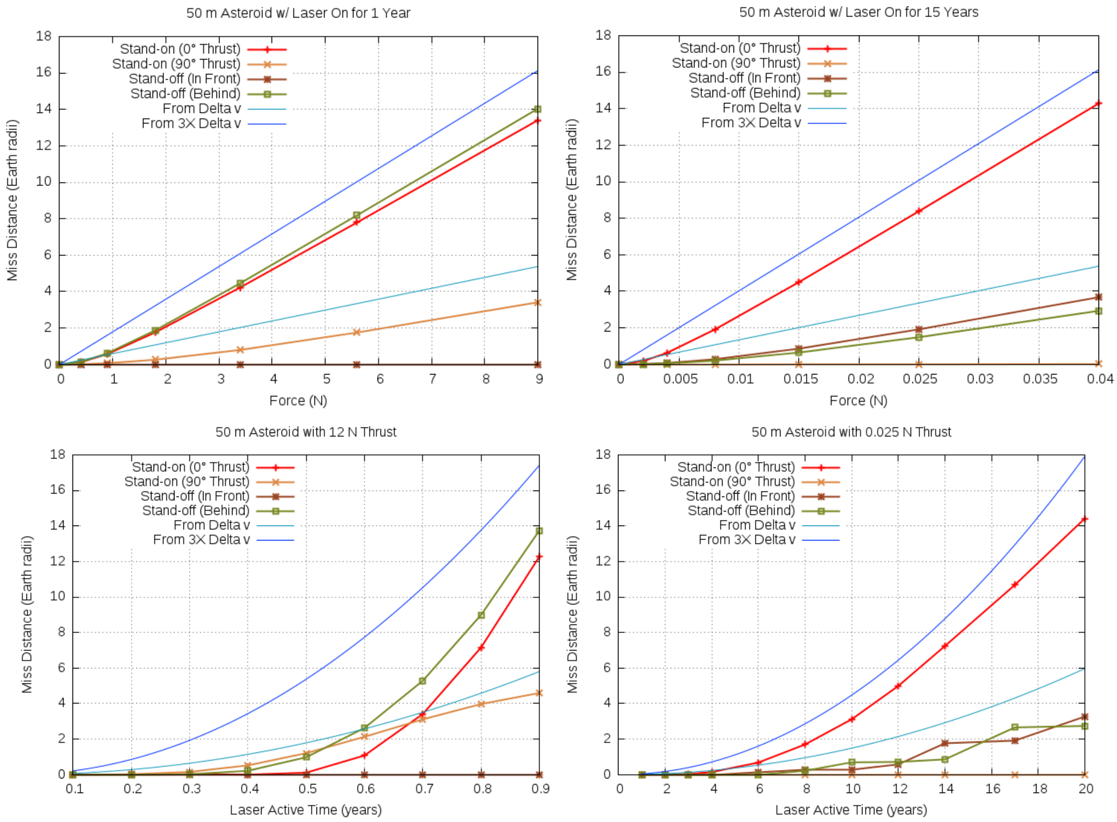



**Figure 4**: Miss distance of a 50 m asteroid to Earth as functions of thrust (top) and laser active time (bottom). Orbital elements, color scheme and labeling are identical to those in Figure 2.

Another point of interest is the relative effectiveness of the $90^\circ$ stand-on thrust (orange) at short timescales. For this case, miss distance grows linearly with time rather than quadratically as the others do. As a consequence, it is a particularly effective method when the laser active time is short despite being comparatively ineffective over longer timescales.

We see similar behavior in Figure 4 with a smaller 50 m asteroid, with 1-year and 15-year scenarios tested. This size of target body is typically linked with the Tunguska event while a 325 m (Apophis) event would be a gigaton class event causing an extremely large number of casualties with an energy release about 100 times larger than Tunguska .

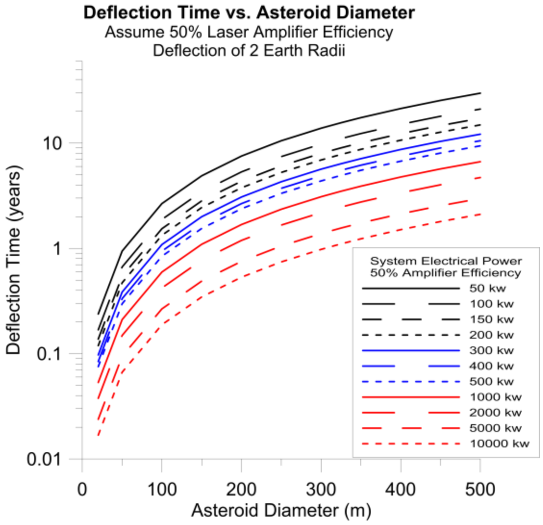



**Figure 5:** Estimated deflection time (laser on time) versus target diameter and DE-STARLITE electrical power input from PV assuming a 3 delta v approximation, which as seen from this paper often over estimates the deflection (miss) distance. True mission planning requires detailed knowledge of the target orbit and the detailed interdiction scenario. The 3 delta v approximation is often used for initial mission planning.

### *2.3 Conclusions and Discussion*

Directed energy is an extremely promising planetary defense technology that is capable of deflecting all known threats with sufficient notice. Given the build out time for a mission it would be wise to consider planetary defense in the same way we consider terrestrial defense -- namely not waiting until the threat is imminent, as it will likely be too late then, but rather plan for and proceed to establish an "offensive" defensive strategy. A critical part of this strategy is obtaining detailed knowledge of the threats and the frequency of collisions. We have some detailed information on this but not enough, particularly on targets in the 10-300 m diameter range. Another part of a future strategy should be placing into orbit systems that are "at ready" if needed rather than waiting until a need is required. Such an approach might be to orbit several systems and start a test "campaign" to go after targets and refine the techniques and deflection and methodology.

A sobering thought is that in the past (approx) 100 years we have been "hit" by at least 2 megaton class events: one in 1908 (Tunguska with an estimated yield in excess of 10 MT) and one in 2013 (Chelyabinsk with an estimated yield of approximately 0.5 MT). Had either of these hit a heavily populated area mass causalities would have occurred. While a full "stand-off" DE-STAR class system [22] is a goal for the future for many reasons, the smaller **DE-STARLITE approach combining conventional chemical propellants to boost the system to LEO and ion engines to propel the system to the asteroid and directed energy to use the asteroid as the deflecting "propellant" offer a uniquely capable system that is realizable and can tackle any known threat even within the SLS Block 1 launch mass.** Since directed energy uses the asteroid as the "fuel" for its own deflection, **such a system is thus able to mitigate much larger targets than would be possible with any other proposed technologies such as IBD, gravity tractors, and kinetic impactors.** For instance, with the equivalent mass of the ARM which is designed to capture a 5-10 m diameter asteroid, Block 1 arrangement (14 tons to LEO), (SLS Block 1 can boost 70 metric tons to LEO for reference), DE-STARLITE with even smaller mass than ARM can mitigate an asteroid larger than Apophis (325 m diameter), even without any keyhole effects [21].

Much smaller DE-STARLITE systems could be used for testing on targets that are likely to pass through keyholes. The same technology proposed for DE-STARLITE has significant long-range implications for space missions, as outlined in other DE-STAR papers [22]. DE-STARLITE can also be used to de-spin an asteroid for capture and mining, a task which is virtually impossible with any other proposed technique. The DE-STAR and LITE systems utilize rapidly developing technologies that can easily be increased or decreased in scope given their intrinsic scalable and modular nature. They are also extremely fault tolerant given their array structure. DE-STARLITE is capable of launching on an Atlas V 551, Falcon Heavy, SLS, Ariane V or Delta IV Heavy, among others. Many of the items needed for the DE-STARLITE system currently have high TRL. DE-STARLITE is a critical step towards achieving the long-term goal of implementing a stand-off system capable of full planetary defense and many other tasks including spacecraft propulsion [22] and [30].

Directed energy represents a practicable technology for planetary defense that can be implemented and is heavily leveraged by terrestrial programs. The detailed orbital simulations we have performed allow us to determine the specific mission requirements for a given threat. The nominal $3\Delta v$ approximation is compared to the detailed simulations and is not always a good indicator.

## Acknowledgements

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