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Author(s):

Gregory H. Canavan, DDP

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LASER DEFLECTION OF SPACE OBJECTS - AN OVERVIEW

Gregory H. Canavan
Senior Scientific Advisor
Los Alamos National Laboratory, MS D545
Los Alamos, New Mexico 87545

Lasers provide the two major attributes required for effective deflection of space objects: agility and efficiency. Lasers act instantaneously over long distances with little losses, but deliver energy at modest power levels. Material interceptors provide large impulses, but deliver only a fraction of the mass launched into space at low speeds. The two deflection concepts are compared, as are some important additional applications.

The Earth is repeatedly subjected to devastating impacts from asteroids and comets, which laser deflection could prevent. There are promising new technologies for both the large optics and efficient lasers required. Deflection velocities are within reach of lasers and optics that are developed or in development. Simple approximations to power and aperture costs can be used to estimate optimal combinations, which reduce cost and sensitivity to NEO size. For a wide range of conditions, laser deflection is competitive with or superior to nuclear explosives on rocket interceptors because of their speed of light delivery and better coupling. Laser deflection also has a number of other space applications ranging from debris clearing to satellite power and deep-space propulsion. This convergence of the requirements for large lasers for near-Earth applications and large optics for deep space applications suggests a progressive set of important problems that lasers could solve. Appropriately optimized combination of lasers and apertures could solve each affordably with technology in development. These applications form a progression from modest to stressing applications, each of which is important in its own right and which motivates the progressive development of the technologies required for the next. For that reason, they provide the basis for a continuing development of both the laser and optics technologies required to address those applications in rough order of urgency.

Comet and asteroid threat and deflection

The Earth is periodically subjected to devastating impacts from asteroids and comets. The most recent reminder of such impacts was Shoemaker-Levy 9 impacting Jupiter, for which the rings from even the smallest objects were larger than the Earth. Such impacts have the potential for global, catastrophic damage. There are about 2,000 near-Earth objects (NEOs) larger than one kilometer on short-period orbits that intersect the Earth's orbit, of which only about 7% have been discovered. As they repeatedly traverse the Earth's orbit, they occasionally hit it, which gives rise to the impact intervals as a function of NEO mass and yield shown in Fig. 1. NEOs the size of the 8 km diameter, 10^8 megaton (MT) yield impactor at the K-T boundary associated with the disappearance of the dinosaurs have an interval of about 50 million years. Tsunamis from $\approx$ 300 m impactors occur at an intervals of about 10,000 years. Thus. there is about one chance in a hundred such an object will impact during an average person's life span, and about one chance in ten that he will die if it does. Damage from MT air disintegration of meteors, as over Tunguska in Siberia in 1908, occur about every 300 years. Objects a few meters across hit the atmosphere each month and are detected by missile warning systems. The energies released are enormous. For K-T sized impactors, the energy scales are a million-fold larger than those for nuclear explosives. The release of these energies, largely in the form of molten material and ejected ash, produces global effects by blocking photosynthesis and injecting sub-micron particles into the stratosphere, where they could persist for months or years. Ejected particles would heat to incandescence at high altitudes during decent, producing radiation fluxes large enough to start fires at the far end of the Earth. Such effects could cause major loss of global crop production and consequent loss of animal and human life.

Laser impulse

It is not necessary to generate energies as large as those of the NEO's in order to negate them; it is only necessary to deliver enough energies to deflect the NEO enough to miss the Earth. Such energies can be generated and delivered by lasers, even those of current design.[1,2] Lasers are well suited to the deflection of NEOs because they can propagate to long ranges with little loss and produce impulse efficiently there by blowing material off the NEO itself. Thus, it is not necessary for them to carry large payloads to deep space to be effective. Laser interaction with matter has been studied extensively for the last few decades. There are three principal regions of interaction involved in NEO deflection, which are distinguished by the relationship of the laser fluence or energy per unit area delivered to the target to the heat to vaporize and ionize the object. Once the target is heated beyond the point of vaporization, material is blown off or ablated away, carrying off an amount of momentum, whose recoil imparts an impulse to the target.

Laser impulse is typically imparted at a pressure of a few atmospheres, so the object is accelerated almost shocklessly. That is an important distinction from nuclear explosives, which deliver their impulse at pressures of thousands or millions of atmosphere. Such pressures can rubbelize NEO material, which reduces the impulse coupling efficiency, necessitating standoff geometries that penalize coupling by one to two orders of magnitude. It is an automatic feature of the relatively slow energy delivery by lasers that they avoid this coupling penalty. It also follows from their generally whole-body irradiation that the differential accelerations to the objects are minimized, which also increases effectiveness.

Low fluence. If the object's thermal diffusion coefficient is S, during a laser pulse of duration t, the energy will diffuse into the object a distance $\approx \sqrt{(St)}$. If the object's heat of vaporization is Q and its density is r, that requires an amount of energy $r\sqrt{(St)}Q$. If the delivered fluence is less than that amount, i.e., $E < r\sqrt{(St)}Q$, essentially all of the energy delivered is used to heat the material, so no material is vaporized or blown off, and little or no impulse is generated. This lower limit fluence for efficient ablation, $r\sqrt{(St)}Q$, can also be expressed in terms of the flux, $F = E/t$, at which the energy is delivered, in terms of which the condition for efficient ablation is $F = E/t > r\sqrt{(S/t)}Q$. This result indicates a useful additional degree of freedom. Most lasers deliver their energy in a sequence of short pulses. It is usually possible to choose those pulse lengths in order to satisfy the constraint on F by each pulse. If that is done, the individual pulses can couple to the object efficiently, even though the average fluence of the pulse train falls below. Thus, the minimum fluence that couple efficiently is somewhat ill defined, and is somewhat less of a constraint than it might appear at first glance.

Intermediate fluence. The second regime is that in which E is greater than $r\sqrt{(St)}Q$, but lower than the fluence at which the blowoff plasma is ionized. In it, much of the deposited energy goes to evaporate material from the surface, which requires a specific energy per unit mass of about Q. The material then blows off with a velocity characteristic of the excess energy deposited, which is also on the order of Q. Thus, in this intermediate regime, the ratio of the momentum of the blowoff, I, to energy is on the order of $I/E \approx mv/mv^2 \approx 1/v \approx 1/\sqrt{Q}$. The heat of vaporization of most NEO materials is on the order of 4-8 MJ/kg, so a typical blowoff velocity is about $v \approx \sqrt{Q} \approx 3$ km/s, and the maximum coupling coefficient is on the order of $C = I/E \approx 1/v \approx 3x10^{-4}$ s/m $\approx 3x10^{-4}$ N-s/J. With inefficiencies, measured coefficients are ≤ 10 dyne-sec/Joule or about 10^{-4} N-s/J.[3] While that value is optimistic, it is used in the examples below, as most results can be scaled down directly for the 3-fold variations seen in current experiments.

High fluence. At higher fluences, the blowoff material absorbs enough additional radiation to ionize, which both shields the object from the beam and increases the velocity of the blowoff, each of which reduce coupling. The reduction in the amount of material removed means the energy is deposited in a smaller amount of mass. And the increase in the blowoff's velocity reduces coupling, which varies as 1/v. The net effect is that in this regime, coupling scales roughly as $I/E \approx 1/\sqrt{E}$, which falls rapidly as E increases. Laser fusion experiments are forced to operate in this regime as the implosion timing of the target dictates the time on which the impulse must be delivered. As fusion fluences are thousands of times larger, efficiencies are reduced to fractions of a percent. Thus, this regime is not attractive for NEO deflection. It requires the efficient delivery of large impulses, but they can be delivered over very long periods of time at low fluxes. Overall, for small fluences, the coupling coefficient is small and sensitive to the physical parameters of the object, although the use of laser pulse structure can reduce these sensitivities. For intermediate fluences, coupling is primarily sensitive to the object's heat of vaporization, which does not vary strongly with material. For high fluences, coupling falls rapidly. Given these sensitivities and efficiencies, it is clear that the deflection of large objects should operate in the intermediate regime, which in general, it is possible to do.

Propagation

For NEO deflection, it is appropriate to leave the laser on the ground, as there are several lasers which are large and efficient, but which are heavy and need large power sources. Conversely, it is appropriate to deploy the large transmitting mirror in space, which frees it from obscuration and damage and maximizes its pointing accuracy and flexibility. However, this combination of choices means that to reach a NEO, the laser beam must propagate from the laser up through the atmosphere and then be re-directed to the object. Each step is difficult. The former because it is necessary to correct for distortion of the beam by atmospheric turbulence; the latter because of the long ranges to the objects.

While turbulence correction is a difficult problem in general, it is simplified in this application by several factors. The first is that the satellites that redirect the energy are cooperative targets, so their beacons can be used to simplify the correction scheme. The second is that the constellation of satellites can be designed to minimize the path length through turbulence. Finally, the beam diameter can be increased to reduce propagation nonlinearities in the uplink. The combination of these factors reduce this problem to one that was largely solved in the missile defense programs of the previous decade.

Propagation to long range is conceptually simple, but technically challenging, because the ranges of interest are on the order of an astronomical unit (AU), which is $r \approx 180$ million km, the mean distance of the Earth from the sun. NEOs with diameters on the order of $D \approx 1$ km are of concern. The spreading of a diffraction limited beam of wavelength λ from a mirror of diameter D_L is λ/D_L; thus, at range r, the beam has diameter $r\lambda/D_L$. For it to be on the order of the diameter of the NEO requires $r\lambda/D_L \approx D$, or $D_L \approx r\lambda/D \approx 2x10^8$km x 10^{-6}m /1 km ≈ 200 m. This estimate slightly underestimates the diameter required, which means large mirrors are required. A wavelength somewhat shorter than 1 micron could be used, and smaller mirrors could be used for larger objects, but the influence of range is strong. It is most efficient to deflect objects near perihelion. NEOs with aphelions at 4-5 AU only spend about 20% of the time within 2 AU of the sun. That makes an average interaction distance of 1 AU from the Earth appropriate. They only have about a 30% probability of approaching the Sun from the same side as the Earth. Overall, there is perhaps a 10-20% probability that a given NEO can be engaged at a distance of 1 AU at any given time. Greater distances are *a priori* more likely. Thus, an "access" factor of $f \approx 0.1$-0.2 is used in the estimates below to approximate this averaging over orbits and geometries, which use a fixed r = 1AU as the range in estimates.

Laser mirrors of 100-200 m diameter are required to match the spot size with objects 1-2 km in diameter. Such diameters are one to two orders of magnitude available for terrestrial and space applications today; however, they are within reach of a number of technologies that received significant development in the last few decades. The use of segmented mirrors to synthesize large apertures is now a familiar technology.[4] In the large optics demonstration experiment (LODE), the DoD fabricated lightweight face sheets for space mirrors 1 cm thick for use in 10 m modules, which corresponds to a weight of ≈ 1 cm x 2 $gm/cm^3 \approx 20 kg/m^2$. That means a 30 m mirror would weigh about 20 tonnes, which could be deployed in a single launch with current boosters. Gas lenses have been demonstrated over a range of the mirror diameters required.[5] Both the DoD and NASA are supporting the development of very large, lightweight, gas filled or deployable mirrors for a variety of programs, which should be deployed in space with requisite apertures in the next decade. Thus, while aperture limitations are a real constraint at present, it is appropriate to study laser-mirror combinations that include very large apertures. It is not necessary to use mirrors that produce spot diameters the same size as the object. It is possible to use mirrors somewhat smaller, which produce spot sizes somewhat larger than the object. That "spills power," losing some power over the edge of the object. However, that can be compensated for by increasing the laser power and hence the fluence on the object. In many of the examples below, spilling power over the object is the economically preferred option, even in cases where larger mirrors are available.

Laser energy, impulse, and deflection velocity

The energy fluence at the range of the target object is approximately $E = fPt/D_s^2$, where P is the average laser power, f is the access fraction for the object irradiated, and t is the total duration of irradiation. The laser beam spot diameter at that range is $D_s = \lambda r/D_L = \lambda r/\sqrt{A}$, where $A \approx D_L^2$ is the laser aperture area. Only the energy that hits the object contributes to the total impulse, I_{tot} imparted to the NEO. It is assumed below that the laser beam is correctly pointed at the object, on average, but that it overfills the target for small mirrors and underfills (i.e., produces an illuminated spot smaller than) it for large mirrors. In the former case the area irradiated is D^2, the whole area of the object. In the latter it is only D_L^2. The total impulse delivered to the object is thus approximately $I_{tot} \approx CE \min (D_s,D)^2$. For small mirrors, $D_s > D$, so that $I_{tot}(D_s > D) \approx CED^2 = C(fPt/D_s^2)D^2 = CftPAD^2/(\lambda r)^2$, which scales on the effective energy delivery time ft, the coupling C, the laser's "power-aperture product" PA, and the object's area D^2. For large mirrors, $D_s < D$, so $I_{tot}(D_s < D) \approx CED_s^2 = C(fPt/D_s^2)D_s^2 = CftP$, which scales only on the energy delivered ftP and coupling C, and is independent of laser parameters other than power. The velocity increment generated in an object of mass M by a total impulse I_{tot} is approximately $\Delta V = I_{tot}/M \approx 2I_{tot}/\rho D^3$, where $M \approx \rho D^3/2$ is the object's mass and ρ is its density.

The velocity increments given to objects of various diameters by a 10 MW laser irradiating the object 10% of the warning time for 100 years with 50, 100, and 200 m diameter mirrors range from 1 to 100 cm/s. Deflecting an object that would impact in a year by a distance equal to the Earth's radius, R_e = 6,400 km, that would avoid collision, would only take $\approx 6.4x10^6 m / 3x10^7 s \approx 0.2$ m/s, which is the same order. For a 50 m mirror, the deflection scales as 1/D throughout. The reason is that it gives a spot size at 1 AU of $\approx 2x10^8 km \times 10^{-6} m /50 m \approx 4$ km, which is much larger than D. Thus, $\Delta V(D_s > D) = 2I_{tot}/\rho D^3 = 2fCtPAD^2/(\lambda r)^2\rho D^3 \propto 1/D$, which scales strongly on effective delivery time ft, coupling C, and power-aperture product, but inversely on the objects diameter. For the 100 m mirror, the deflection falls as 1/D to 2 km. Beyond that diameter, the minimization shifts to $\min (D_s,D)^2 = D_s^2$, and $\Delta V = I_{tot}/M = 2fCPt/\rho D^3 \propto 1/D^3$. A 200 m mirror produces a 1 km spot, so its scaling breaks at a still smaller diameters. The scaling for large objects is independent of laser optics, and decreases strongly with object diameter. For NEO diameters less than 1 km, both mirrors scale the same with D because they are both undersized. For the larger mirror the deflection of the larger objects falls off more rapidly beyond 1 km, because no more impulse is generated with increasing D, while the mass to be deflected increases as D^3. At about 4 km the two diameters would join, because even the small mirror could resolve NEOs that large.

A 4-fold increase in mirror diameter from 50 to 200 m produces a 16-fold increase in deflection for objects smaller than the laser spot, but that advantage decreases rapidly for objects larger than their spot size. The deflection velocities scale directly over the range of experimental values, which range down to about a factor of three smaller values. The estimates also use a 10 year time to impact, which is assumed to be 10 times longer than the 1 year irradiation time. In some geometries the irradiation time could be a larger fraction. For longer irradiation times, a given laser would produce a ΔV proportionally longer, giving $\Delta V \propto CftPA/(\lambda r)^2$. Thus, the laser parameters to manipulate to maximize deflection are coupling, irradiation time, power-aperture, range, and wavelength. These estimates assume that the coupling and time have been optimized and that the range has been averaged. Little more can be done with wavelength. Thus, the principal remaining variable is the power-aperture produce, PA, which is useful combination because for small objects, the laser parameters appear only in this combination, not separately.

Limits on aperture are discussed in the previous section. The options in lasers are somewhat greater. DoD efforts of the last three decades have demonstrated that lasers can be scaled to very large powers affordably with existing technology. A number of lasers at the MW level were built and tested several decades ago, and there was a program to build a free electron laser (FEL) at the 10-100 MW level in the last decade. Though not completed, there were no insuperable technological barriers to the program. The FEL program is an important benchmark for NEO deflection because it demonstrated the power, cost, and flexible pulse structure needed for this application. For the most part, scaling of DoD lasers to higher powers was limited by the lack of tactical utility of large, immobile devices.[6] Such efficient lasers are well suited to this application. Developing the devices required would largely be a matter of resuming programs put back into research at the beginning of this decade.

Laser requirements and performance

To deflect an object just enough to miss the Earth, the velocity increment must be on the order of $\Delta V \approx R_e/t$, where t is the time before impact. For an irradiation time of t = 10 years, the deflection velocity is only $\Delta V \approx 6.4\times10^6 m / 3\times10^8 s \approx 20$ cm/s; for a warning time of 100 years, the required deflection would be $\approx$ 2 cm/s, which is within the range of the modest systems above. This requirement on ΔV translates into a maximum object size and mass that can be negated by a given laser. For successful deflection, the velocity must satisfy $R_e/t \approx \Delta V \approx I_{tot}/M$ or $M \approx t\, I_{tot}/R_e$. For small mirrors or objects that gives $M \approx \rho D^3/2 \approx fCt^2PAD^2/(\lambda r)^2 R_e$, which can be solved for

$$PA \approx (\lambda r)^2 R_e \rho D/2fCt^2. \qquad (1)$$

For small mirrors or objects the key laser parameter is again the product PA, which scales primarily on object diameter D. For 100 years of warning, or 10 years of radiation, a 500 m object requires $PA \approx 10^3$MW-m^2, which could be provided by a 1 MW laser and a 30 m mirror. A 2 km object would require about 5 MW. For shorter warning times, PA increases rapidly. By 30 years it is about 15,000MW-m^2 for the 500 m object, which could be provided by a 4 MW laser and a 60 m mirror. 10 years warning would require $PA \approx 10^5$MW-m^2, which is 100-fold greater than the product needed for 100 years. While the product of P and A is determined, it is not clear from this analysis which combination of power and aperture should be used to meet this increase. However, the structure of the costs of P and A suggest a simple optimization discussed in the next section, which makes overall performance clearer. For large optics or objects, $M \approx I_{tot}(D_s < D)/\Delta V \approx Cft^2P/R_e$, which places a limit on laser power of

$$P \approx R_e M/fCt^2 \approx R_e \rho D^3/2Cft^2, \qquad (2)$$

which increases as object mass, or D^3. The power required for deflection by R_e is again less than a MW for long times and diameters under 1 km, but it increases rapidly as t decreases or D increases, although for a 500 m object, a few MW would still suffice with 10 years warning. The power increases more rapidly with size due to the D^3. The large optics limit delivers all of the power to the object, which minimizes the energy required. However, this mode of operation is not always possible. The common feature and strongest scaling of both the small and optics limits are their strong scaling on $1/t^2$, which makes PA and P increase sharply for short warning, which limits the application of laser deflection to objects detected shortly before impact. The laser power required for a given warning time can also be determined by equating the impulse expression to $\Delta V \approx R_e/t$ to obtain $\Delta V \approx I_{tot}/M \approx CE \min(D_s,D)^2/M \approx R_e/t$, which can be solved for

$$P \approx R_e D_s^2 M/Cft^2 \min(D_s,D)^2, \qquad (3)$$

as the power that just achieves the required deflection of the object with the given mirror diameter. For a 500 m object and a 200 m mirror, the power required is about 3 MW, but as the diameter is reduced to 25 m, the power increases to several hundred MW. For a 500 m object, the power increases in proportion to object diameter throughout. However, for a 2 km object, the aperture scaling saturates at 200 m, where the power becomes independent of optics. For 2 km, saturation is at 100 m at a power of $\approx$ 60 MW. While these results indicate how P and A can be combined, they do not indicate which combinations are most effective, which is addressed next.

Optimization

Simple approximations to the costs of power and aperture can be used to estimate optimal combinations of power and aperture. The hardware costs of a laser system can be estimated very roughly as the sum of costs for aperture and power, which are the dominant components of a ground-based laser, space-based reflector system. That approximate cost relationship can be written as $C_o = aA + pP$, where a and p are parameters. The value of p can be determined roughly by the goals of DoD lasers programs, which built several MW class lasers for a few \$M each, and attempted to build 10-100 MW FELs for marginal costs of a few \$1M/MW. Together, developmental and scaling programs suggest a value for p of a few \$/W; however, earlier programs had large fixed costs and significant experimental programs, so it would appear that for scaling to very large powers a value of $p \approx$ \$1/W is appropriate, which is used below. Estimating the cost of mirrors is difficult. That the Hubble Space Telescope cost \$100M for a few m^2 aperture does not mean that it is a useful scaling cost. The array, gas lens, and lightweight technologies discussed above each have the potential to reduce the cost of large optics by orders of magnitude. The choice of a ≈ $10K/m^2 is a subjective estimate based on the assumption of a factor of 100 reduction over the next few decades. It is straightforward to assess the impact of other choices.

These costs are essentially the hardware costs for constructing the system. Costs for integrating the laser into the overall defense could easily double these costs, and lifetime operating costs could double them again. But these additional costs typically scale on the hardware costs, which can be related directly to the requirements of the application, so it is most useful to express cost estimates in terms of these fundamental quantities.

Figure 2 shows the power, aperture, and total costs that result from substituting P and A into C_o, using the p and a parameters indicated above for 10 year, 10% irradiation of a 500 m object by lasers with the apertures shown. The downward sloping curve is for power; the upward sloping curve is for aperture; the top curve is their sum. For small apertures, the cost for mirrors is small, and the dominant cost is for power. At 25 m it is about $1/W times the 230 MW. For large mirrors, aperture costs dominate, and power costs are small. At 145 m the cost is approximately (145 m)^2 x $10K/m^2 ≈ $210 M. At an intermediate value of ≈ 65 m, there is a balancing of power and aperture costs which produces a lower total cost than either extreme. The hardware costs there are about $75 M. At small apertures, the costs for the system are dominated by that for power, which scales as 1/D, so the costs for deflecting 500 and 1,000 km objects converge to essentially the cost of aperture. The 2,000 m object costs are somewhat higher; it saturates at about 60 MW at 100 m, while that for the 500 and 1,000 km objects continue to fall. That gives about the 60 MW x $1/W ≈ $60M offset of the 2 km object. The minimum in the total cost is at about a 55 m mirror for a 500 m object; a 70 m mirror for a 1,000 m object; and a 85 m mirror for a 2.000 m object. The corresponding minima increase from about $80M through $110M to $150M. Thus, neither the optimal aperture or cost vary rapidly with object size.

It is possible to determine the optimal aperture, power, and cost analytically, which makes the investigation of the sensitivity of these results to various parameters, particularly engagement time, somewhat clearer. For small apertures, the key parameter is PA, which scales as D. Thus, for a given cost C_o, the differential of performance with respect to P and A gives dA = -Pp/a. Substituting its derivative with respect to P and A gives A = Pp/a; PA = P(Pp/a) = P^2p/a; and $C_o = pP + aA = 2pP$. On substitution this gives

$$P \approx \sqrt{[a(\lambda r)^2 R_e \rho D/2pfCt^2]}, \qquad (4)$$

which shows that the optimal power scales as $\sqrt{D}/t$ rather than as the D/t^2 for fixed aperture. An increase in p relative to a causes a substitution of A for P, and vice versa. $C_o = 2pP \propto p\sqrt{(a/p)} = \sqrt{(ap)}$, which means that a 100-fold increase in either p or a would only cause a 10-fold increase in C_o due to the substitutions noted above. For large apertures, the key parameter is P, which scales as D^3. In this limit, there is no advantage to further decreasing the spot size below D, so the mirror diameter is fixed at $\lambda r/D$. Thus, there is no optimization; the power is $P = R_eM/fCt^2$; and the cost is $C_o = pP + aA = pR_eM/fCt^2 + a\lambda r/D$. For small objects the cost of the large mirror system would be much larger than that of the small mirror system, so it is preferable to use the latter. For increasing diameter, the cost of the large mirror system drops rapidly and that of the small mirror system increases slowly; thus, the two gradually converge. They meet at about 2 km, where the two give the same power and aperture. At that point, one is indifferent between the two. For larger objects, cost of the large object system are greater than that of the small optic system, but the latter is not realizable, since the optimum aperture gives a beam size smaller than the object. Thus, the system cost follows the straight small optics curve up to the point of indifference and then switches over to the large optic cost.

Deflection capabilities

The equations for the power and aperture required for various sized objects can be inverted to determine the maximum object diameter that can be deflected by a laser system of a given power and aperture. For $D_s > D$, $D \approx 2pfCt^2P^2/a(\lambda r)^2R_e\rho$, while for $D_s < D$, $D = (2fCt^2P/R_e\rho)^{1/3}$, which are shown on Fig. 3 for P = 10, 30, and 100 MW and 10% availability. The top curve for 1 MW gives ≈ 30 m object at 1 year, and a 3 km object at 10 years. It then switches at an aperture A ≈ Pp/a ≈ 10,000 m^2 or a mirror diameter of ≈ 100 m, after which it increases to about 10 km at 100 years. The 30 MW curve follows the small optics curve to about 30 years, where it gives about 3 km. The 10 MW curve follows it to slightly over 100 years. Before transition, the differences between the three curves is significant; the 100 MW laser could deflect in 5 years a 1 km object that would take the 10 MW laser 50 years. After the transition, the diameter that can be deflected in a given time only increases as $D \propto P^{1/3}$, and the time taken to deflect a given object only varies as $t \propto \sqrt{P}$.

The solid curve is for a standoff nuclear explosion, corrected for the simplified orbital mechanics used above.[7] The nuclear curve intersects the 100 MW laser curve at about 10 years, which is appropriate in that by then the laser has delivered about 100 MW x $3\text{x}10^7$s/yr x 10 yr x 10% ≈ $3\text{x}10^{15}$J ≈ 1 MT. The rocket interceptor might deliver 10 times more energy, but would do so less efficiently. For a 10 year intercept, a rocket flying outward at 3 km/s to meet a NEO approaching at ≈ 30 km/s, which reduces its effective deflection by an order of magnitude, which is why the two give comparable results. An additional reason is that the laser's coupling coefficient is generally much higher than that of nuclear explosives, whose energy deposits in shallow layers of material that are blown off at very high velocities. Also important for very long time scales is that the small optic object diameter scales at t^2, and even the large optic diameter scales as $t^{2/3}$; the nuclear diameter only increases as $t^{1/3}$.

Other applications, summary, and conclusions

The Earth is periodically subjected to devastating impacts from asteroids and comets, which could be prevented by laser deflection. The lasers can operate at near-optimal coupling fluences that minimize their propagation and generation requirements. There are promising new technologies for both large optics and efficient lasers. Because warning times are generally measured in decades, the deflection velocities are within the capability of lasers and optics that are developed or in development. Simple approximations to the costs of power and aperture can be used to estimate optimal combinations of power and aperture. Scaling them together greatly reduces cost and sensitivity to NEO size. For short warning times, laser power is significant. For longer times, the diameter that can be deflected in a given time only increases as the cube root of power, and the time to deflect a given object only varies as the square root of power. However, for a wide range of conditions laser deflection is competitive with or superior to nuclear explosives on rocket interceptors because of their speed of flight and better coupling.

Laser deflection has a number of other space applications ranging from debris clearing to satellite power and deep-space propulsion. Figure 4 shows the rough power requirements of optimized systems for these applications. Space debris is argued to have the potential to cascade collisionally to levels that could limit the use of low Earth orbit (LEO). While the ranges are only a few times R_e, the particle diameters are on the order of centimeters, so the optimal strategy is generally to use high powers and small apertures as in Eq. (4). Even then, the power is under 0.1 MW. Orbit maintenance of low altitude satellites requires slightly higher power. Laser propulsion to orbit requires about 10 MW, as do large, fast orbit changes.[8] GEO orbit maintenance and deep space insertion require about the same power, because both can deploy cooperative collectors to enhance the energy transfer efficiency. Those techniques also bring the power requirements for interplanetary probes and deep space exploration down into the range required for NEO deflection.

This convergence of the requirements for large lasers for near-Earth applications and large optics for deep space applications suggests a progressive set of applications to serious problems that lasers could solve, ranging from debris and satellite maintenance to comet and asteroid deflection. Appropriately optimized combination of lasers and large apertures could solve each problem affordably with technology that is developed or in development. These applications form a progression from modest to stressing applications, each of which is important in its own right and each of which motivates the progressive development of the laser technologies required. Thus, they could provide the basis for a continuing development of both the laser and optics technologies required to address each problem in rough order of urgency.

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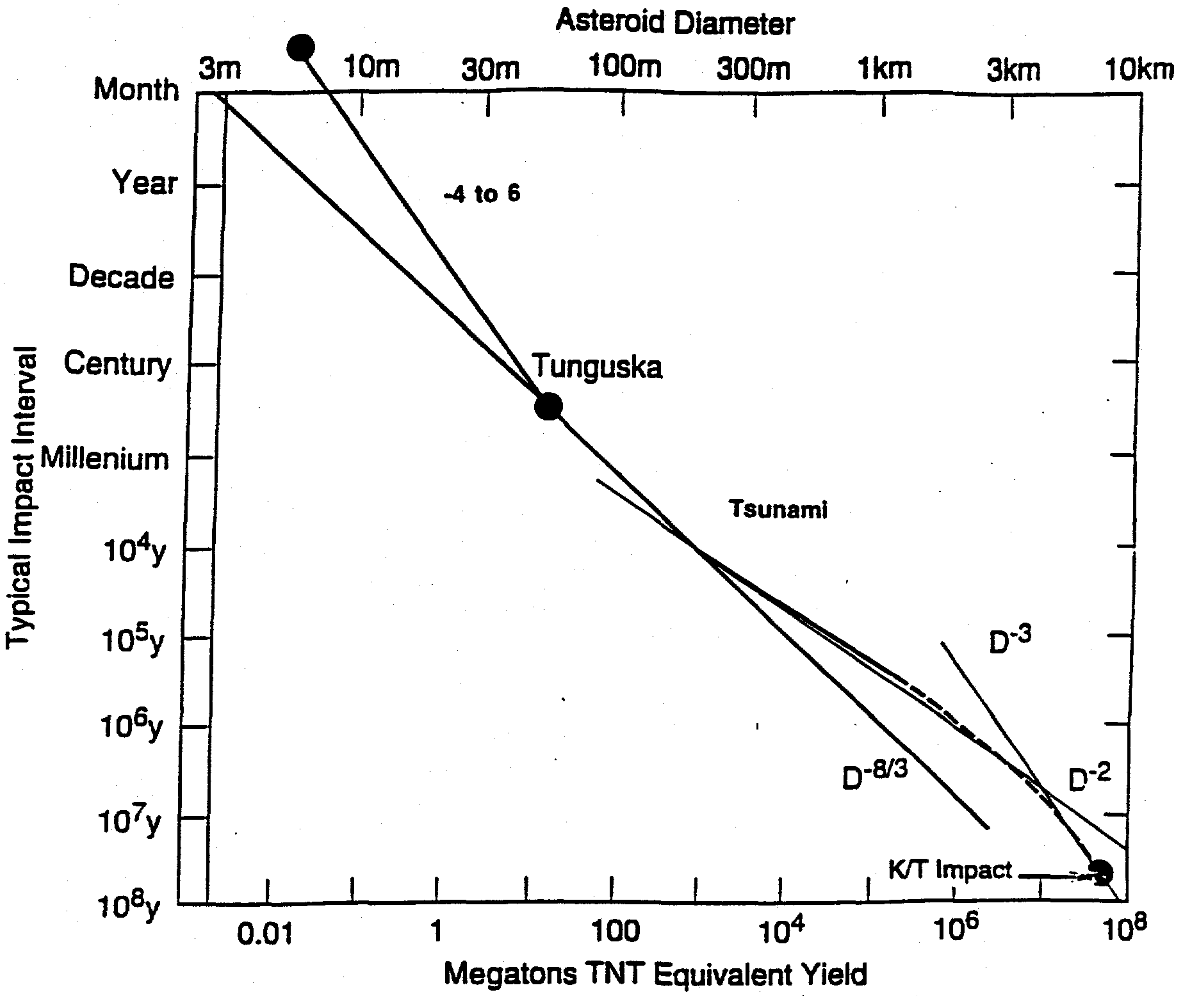

Fig. 1. NEO Impact Frequency and Energy

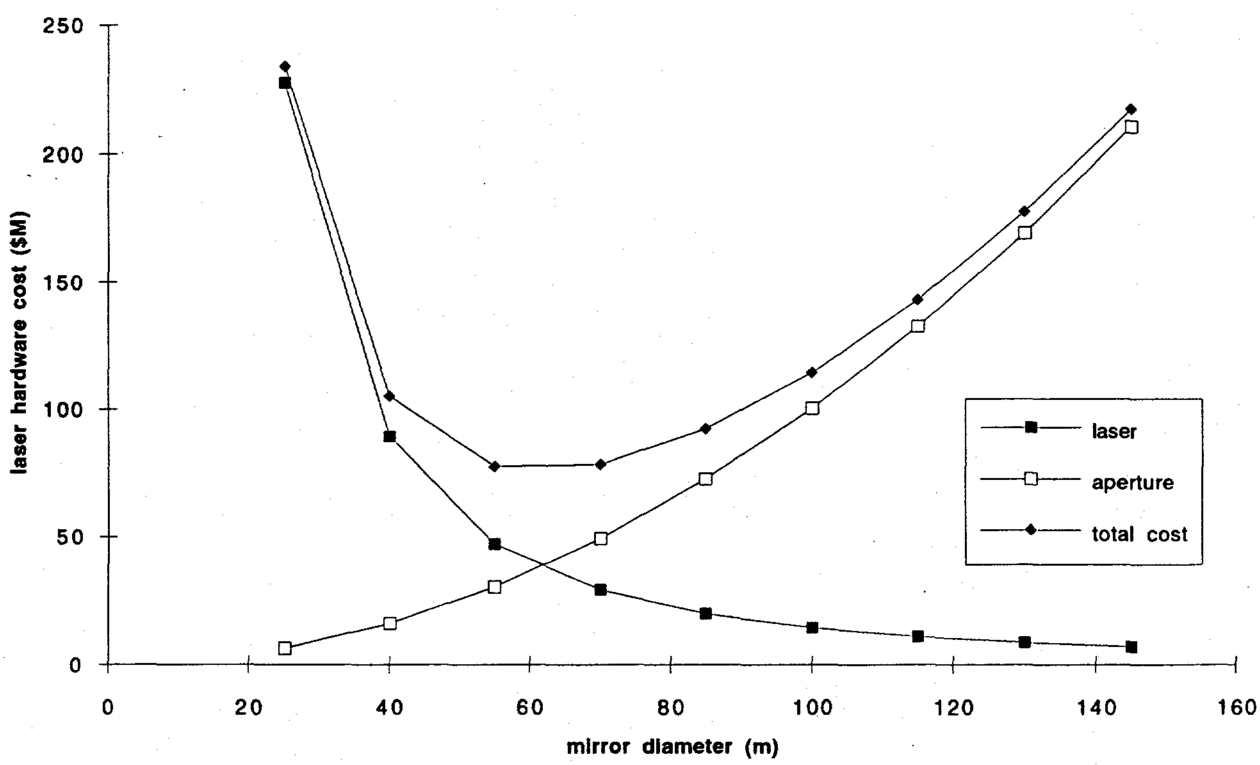

Fig. 2. Power, aperture, and total hardware costs versus mirror diameter for 10 year 10% irradiation of 500 m object.

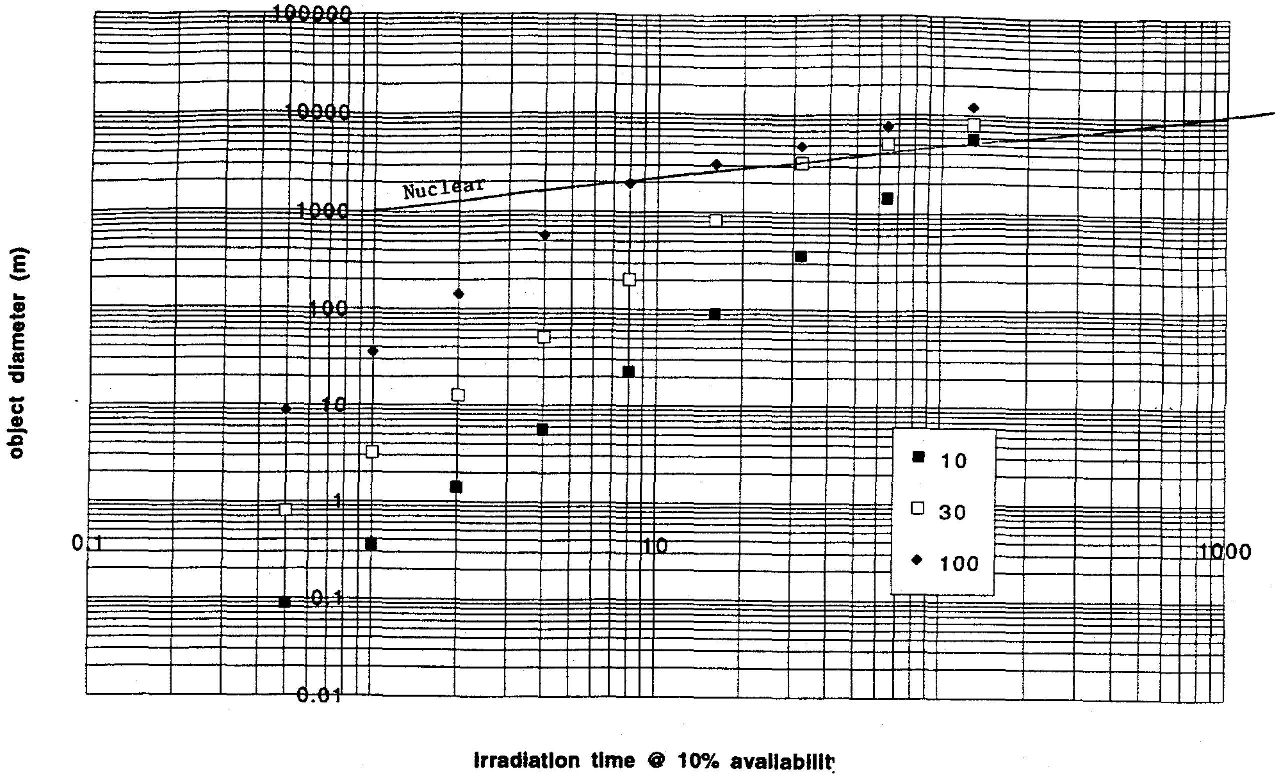

Fig. 3. Diameter of object that can be deflected versus irradiation time for various powers (MW).

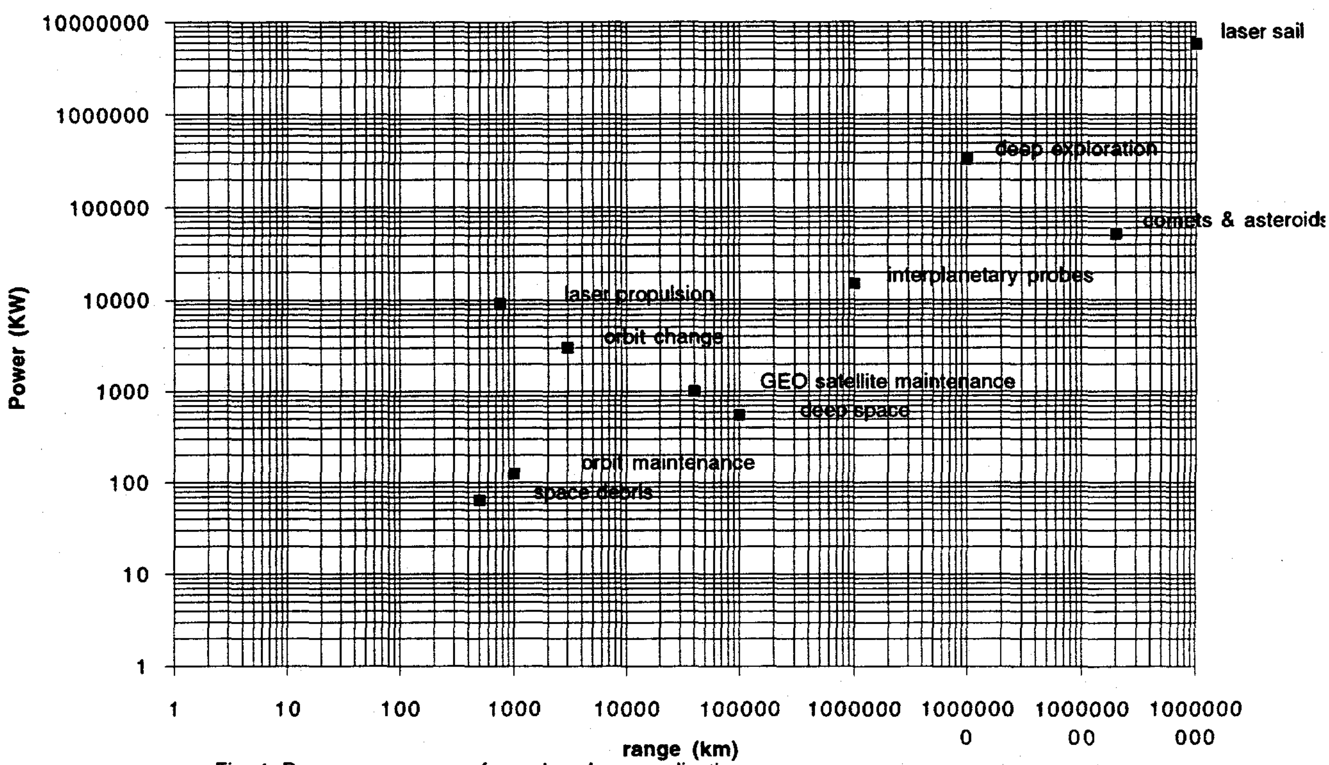

Fig. 4. Power versus range for various laser applications.