

Directed energy active illumination for near-Earth object detection

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ABSTRACT

On 15 February 2013, a previously unknown ~20 m asteroid struck Earth near Chelyabinsk, Russia, releasing kinetic energy equivalent to ~570 kt TNT. Detecting objects like the Chelyabinsk impactor that are orbiting near Earth is a difficult task, in part because such objects spend much of their own orbits in the direction of the Sun when viewed from Earth. Efforts aimed at protecting Earth from future impacts will rely heavily on continued discovery. Ground-based optical observatory networks and Earth-orbiting spacecraft with infrared sensors have dramatically increased the pace of discovery. Still, less than 5% of near-Earth objects (NEOs) ≥ 100 m/~100 Mt TNT have been identified, and the proportion of known objects decreases rapidly for smaller sizes. Low emissivity of some objects also makes detection by passive sensors difficult. A proposed orbiting laser phased array directed energy system could be used for active illumination of NEOs, enhancing discovery particularly for smaller and lower emissivity objects. Laser fiber amplifiers emit very narrow-band energy, simplifying detection. Results of simulated illumination scenarios are presented based on an orbiting emitter array with specified characteristics. Simulations indicate that return signals from small and low emissivity objects is strong enough to detect. The possibility for both directed and full sky blind surveys is discussed, and the resulting diameter and mass limits for objects in different observational scenarios. The ability to determine both position and speed of detected objects is also discussed.

Keywords: DE-STAR, Directed Energy, Laser Phased Array, Planetary Defense, LIDAR, active illumination

1. INTRODUCTION

Near-Earth objects (NEOs) are defined to be asteroids or comets that can approach within 0.3 AU of Earth's orbit.¹ As of last year, 90 percent of NEO's larger than 1 km have been discovered.¹ This is approximately the size of asteroid that would be globally catastrophic should it collide with the Earth. Fortunately, NASA has determined that none of these large NEOs pose a current impact threat, although it is predicted that there are still a few dozen more that remain to be discovered.¹ The vast majority of NEOs, however, are smaller than 1 km, and these smaller potential impactors still pose a serious threat to Earth and the general population. NEOs as small as 30 m could cause significant devastation should one hit a populated area, and less than 1 percent of 30 m NEOs have been detected.¹ Evidence of this smaller potential hazard was witnessed on February 15, 2013 when a previously undetected ~20 m asteroid struck near Chelyabinsk, Russia, releasing ~570 kt TNT worth of kinetic energy and injuring hundreds of people.

Continued discovery of NEOs, both large and small, is essential for protecting Earth from future impacts. The development of ground-based optical observatory networks and Earth-orbiting spacecraft with infrared sensors has increased the rate of discovery, but detection remains a difficult task. A large problem is that NEOs spend much of their orbit in the direction of the Sun when viewed from Earth, blinding current systems and leaving a large part of the sky unresolved. Another issue that current systems are facing is that the low emissivity of some objects makes detection by passive sensors difficult. Generally, asteroids are found by using their reflected sunlight and then looking for them in the visible bands or looking for them in their thermal IR using their heat signature. A proposed orbiting laser phased array directed energy system^{2,3} called DE-STAR (**D**irected **E**nergy **S**ystem for **T**argeting of **A**steroids and **e**xplo**R**ation) could be used for active illumination of NEOs.

The baseline DE-STAR design consists of laser fiber amplifiers, which emit very narrow-band energy beams, to enhance discovery for much smaller and lower emissivity objects with a greater increase in range. This general technique is sometimes referred to as Light Detection and Ranging (LIDAR). Not only could it be used for detection of

asteroids, DE-STAR, could also be used for vaporization, deflection and the compositional analysis of asteroids. The focused directed energy of a DE-STAR could raise the surface spot temperature of a potential impactor to ~3,000 K, allowing the direct vaporization of all known substances. The process of heating the surface, and the ejecting evaporated material, would produce a vaporization plume that would cause a large back reaction force, altering the asteroid's orbit and ultimately deflecting the asteroid. Observation of absorption lines in the blackbody spectrum of a vaporizing surface spot could allow for standoff analysis of an asteroid's composition. Narrow bandwidth and precision beam control would aid in ephemeris refinement and Doppler velocity determination of objects already identified with wide-field surveys.

The system would consist of an array of phase-locked modest power (kW class each) laser amplifiers that are powered by solar photovoltaics, of essentially the same area as the laser array. The current system design uses Yb doped fiber lasers at a wavelength of 1.06 μm . The phased array configuration is capable of creating multiple beams, so a single DE-STAR of sufficient size would be able to search for as well as vaporize and deflect, simultaneously, multiple asteroids or one that has broken apart. DE-STAR is intrinsically a multi-tasking system, the phased array configuration consists of a large number of elements that can be simultaneously used for multiple purposes and a wide variety of functions. DE-STAR's inherently modular and scalable design allows for incremental development, testing, and initial deployment that would be developed in stages as the required technology advances. This paper focuses on the LIDAR aspect of DESTAR. The general approach is presented, relevant backgrounds are discussed, and results are presented from simulations for various sizes and powers of DE-STARs, including the photon rate received and time per area of sky required for the blind detection of different size objects.

2. TARGETING AND LIDAR MODE

2.1 General Approach

One of the difficulties with asteroid mitigation in general is knowing where the targets are. Generally, asteroids are found by looking for them in the visible bands using their reflected sunlight or in the thermal IR using their thermal IR signature. It is possible to use a DE-STAR system for active illumination of targets to aid in both their detection and orbital refinement. This is done in much the same way that a radar system works except with a laser the beams are much smaller, providing finer target determination and much greater range. The same phased array optical system is used for reception of the return light as is used for transmission of the laser. In this case, the system is run in a gated or long term pulsed mode. The light travel time to 1 AU is about 8 minutes or a round trip light travel time of 16 minutes. The laser could be turned on to scan potential targets and then turned off just before the photons that are scattered off the target are expected to return and switch to a receive mode. This then forms a complete LIDAR system with the same optics used for transmitting and receiving. The receive system could also be phased to form a full phased array receiver or could be run in a mode where each element acts as an independent receiver with the sum of all sub elements co-added before detection. There are advantages to this latter mode in both simplicity of operation and in that a much larger field of view is received eliminating scanning the field for reception. The disadvantage is the increased background from a larger field of view per sub element.

The return signal is computed for a variety of mission scenarios, as well as the equivalent mapping times for small error boxes to full sky blind surveys. The relevant backgrounds are the Cosmic Infrared Background (CIB), the Zodiacal background, and the asteroid's scattered sunlight and thermal emission. This technique not only allows for an "in situ" and "co-aligned" determination of the target position, but also gives ranging from time of flight (or phase modulation) as well as speed from measured Doppler. Here a heterodyne technique is assumed for detection, which is now feasible at the baseline wavelength. This is another relatively new development in photonic technology.

2.2 Backgrounds for Remote Targeting

In order to determine the signal to noise of the return signature it is necessary to understand the non targeting signal related sources of photons. This is generically referred to as the background. There are a number of such backgrounds that are important. Going outward from the detector to the target and beyond, there is:

- Dark current and "readout noise" associated with the detector
- Thermally generated photons in the optical system, under the assumption that the optical system is mostly running near 300 K.

- Solar system dust that both scatters sunlight and emits from its thermal signature. Dust in the solar system is typically at a temperature of about 200 K. This is generically called "Zodiacal" scattering and emission respectively or "Zodiacal light" or Zodi for short.
- Photon statistics noise from the laser hitting the target. This is due to both the counting statistics nature of the light and its bosonic nature (spin 1 statistics).
- Scattering of sunlight from the target itself as it is illuminated by the sun
- Thermal emission of the target
- Distant background stars that are in the field of view
- Sunlight scattered into the field of view for targets that are near to the sun in the field of view. This is generally only important for targets that are very close to the sun along the line of sight, though off axis response of the optical system can be an issue as well.
- The far IR background of the universe is known as the Cosmic Infrared Background or CIB. This is the total sum of all galaxies (both seen and unseen) in the field of view in the laser band that are NOT blocked by the target. This is relevant IF the target is smaller than the receive beam. It is not relevant to first order IF the target is larger than the received beam (or spot at the target distance).
- The Cosmic Background Radiation or remnant radiation from the early universe. This is negligible for the operational wavelength of 1.06 μm .

In all of these cases the fact that the laser linewidth (bandwidth) is extremely narrow (from kHz to GHz depending on the system design) and the field of view is extremely narrow, mitigates these effect which would otherwise be overwhelming for a broadband photometric band survey. Heterodyning is possible at 1 μm and will greatly aid in detection.

2.3 Cosmic IR Background

The CIB was first detected by the Diffuse IR Background Explorer (DIRBE) instrument on the Cosmic Background Explorer (COBE) satellite launched in 1989. It is an extremely faint background now thought to be due to the sum of all galaxies in the universe from both the stellar (fusion) component at short wavelengths near 1 μm and from the re-radiated dust component near 100 μm . On large angular scales (degrees) it is largely isotropic though at very small angular scales (arc sec) individual sources can be detected. The diffuse CIB component, using data collected by DIRBE, is shown in Fig. 1.

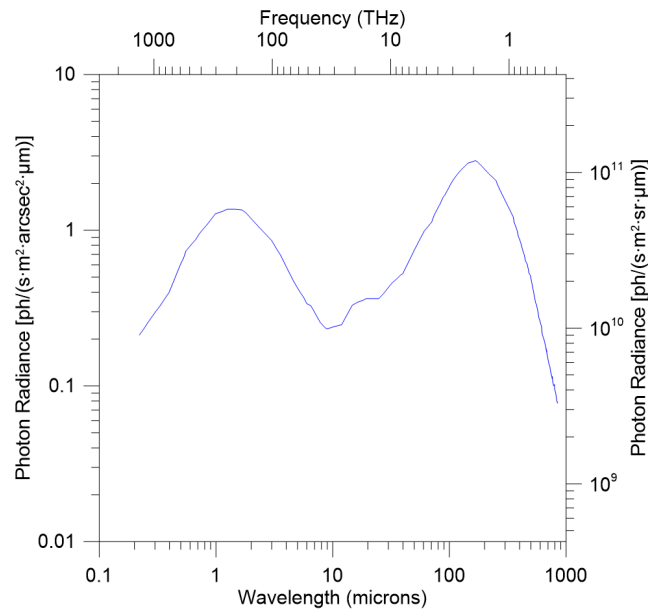


Figure 1. Diffuse CIB background component.

2.4 Zodiacal Light

Like the CIB the zodiacal light has two components and both involve dust in the solar system and the Sun. The sunlight both scatters off the interplanetary dust grains giving a "streetlight in fog" effect as well as heating the dust grains which then reradiate in the mid to far IR. The scattered component can be seen with the unaided eye in dark extreme latitudes and is sometimes known as the "Gegenschein" and traces the ecliptic plane. The dust grains are in rough equilibrium through being heated by the Sun and cooling through their own radiation. This "background" is NOT isotropic but is highly anisotropic depending on the position and orientation of the observer in the ecliptic plane. This was studied in detail by the DIRBE instrument on COBE. As seen in Fig. 2, based on some of the DIRBE measurements, the brightness of both the scattered and emitted components vary dramatically with the observed line of sight relative to the ecliptic plane. In the plot the angle relative to the ecliptic plane is given by the ecliptic latitude (Elat) where Elat = 0 is looking in the plane and Elat = 90 is looking perpendicular. The situation is even more complex as the scattered and emitted components vary with the Earth's position in its orbit around the Sun. By comparing the CIB and the Zodi it is clear that even in the best lines of sight (perpendicular to the ecliptic plane) the Zodiacal light completely dominates over the CIB. For the JWST mission the Zodi light is typically the limiting factor for IR observations, for example. When observing asteroids with active illumination (LIDAR mode) the Zodi is also an important factor. However, since illumination will occur in a system with an extremely narrow laser bandwidth, and detection occurs with a matched narrow bandwidth (allowing for Doppler shifting), it is possible to largely reduce the Zodi and the CIB to negligible levels, the calculations for which will be covered in section 3.3. This is NOT necessarily true in broadband photometric (typically 30% bandwidth) surveys that search for asteroids using scattered sunlight or using the thermal IR signature of the asteroid.

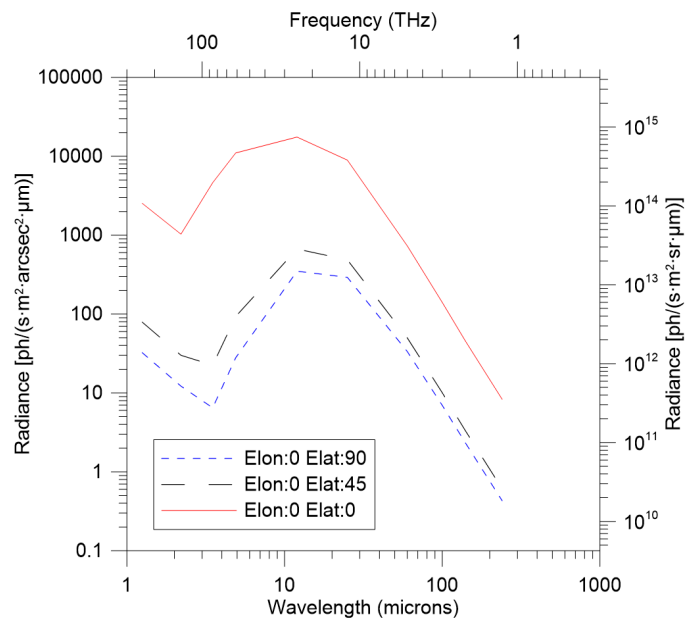


Figure 2. Zodiacal background component at three different directions of sight from Earth.

2.5 Optical Emission

Since the plan is to use the same phased array elements used to transmit the optical emission of the laser illuminator, it is necessary to compute the optical emission rate into the detector. The optics are assumed to be at roughly 300 K for simplicity (this could be changed in some scenarios), indicating a brightness or emission rate of about 1×10^7 ph/s·m²·st·μm for unity emissivity (or for a blackbody emitter) at the baseline wavelength of 1.06 μm. Unity emissivity is clearly an over estimate but represents a worst case. Under the assumption of a diffraction limited system, the entendue of the optics is such that $A \Omega = \lambda^2 \sim 10^{-12}$ m²·st where A is the effective receiving area and Ω is the received solid angle. The bandwidth of reception must also be included. Here a matched filter spectrometer is assumed (to get Doppler) with a bandwidth equal to the laser linewidth. As mentioned above, this is typically $10^4 - 10^{10}$ Hz or

approximately 4×10^{-11} to 4×10^{-5} μm . The total per sub element is thus an emission of about 4×10^{-16} to 4×10^{-10} ph/s again for an emissivity of 1. This is an extremely small rate compared to the return LIDAR flux. Comparing the optics emission of 1×10^7 ph/s- m^2 -st- μm for unity emissivity to the CIB and Zodiacal light shows the CIB and ZODI are both much larger. For comparison, note that when **looking directly at the Sun** the brightness of the solar surface is $\sim 5 \times 10^{25}$ ph/s- m^2 -st- μm at 1.06 μm . Assuming a diffraction-limited system, the resulting photon rate would be about 2×10^3 to 2×10^9 ph/s for laser (receiver) bandwidths from 10^4 to 10^{10} Hz as above. This is NOT small compared to the CIB and Zodi (as was the optical thermal emission) but it is still small compared to the LIDAR photon return rate for several of the DE-STARs scenarios for larger asteroid which are shown in Fig. 3. It does however, point out the need to be reasonably careful in rejecting direct solar illumination in the off axis response. In particular in searching for smaller asteroids at larger distances the off axis solar rejection is extremely important.

3. SIMULATIONS

3.1 System Specifications

The DE-STAR system consists of an array of phase-locked power laser amplifiers. The proposed system would consist of an array of highly efficient Yb doped fiber amplifiers emitting at a wavelength of $\lambda = 1.06 \mu\text{m}^2$. Each DE-STAR is numbered according to its size. A DE-STAR X is of size 10^X m. In these simulations, the smallest DE-STAR is a DE-STAR 0 and the largest is a DE-STAR 4. A square array is assumed for simplicity. Each DE-STAR would be powered by a photovoltaic (PV) solar panel that is either equal or greater in size. For the cases of DE-STAR 1 and DE-STAR 2, this would assume a 100 m solar panel. For the case of DE-STAR 3, a 1,000 m solar panel, and for the DE-STAR 4, a 10,000 m solar panel, would be assumed. To calculate the power of each DE-STAR simply multiply the solar constant, which is approximately 1360 W/m^2 , above the Earth's atmosphere, by the area of the proposed solar panel and the assumed conversion efficiency of sunlight to laser power. Currently, Yb laser fiber amplifiers at 1.06 μm have efficiencies near 40%, and, under concentrated sunlight, PV solar panels have efficiencies near 50%.² Modest efficiency improvements of both laser and PV to approximately 70% over 20 years are assumed, which is not unreasonable in the realistic time scale of a full DE-STAR 4 system.² Operating under these assumptions, the calculated power of a DE-STAR 0 is approximately 65 kW. A DE-STAR 1 and DE-STAR 2 should be able to produce approximately 6.5 MW, a DE-STAR 3 is 650 MW, and a DE-STAR 4 is 65 GW. In order to optimize detection, the receive bandwidth is set to be equal to the laser linewidth, here assumed to be $f = 1 \times 10^5$ Hz. This bandwidth is a prediction of what will be achievable for high power lasers in the future. The linewidth of current Yb fiber amplifiers is intrinsically about 5-10 kHz, but for amplifiers run at their highest power levels, this bandwidth is usually artificially broadened to about 10 GHz in order to overcome the Stimulated Brillouin Scattering (SBS) limit, which limits the amplification power.² Already, however, technological progress is being made to allow for the development of laser fiber amplifiers with both high power and a narrow linewidth. In the time scale of a full DE-STAR 4 system, a bandwidth of 1×10^5 Hz is achievable, however, even with the current laser linewidths the conclusions that follow are still basically unchanged. Using these specifications as inputs for the simulations, it is possible to calculate the photon rates received, and time per square degree, full sky, and arc second for blind detection for each DE-STAR.

3.2 Photon Rate Received

The first simulations calculate the photon rate received at Earth that a DE-STAR would produce. In order to calculate this, it is required to know how much power from the array actually lands on the asteroid. The asteroid's diameter is defined to be D_A and its distance to be L . The length of the DE-STAR's sides is defined to be d , its surface area to be A , its optical output power to be P , its laser spot diameter to be D_S , and its transmitted laser beam divergence to be θ_T [rad]. Since the DE-STAR both transmits and receives in space where there is no atmospheric distortion, the system is diffraction limited, so, with λ in meters and assuming L is much, much larger than D_S (assuming a square array for simplicity):

$$\theta_T = 2 \cdot \frac{\lambda}{d} \quad (1)$$

$$D_S = \theta_T L \quad (2)$$

In order to determine the photon rate reflected back to Earth, the fraction of the DE-STAR's power is actually incident on the asteroid must first be determined. The fractional area of the transmitted beam that lands on the asteroid is defined to be Γ_T .

$$\Gamma_T = \begin{cases} 1, & \left(\frac{D_A}{D_S}\right)^2 > 1 \\ \left(\frac{D_A}{D_S}\right)^2, & \left(\frac{D_A}{D_S}\right)^2 < 1 \end{cases} \quad (3)$$

Then the power incident on the asteroid, P_A [W], is simply:

$$P_A = P \cdot \Gamma_T \quad (4)$$

The laser photon flux received at Earth is defined to be N_E [ph/(s·m²)], and the albedo, or reflection coefficient, of the asteroid to be α . An assumption of isotropic emission into the forward 2π hemisphere is made.

$$N_E = \frac{\alpha(P_A/E_{\text{photon}})}{2\pi L^2} \quad (5)$$

$$N_E = \frac{\alpha P_A \lambda}{hc 2\pi L^2} \quad (6)$$

Finally, the laser photon rate received at Earth is defined to be R_E [ph/s]:

$$R_E = N_E \cdot A = N_E \cdot d^2 \quad (7)$$

The results for this simulation for DE-STAR's 1 through 4 are depicted in Fig. 3. An asteroid albedo of 0.1 was assumed.

Case of non-phased array reception - If the receive array is NOT phased as a single unit but rather used as a "light bucket" with each individual element being a diffraction limited element in itself then the entendue of each optical sub element of the array is $A_{\text{element}} \Omega_{\text{element}} = \lambda^2 \sim 10^{-12} \text{ m}^2\text{-sr}$ where A_{element} is the effective receiving area of the sub element and Ω_{element} is the received solid angle of the sub element and the total background is simply multiplied by $n \cdot A_{\text{element}} \Omega_{\text{element}} = \lambda^2$ where n is the total number of sub elements. **Hence the background is "n" times larger.** It is desirable to phase all the elements in the receive mode if possible for distant targets where the return flux is low. The transmit side is always assumed to be phased into one single phased array.

Assuming a minimum of 10 ph/s required for detection, the DE-STAR 1 could detect asteroids as small as 2m out to 0.03 AU, asteroids 200 m or larger out to 0.3 AU, and 10 km or larger out to 1 AU. The DE-STAR 2 should be able to detect asteroids as small as 1m at 0.03 AU, as small as 2 m at 0.3 AU, and asteroids 30 m or larger at 1AU. The DE-STAR 3 produces a photon received rate large enough to theoretically be able to detect asteroids as small as 1m out to distances of 1 AU. The DE-STAR 4 should even be able to detect asteroids as small as 1m out to 5 AU. Based on these results, it is clear that DE-STAR has the potential to detect asteroids of smaller size and at greater distances than any current or proposed detection system. Photon received rates, however, are not the only factor in determining whether a detection can be made. The background noise in the return signal must be considered, as well as the time required to scan a certain area of sky, out to a certain distance, in order to detect asteroids of a certain size. These concerns are discussed in the following sections.

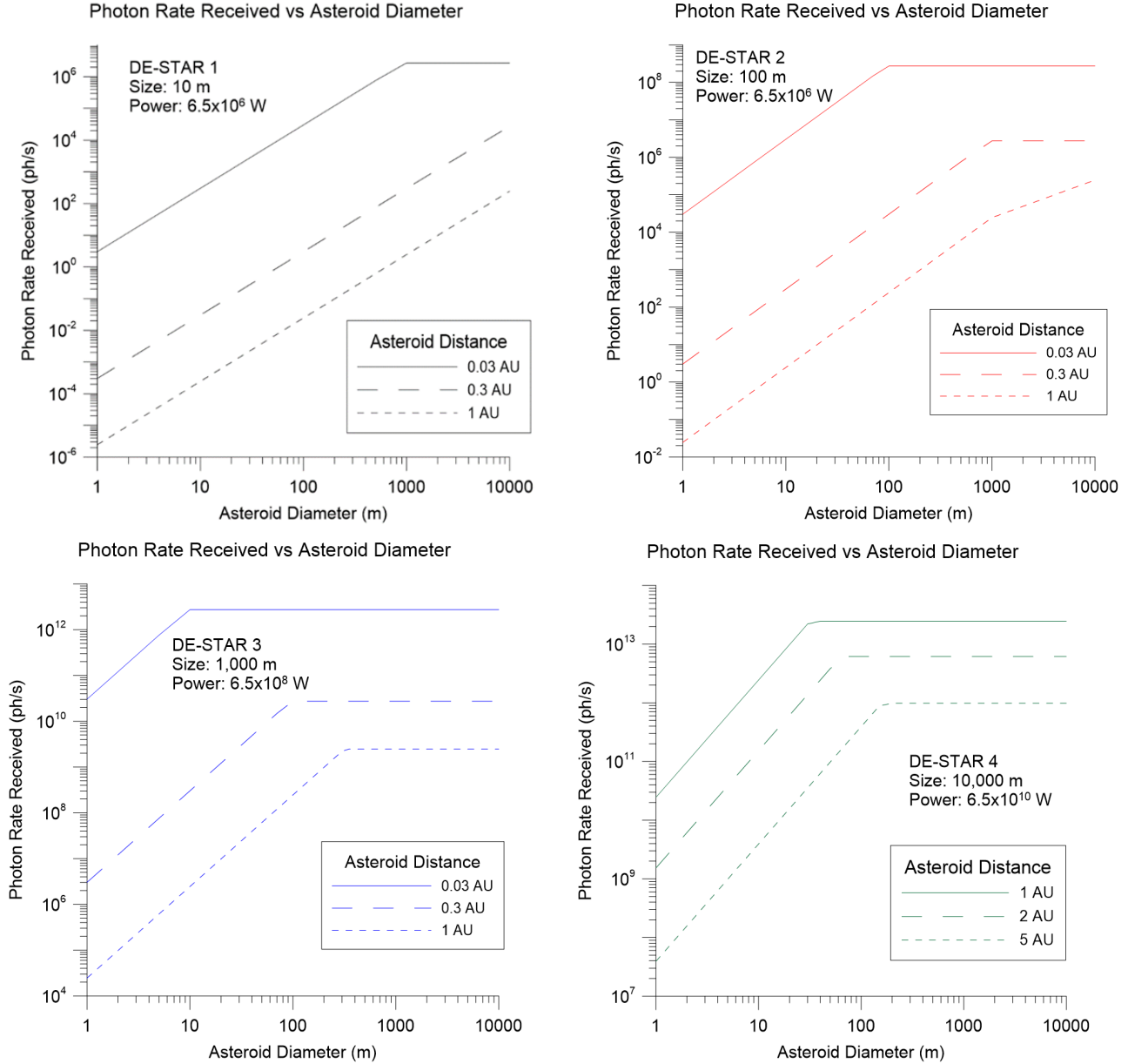


Figure 3. Simulations of laser photon rate received at Earth vs. the diameter of asteroid desired to detect for various size and power DE-STAR's at different asteroid distances. **Upper Left:** DE-STAR 1 with side length of 10m and 6.5×10^6 W of power. **Upper Right:** DE-STAR 2 with side length of 100m and 6.5×10^6 W of power. **Lower Left:** DE-STAR 3 with side length of 1,000 m and 6.5×10^8 W of power. **Lower Right:** DE-STAR 4 with side length of 10^4 m and 6.5×10^{10} W of power.

3.3 Backgrounds

A serious concern for reaching DE-STAR's full potential is the magnitude of background noise sources. If the backgrounds produce a large enough photon rate of their own, the LIDAR return signal could be swamped in the noise and impossible to detect. Backgrounds that could interfere with the return signal are the CIB and ZODI backgrounds as well as the asteroid's in-band thermal and sunlight emission. Since this is an orbital system, there is no atmospheric component. The total background will be denoted R_B [ph/s]. Note that the backgrounds are treated as random fields while the LIDAR signal is a controlled field and thus it is possible to integrate the signal to increase the SNR.

It is possible to calculate the background from the CIB and ZODI, not including the asteroid thermal and sunlight emission, which will be denoted $R_{CIB+ZODI}$ [ph/s]. Using the data in Fig. 2 and Fig. 3, it is possible to determine

the background flux from the CIB, N_{CIB} , and ZODI, N_{ZODI} , at wavelength $\lambda = 1.06 \mu\text{m}$. Under a worst case scenario, use $E_{\text{lat}} = 0$ for the ZODI component.

$$\begin{aligned} N_{\text{CIB}} &\approx 5.5 \times 10^{10} \text{ ph}/(\text{s} \cdot \text{m}^2 \cdot \text{sr} \cdot \mu\text{m}) \\ N_{\text{ZODI}} &\approx 1 \times 10^{14} \text{ ph}/(\text{s} \cdot \text{m}^2 \cdot \text{sr} \cdot \mu\text{m}) \end{aligned}$$

Again, since there is no atmospheric interference, it is possible to assume a diffraction-limited system and calculate the receive telescope solid angle, Ω_{R} [sr]:

$$\Omega_{\text{R}} = \left(2 \cdot \frac{\lambda}{d}\right)^2 = \theta_{\text{R}}^2 \quad (8)$$

Where θ_{R} [rad] is the divergence of the receive beam. The received bandwidth is defined to be β_{R} [μm], which, as mentioned earlier, is the same as the laser bandwidth. The effective receive area is $A (=d^2)$.

$$\begin{aligned} R_{\text{CIB+ZODI}} &= [N_{\text{CIB}} + N_{\text{ZODI}}] \cdot A \cdot \Omega_{\text{R}} \cdot \beta_{\text{R}} \\ R_{\text{CIB+ZODI}} &\approx 1.68 \times 10^{-7} \text{ ph/s} \end{aligned} \quad (9)$$

The asteroid's in-band thermal emission is defined to be N_{th} and its in-band sunlight emission to be N_{s} . To calculate the asteroid's thermal emission, the asteroid is treated as a blackbody with a temperature of 200 K and an emissivity of 1. Starting with Planck's law for spectral radiance [$\text{W}/(\text{m}^2 \cdot \text{sr} \cdot \text{m})$]:

$$B_{\lambda} = \frac{2hc^2}{\lambda^5 \left(e^{\frac{hc}{\lambda kT}} - 1\right)} \quad (10)$$

Dividing by the energy of a photon and multiplying by 10^{-6} gives a result in units of $\text{ph}/(\text{s} \cdot \text{m}^2 \cdot \text{sr} \cdot \mu\text{m})$.

$$\begin{aligned} N_{\lambda} &= \frac{2 \cdot 10^{-6} \cdot c}{\lambda^4 \left(e^{\frac{hc}{\lambda kT}} - 1\right)} \\ N_{\text{th}} &\approx 1.59 \times 10^{-3} \text{ ph}/(\text{s} \cdot \text{m}^2 \cdot \text{sr} \cdot \mu\text{m}) \text{ at } 1.06 \mu\text{m}. \end{aligned} \quad (11)$$

To calculate the asteroid's sunlight emission (at the asteroid assuming it is 1 AU from the Sun), divide the solar constant (at 1 AU), $\approx 1,360 \text{ W}/\text{m}^2$, by the energy of a photon with a wavelength $\lambda = 1.06 \mu\text{m}$ and by π to account for the assumed isotropic forward scattering and multiply by the albedo of the asteroid, $\alpha = 0.1$ to get:

$$N_{\text{s}} \approx 2.3 \times 10^{20} \text{ ph}/(\text{s} \cdot \text{m}^2 \cdot \text{sr} \cdot \mu\text{m})$$

The DE-STAR receive beam size at the target is defined to be D_{R} and the fractional area of the receive beam that lands on the target to be Γ_{R} .

$$\begin{aligned} D_{\text{R}} &= \theta_{\text{R}} L \\ \Gamma_{\text{R}} &= \begin{cases} 1, & \left(\frac{D_{\text{A}}}{D_{\text{R}}}\right)^2 > 1 \\ \left(\frac{D_{\text{A}}}{D_{\text{R}}}\right)^2, & \left(\frac{D_{\text{A}}}{D_{\text{R}}}\right)^2 < 1 \end{cases} \end{aligned} \quad (12)$$

$$\Gamma_{\text{R}} = \begin{cases} 1, & \left(\frac{D_{\text{A}}}{D_{\text{R}}}\right)^2 > 1 \\ \left(\frac{D_{\text{A}}}{D_{\text{R}}}\right)^2, & \left(\frac{D_{\text{A}}}{D_{\text{R}}}\right)^2 < 1 \end{cases} \quad (13)$$

Putting everything together, calculate the total background (not including direct viewing of the Sun) is calculated to be:

$$\begin{aligned} R_{\text{B}} &= R_{\text{CIB+ZODI}} (1 - \Gamma_{\text{R}}) + [N_{\text{th}} + N_{\text{s}}] \cdot A \cdot \Omega_{\text{R}} \cdot \beta_{\text{R}} \cdot \frac{\Gamma_{\text{R}} \cdot D_{\text{A}}^2}{4\pi \cdot L^2} \\ R_{\text{B}} &\approx 1.68 \times 10^{-7} \text{ ph/s} \end{aligned} \quad (14)$$

Looking at Table I below it is clear that the dominant background is the Zodiacal light from scattered Sunlight except in the case of directly viewing the Sun in which case the direct viewing of the Sun dominates. Looking back to the calculated values for expected photon rates received for the various DE-STAR's in Fig. 4, it is clear to see that the

expected total background, even in the worst case, is negligible for all sizes of DE-STAR. When viewing asteroids very near the sun, however, the direct sunlight background can become too large for the smaller DE-STARS.

Table 1. Summary of approximate photon rates received at Earth and produced by relevant backgrounds assuming a DE-STAR 4 with a wavelength of $\lambda=1.06 \mu\text{m}$, a receiver bandwidth of $\beta_R=3.75 \times 10^{-10} \mu\text{m}$ ($1 \times 10^5 \text{ Hz}$) and $L=3 \text{ AU}$. The current generation of SBS limited laser amplifiers have a $\beta_R \sim 10^{10} \text{ Hz}$ and hence the backgrounds in the table would be 10^5 times higher. Even at this level the only background that would be a problem would be the direct viewing of the Sun.

Background Source	Photon Rate (ph/s)		
	10 m asteroid	100 m asteroid	1 km asteroid
Zodiacal Light (Ecliptic Lat. 0°)	1.68×10^{-7}	1.68×10^{-7}	1.68×10^{-7}
(Ecliptic Lat. 45°)	6.73×10^{-9}	6.73×10^{-9}	6.73×10^{-9}
(Ecliptic Lat. 90°)	3.37×10^{-9}	3.37×10^{-9}	3.37×10^{-9}
Cosmic Infrared Background (CIB)	9.26×10^{-11}	9.26×10^{-11}	9.26×10^{-11}
Thermal Emission	1.06×10^{-44}	1.06×10^{-42}	1.06×10^{-40}
Scattered Sunlight	1.53×10^{-21}	1.53×10^{-19}	1.53×10^{-17}
Optics	4×10^{-15}	4×10^{-15}	4×10^{-15}
Direct Sunlight – Pointed at Sun	2×10^4	2×10^4	2×10^4

3.4 Time for Blind Detection

The second concern in determining DE-STAR's detection capability is the amount of time it would require to scan a particular area of sky in order to detect a certain size of asteroid. The integration time to get a detection T , and the number of photons required for detection, are defined to be $\rho = 10 \text{ ph}$. Assuming that the total background is small, as shown in section 3.3, the integration time per beam can be calculated as:

$$T = \frac{\rho}{R_E} \quad (15)$$

The number of DE-STAR laser beams per square degree of sky are defined to be beams_D and the time per square degree of sky to get a blind detection is T_D . Recalling that the DE-STAR transmitted laser beam divergence is defined to be θ_T :

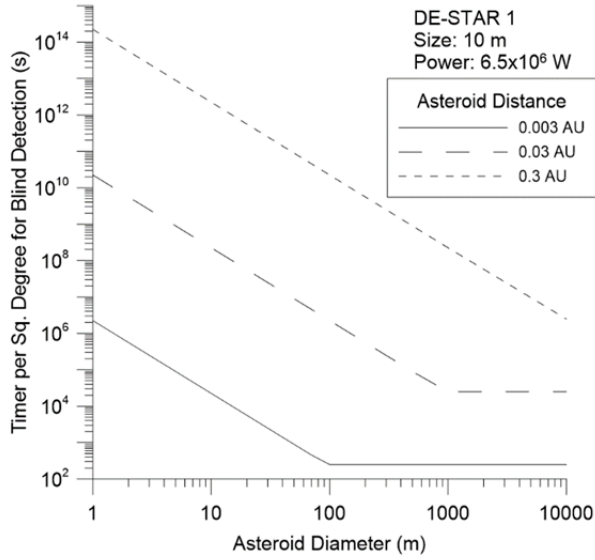
$$\text{beams}_D = \left(\frac{\pi/180}{\theta_T} \right)^2 \quad (16)$$

$$T_D = \text{beams}_D \cdot T \quad (17)$$

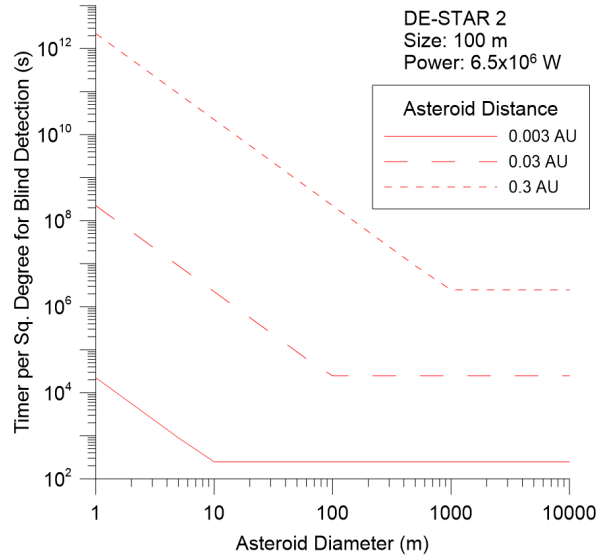
An actual search algorithm would be optimized based on some prior information, if available. This could come in the form of auxiliary datasets such as ground or space based surveys. Below completely blind surveys with no prior are assumed. To confirm detection the system would "peak up" on a return signature with an algorithm that takes into account the time of flight and the pointing history. The results for the blind simulation for DE-STAR's 1 through 4 are depicted in Fig. 4.

A DE-STAR 1 could scan a square degree of sky out to 0.003 AU in 6 hours and detect any asteroid 10 m or larger, or in 15 minutes and detect asteroids 50 m or larger. Beyond 0.003 AU, the DE-STAR 1 becomes very limited in its detection abilities, but it could still detect a 1 km asteroid within a square degree of sky out to 0.03 AU in 7 hours. A DE-STAR 2 could detect a 10 m, or larger, asteroid within a square degree out to 0.003 AU in 4 minutes. Within the same amount of time as the DE-STAR 1 out to 0.03 AU, a DE-STAR 2 could detect asteroids 100 m or larger. A DE-STAR 3 could detect a 10 m asteroid in a square degree of sky out to 0.03 AU in 4 minutes. Out to 0.3 AU, a DE-STAR 3 could detect a 100 m asteroid in 7 hours. A DE-STAR 4 could detect asteroids as small as 5 m, within a square degree of sky, in 28 seconds and out to a distance of 0.1 AU. In 4 minutes, a DE-STAR 4 could detect an asteroid as small as 10 m at a distance of 0.3 AU. In 50 minutes, a DE-STAR 4 could blindly detect a 40 m, or larger, asteroid within a square degree and as far out as 1 AU.

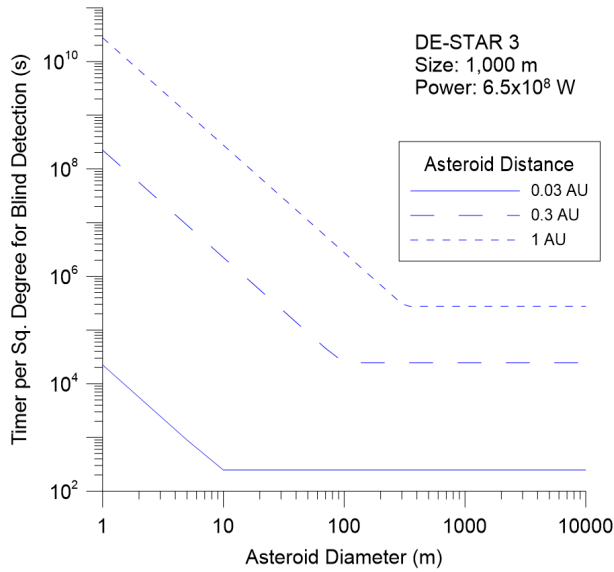
Time per Sq. Degree for Blind Detection vs Asteroid Diameter



Time per Sq. Degree for Blind Detection vs Asteroid Diameter



Time per Sq. Degree for Blind Detection vs Asteroid Diameter



Time per Sq. Degree for Blind Detection vs Asteroid Diameter

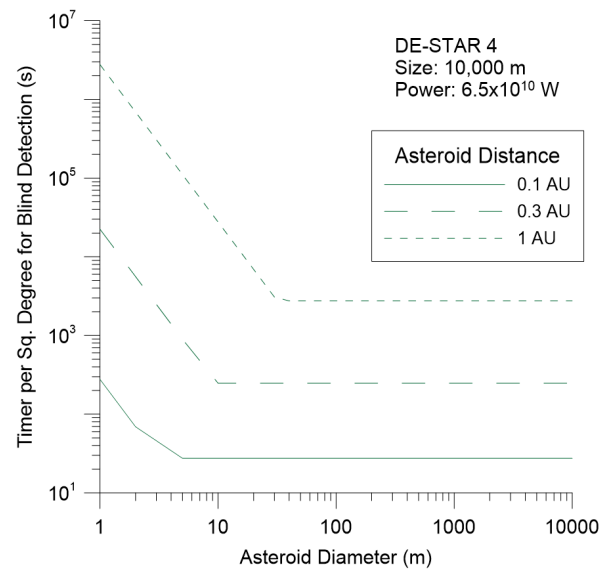


Figure 4. Simulations of time required to scan a square degree of sky vs. the diameter of asteroid desired to detect for various size and power DE-STAR's at different asteroid distances. **Upper Left:** DE-STAR 1 with length of 10 m and 6.5×10^6 W of power. **Upper Right:** DE-STAR 2 with length of 100 m and 6.5×10^6 W of power. **Lower Left:** DE-STAR 3 with length of 1,000 m and 6.5×10^8 W of power. **Lower Right:** DE-STAR 4 with length of 10^4 m and 6.5×10^{10} W of power.

Next, it is possible to calculate how long it would take DE-STAR to blindly detect different sizes of asteroid at different distances in a full sky survey. The number of DE-STAR laser beamwidths to cover the full sky, $beams_F$, is

$$beams_F = beams_D \cdot 4\pi \left(\frac{180}{\pi}\right)^2 \quad (18)$$

and the time per full sky survey necessary for a blind detection, T_F , is

$$T_F = \text{beams}_F \cdot T \quad (19)$$

The results for this simulation for DE-STAR 3 and 4 are depicted in Fig. 5.

Only the DE-STAR 3 and 4 have the possibility of completing a full sky blind survey in a reasonable amount of time. A DE-STAR 3 could complete a full sky survey out to 0.003 AU in 1 day, and it would be able to detect asteroids as small as 1 m out to that distance. In approximately 2 weeks, a DE-STAR 3 could complete a full sky survey out to 0.01 AU and detect any asteroid 5 m or larger. Given 4 months, a DE-STAR 3 could detect asteroids 10 m or larger in a full sky survey out to 0.03 AU. A DE-STAR 4 could complete a full sky survey out to 0.01 AU in 3 hours, and it would be able to detect asteroids as small as 1 m out to that distance. Out to 0.03 AU, a DE-STAR 4 could detect asteroids as small as 1 m in 1 day. In 1 week, a DE-STAR 4 could complete a full sky survey out to 0.1 AU and detect any asteroid 5 m or larger. Given 4 months, a DE-STAR 4 could detect asteroids 10 m or larger in a full sky survey out to 0.3 AU, covering the entire "Near Earth" area that contains all "Near Earth Asteroids".

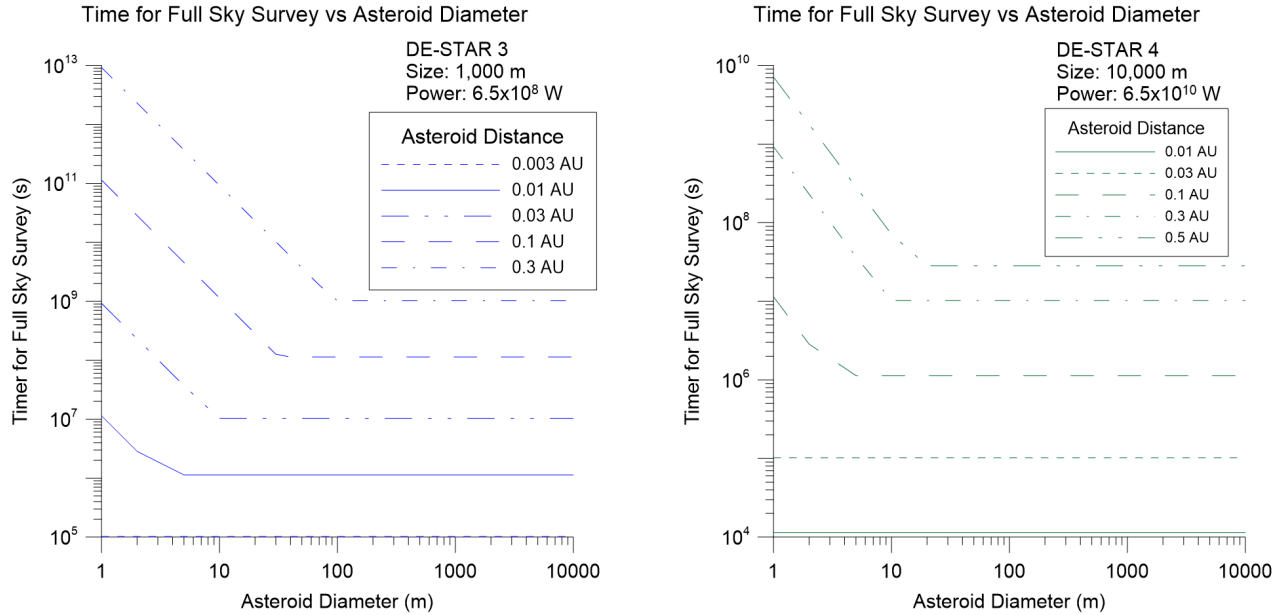


Figure 5. Simulations of time required to scan the entire sky vs. the diameter of asteroid desired to detect for various size and power DE-STAR's at different asteroid distances. **Left:** DE-STAR 3 with length of 1,000 m and 6.5×10^8 W of power. **Right:** DE-STAR 4 with length of 10^4 m and 6.5×10^{10} W of power.

3.6 DE-STAR versus Optical and Infrared systems

Now the question becomes, based on these simulations, how does DE-STAR compare to other current and proposed future detection systems? The majority of the current and proposed asteroid detection systems are ground-based optical surveys such as Pan-STARRS, the Catalina Sky Survey (CSS), the Large Synoptic Survey Telescope (LSST), and the Asteroid Terrestrial-Impact Last Alert System (ATLAS). A major problem with all of these ground-based optical surveys is that their field of vision is limited. They are only able to view the part of the sky that is visible from their stationary position on the Earth, and they can only operate at night. These ground-based telescopes are further limited by their inability to detect asteroids approaching from the direction of the sun or that approach during periods of bad weather. DE-STAR is not hindered by such problems as it would orbit around the Earth, fully operational at all times, able to scan more than just one section of the sky, unhindered by weather or interferences in the atmosphere, and, with the use of a narrow transmitted and received bandwidth, able to detect asteroids near the sun. These systems are, however, able to scan their visible area of sky much quicker, sometimes thousands of square degrees of sky a night, than a DE-STAR, which requires the largest and most powerful models be used in order to complete a full sky survey within a reasonable amount of time. Another problem with a lot of these large, powerful telescopes is that they are used to look for a variety of phenomena in the universe, not just asteroids, and they must be reserved for months, sometimes years, in advance. DE-STAR would be a system fully dedicated to the detection and mitigation of potential impactors.

Asteroids are also currently detected with the use of orbiting infrared sensors such as the Near-Earth Object Wide-field Infrared Survey Explorer (NEOWISE) and the in progress Sentinel. While these systems do not face the ground-based telescopes' challenges of a stationary position or bad weather or atmospheric interference, they still have vulnerabilities of their own. Their biggest weakness is that, similar to the optical surveys, infrared sensors are still passive detectors and are unable to scan for asteroids close to or approaching from the direction of the sun. They are also unable to scan as much of the sky as quickly as the ground-based telescopes. They are, however, able to detect darker asteroids than the optical surveys. As already stated, DE-STAR does not have the same problem with direct sunlight, although, since it does rely on the reflectivity of the asteroid, it may not be able to detect asteroids that are as dark as the infrared can detect.

DE-STAR is able to avoid many of the problems that current systems must face. Even if a full DE-STAR 4 system is not currently realizable, the inherently modular design of this system will allow for the construction and testing of the smaller models now. While these smaller models are unable to perform full sky surveys out to large distances efficiently, they can be used, collaboratively, to scan smaller areas of sky that are unobservable to current systems, specifically areas close to the sun. Another advantage to the DE-STAR system is one that is not discussed in this paper, and that is its other functions. Not only would a DE-STAR be able to provide detection abilities not currently possessed by current systems, it would also be able to vaporize and deflect the threats that it identifies. It is thus a full-time, front-line defense for Earth. The many other functions of such a system are covered in other papers on DE-STAR.

3.5 Quantifying Orbits

Not only could a DE-STAR be used to detect asteroids, but it could also provide valuable information on an asteroid's speed and orbit. Similar to radar systems, a LIDAR system could use time delay and Doppler shift measurements to determine an asteroid's speed and position. Having complete control of the emitted beam allows us to perfectly know its characteristics, and, by comparing the transmitted beam's characteristics with the reflected beams, a wealth of information can be derived. This is another considerable advantage of the DE-STAR system over the passive optical and IR systems. In order to make these measurements for a known asteroid, it is only necessary to scan a few arc-seconds of sky. The number of DE-STAR laser beams per square arc-second of sky, $beams_A$, is

$$beams_A = \left(\frac{\text{arcsec}}{\theta_T} \right)^2 \quad (20)$$

And the time necessary per square arc-second of sky is $beams_A$ times the integration time. The results for this simulation for DE-STAR's 1 through 4 are depicted in Fig. 6.

A DE-STAR 1 could scan a square arc-second of sky containing a 5 m asteroid out to 0.03 AU in 1 minute. Out to 0.3 AU, a DE-STAR 1 would be able to scan a square arc-second containing a 200 m asteroid in 3 minutes. Reaching out to 1 AU, the DE-STAR 1 becomes much more limited, but could still scan a square arc-second containing a 1 km asteroid in 36 minutes. A DE-STAR 2 could scan a square arc-second of sky out to 0.03 AU, containing an asteroid as small as 1 m, in 17 seconds. Out to 0.3 AU, a DE-STAR 2 could scan a square arc-second containing a 50 m asteroid in 1 minute. Once again, for simulated asteroids at a distance of 1 AU, the DE-STAR 2 becomes more limited, but would still be able to scan a square arc-second of sky containing a 100 m asteroid in approximately 36 minutes, or containing a 300 m asteroid in 5 minutes. A DE-STAR 3 could scan a square arc-second of sky containing an asteroid as small as 1 m out to 0.3 AU in 17 seconds. Out to 1 AU, a DE-STAR 3 could scan a square arc-second containing a 10 m asteroid in 21 seconds. A DE-STAR 4 would be able to scan a square arc-second of sky containing an asteroid as small as 1 m, and out as far as 5 AU, in 2 minutes. While only the larger DE-STARs are useful for detecting asteroids in large areas of sky, even the smallest DE-STAR could be very useful in quantifying the orbits of known asteroids.

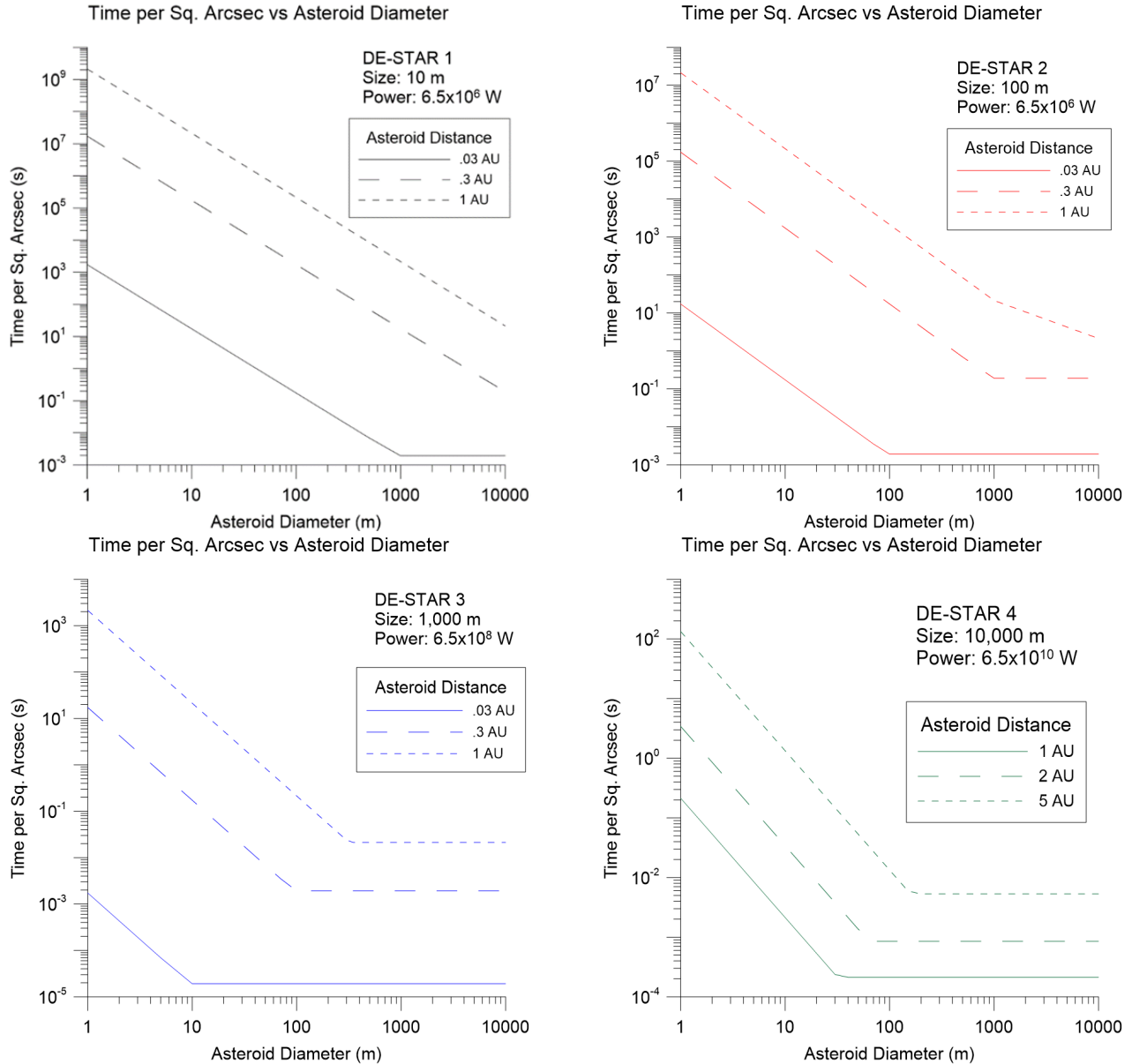


Figure 6. Simulations of time required to scan a square arc second of sky vs. the diameter of asteroid desired to detect for various size and power DE-STAR's at different asteroid distances. **Upper Left:** DE-STAR 1 with length of 10 m and 6.5×10^6 W of power. **Upper Right:** DE-STAR 2 with length of 100 m and 6.5×10^6 W of power. **Lower Left:** DE-STAR 3 with length of 1,000 m and 6.5×10^8 W of power. **Lower Right:** DE-STAR 4 with length of 10^4 m and 6.5×10^{10} W of power.

3.6 DE-STAR versus Radar systems

Given their large beam size and hence small signal to noise ratio (SNR), Radar systems are not used for discovering new asteroids, instead, they are used to further determine a known asteroid's orbit, speed and physical characteristics. Two of the most well known and most effective systems are Goldstone and Arecibo. Since these are ground-based systems, they face problems that are similar to the optical systems' including a stationary position with a fixed field of view and atmospheric interferences, which, as already stated, would not affect an orbiting DE-STAR system. A large enough DE-STAR can also out perform these systems. Arecibo is able to detect a 50 m asteroid at less than 0.1 AU.⁴ Goldstone is only able to detect a 50 m asteroid at less than 0.05 AU.⁴ Even the DE-STAR 1 has the potential to detect smaller asteroids at greater distances. The DE-STAR system has the ability to not only surpass optical

and IR systems in the discovery of asteroids, but also to surpass radar systems in the orbital refinement of previously detected asteroids.

3.7 Space Debris Detection

The smaller DE-STARS proved to be unrealistic for full sky surveys out to distances necessary for asteroid detection. These smaller DE-STARS have the potential to be very useful in the detection of close objects, specifically objects orbiting Earth. Many thousands of pieces of man-made, non-functional objects are currently in orbit around Earth, most commonly known as space debris. These objects can travel at orbital speeds, making even small pieces potentially very dangerous to satellites and other spacecraft.⁵ Using the same calculations for asteroid detection, it is possible to run similar simulations for space debris detection, the results of which are shown in Fig. 7. Now, however, the objectives include much smaller targets and much shorter distances.

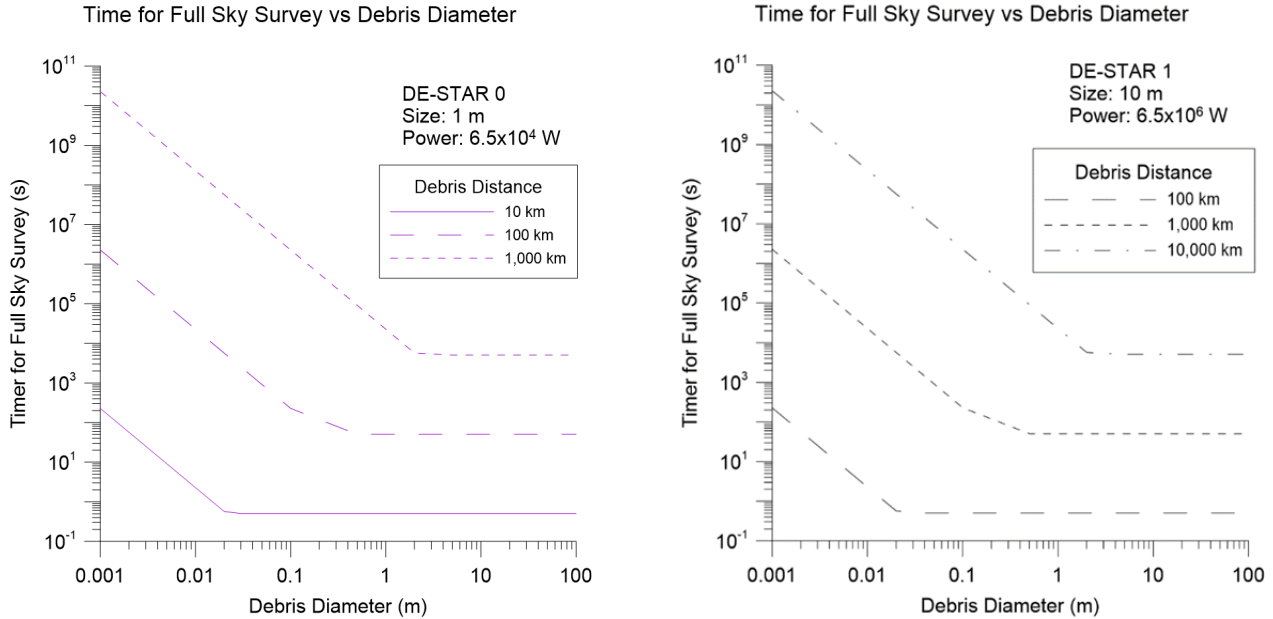


Figure 7. Simulations of time required to scan the entire sky vs. the diameter of space debris desired to detect for various size and power DE-STAR's at different debris distances. **Left:** DE-STAR 0 with length of 1m and 6.5x10⁴ W of power. **Right:** DE-STAR 1 with length of 10m and 6.5x10⁶ W of power.

A DE-STAR 0 could complete a full sky survey in 4 minutes and be able to detect debris as small as 1 mm out to 10 km. Out to 100 km, a DE-STAR 0 could detect debris as small as 1 cm in 6 hours, or as small as 1 mm in 4 weeks. Once detection distances reach 1,000 km, the DE-STAR 0 becomes much more limited, but it could still complete a full sky survey in 4 weeks and detect debris as small as 10 cm. In 4 minutes, a DE-STAR 1 could complete a full sky survey out to 100 km and detect debris as small as 1mm. Out to 1,000 km, a DE-STAR 1 could detect debris as small as 1 cm in 6 hours, or as small as 1 mm in 4 weeks. The DE-STAR 1 becomes much more limited when performing a full sky survey out to 10,000 km, but it could still detect debris as small as 10 cm in 4 weeks. **Note that this same system, like in the case of asteroids, can be used not only for detection but for mitigation where the focus beam can vaporize space debris once it is located.** These times are over-estimates, since it is not necessary to scan the full 4π sr in general since it is more common to be concerned with a narrower cone in elevation for a space based system. Typically the time given are an over estimate by factor of 4. **This same model can be used for a ground based system which can be used for both detection and space debris vaporization.**

4. CONCLUSIONS

DE-STAR provides a self-contained detection and protection system for asteroids and comets that threaten the Earth. Simulations of return photon rates and times required to scan various areas of sky to do a blind survey of asteroids and comets are presented. While only the larger models of the DE-STAR system are able to efficiently detect asteroids through full sky blind surveys, the smaller models that could be built today can still provide valuable services

such as looking for asteroids in smaller areas of sky that current systems are unable to scan, including parts of the sky that are close to the sun, orbital refinement of known asteroids and space debris detection. As technology continues to advance, even larger systems can be envisioned that can provide a full-time, frontline defense for Earth. It was not discussed in this paper, but DE-STAR also has the ability to perform a variety of other functions besides detection including deflection, vaporization and compositional analysis of NEOs.^{6,7,8,9,10,11}

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