Articles

Cost of Space-Based Laser Ballistic Missile Defense

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Orbiting platforms carrying infrared lasers have been proposed as weapons forming the first tier of a ballistic missile defense system under the President's Strategic Defense Initiative. As each laser platform can destroy a limited number of missiles, one of several methods of countering such a system is to increase the number of offensive missiles. Hence it is important to know whether the cost-exchange ratio, defined as the ratio of the cost to the defense of destroying a missile to the cost to the offense of deploying an additional missile, is greater or less than 1. Although the technology to be used in a ballistic missile defense system is still extremely uncertain, it is useful to examine methods for calculating the cost-exchange ratio. As an example, the cost of an orbiting infrared laser ballistic missile defense system employed against intercontinental ballistic missiles launched simultaneously from a small area is compared to the cost of additional offensive missiles. If one adopts lower limits to the costs for the defense and upper limits to the costs for the offense, the cost-exchange ratio comes out substantially greater than 1. If these estimates are confirmed, such a ballistic missile defense system would be unable to maintain its effectiveness at less cost than it would take to proliferate the ballistic missiles necessary to overcome it and would therefore not satisfy the President's requirements for an effective strategic defense. Although the method is illustrated by applying it to a space-based infrared laser system, it should be straightforward to apply it to other proposed systems.

JAMES C. FLETCHER, FORMER ADMINISTRATOR OF THE National Aeronautics and Space Administration, chaired the Defensive Technologies Study for the Department of Defense at the request of the President. He describes (*1*) a number of space-based ballistic missile defense (BMD) systems considered by the study and concludes (i) that a comprehensive ballistic missile defense against a massive full-scale attack requires a multi-tier system in order to reduce leakage to an acceptable level and (ii) that each tier would have to destroy 70 to 90 percent of the threatening objects it encounters to be effective (*1*). According to Fletcher, one tier almost certainly would be directed against missiles in the boost phase, as current missiles are believed to be vulnerable at that time to appropriate weapons; in the boost phase the threatening objects are missiles. A number of weapons have been proposed for this purpose; one viewed as promising by Fletcher is based on a high-power laser, whose beam is directed at missile targets by a large mirror on an orbiting laser platform (*1*). The beam must dwell for a certain time on a missile in order to destroy it, and so each laser can destroy a limited number of missiles. Thus, to any specific number of laser platforms in orbit there corresponds a maximum number of missiles that can be destroyed. In these circumstances, one of several steps that the offense can take to counter a BMD system is to deploy additional missiles to replace those nullified by the BMD system, thus restoring the original offensive capability; in turn, the defense can counter the additional missiles by adding laser platforms.

The President's Strategic Defense Initiative (*2*), released by President Reagan on 28 December 1984, states "the defensive system must be able to maintain its effectiveness against the offense at less cost than it would take to develop offensive countermeasures and proliferate the ballistic missiles necessary to overcome it" (*2*, p. 5). The President's statement refers both to the development of countermeasures and to the proliferation of missiles. In this article, we estimate the cost of maintaining the effectiveness of a BMD system relative to that of proliferating the additional missiles necessary to overcome it. An appropriate quantity to measure this is the cost-exchange ratio, or CER, defined as the cost to the defense of destroying a missile, divided by the cost to the offense of deploying an additional one (*3*). The question of offensive countermeasures beyond proliferation of missiles and the steps required to maintain the effectiveness of the defensive system in the face of them is beyond the scope of the analysis presented here. Limiting ourselves to the proliferation of offensive missiles, we interpret the President's statement as requiring the CER to be less than 1.

As an example of our method of estimating the CER, we consider a space-based laser BMD system employed against a massive attack by ground-launched intercontinental ballistic missiles (ICBM). [Submarine-launched ballistic missiles (SLBM) and cruise missiles present difficult problems for space-based laser defense; we have not included them in the analysis.] In estimating the costs of the components of such a system, it became clear that the CER is likely to be considerably larger than 1. As our cost estimates are extremely uncertain, and it is desirable that our conclusions be as robust as possible, we have derived an estimated lower limit to the CER by adopting at each stage of the analysis lower limits to the costs involved in the BMD system and upper limits to the costs to the offense. In adopting this procedure, we are trying to develop the best possible case that the proposed BMD system will meet the President's requirements. In what follows, we first estimate the number of missiles destroyed by a typical laser platform, then the cost of each platform (and hence, the cost of destroying a missile), and finally, the cost of deploying an additional missile (and hence, the CER), at each stage employing lower or upper limits. Although we have considered only one tier of a proposed BMD system, the method can be applied to estimate a lower limit to the CER of other tiers of the proposed system, or of different systems. The reader should keep in mind that cost effectiveness is only one of the requirements that must be met by a BMD system.

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Number of Missiles Destroyed by a Laser Platform

The BMD system described by Fletcher (*1*) requires a number of laser platforms in earth orbit. At the time of a missile attack, many platforms will be beyond the horizon from ICBM launch sites, and hence ineffective for defense. In keeping with our procedure, we shall assume that every platform within line of sight of a launch site can be used effectively (even though for various reasons, such as atmospheric attenuation, described later, that is unlikely) and, therefore, we will refer to any platform within line of sight of a launch site as an "effective platform." In what follows, we will calculate N, the number of missiles that can be destroyed by an effective platform. By averaging N over all configurations of laser platforms that could exist at the time of an attack, we obtain n, the number of missiles that can be destroyed, on the average, by any platform in orbit—that is, by a typical platform.

We define the dwell time t_D as the time that a laser beam must dwell upon a missile in order to destroy it. The quantity t_D depends upon the hardness H of the missile (defined as the energy per unit area delivered normal to the missile's skin required to destroy the missile), the brightness B of the laser beam (defined as the energy per unit time per unit solid angle in the beam), the range R (defined as the distance between the laser platform and the target missile), and the angle of incidence θ (defined as the angle between the laser beam and the normal to the surface of the missile), according to

$$t_D = \frac{HR^2}{B\cos\theta} \quad (1)$$

The factor $\cos\theta$ converts the energy per unit area normal to the beam to the energy per unit area measured parallel to the skin of the missile. In Eq. 1 we are assuming that the vulnerability of the missile depends only on the total energy deposited. In fact, if t_D exceeds some (unknown) value, the energy can be dissipated without damaging the missile. In accordance with our procedure, we neglect this effect. Moreover, we have not considered the case in which a large burst of energy is delivered in such a short time that damage is effected by a shock wave in the skin of the missile; in that case, damage might require less total energy.

According to Pawsey and Bracewell (*4*), the brightness B depends on the laser power P, the diameter of the mirror D, and the operating wavelength of the laser λ, according to

$$B = \frac{\pi PD^2}{4\lambda^2} \quad (2)$$

From Eqs. 1 and 2, we see that

$$t_D = \frac{4\lambda^2 HR^2}{\pi PD^2\cos\theta} \quad (3)$$

As expected, t_D is larger for harder missiles, greater ranges, smaller laser powers, smaller mirrors, and larger angles of incidence.

We define t_B as the typical duration of boost phase for an attacking ICBM. A massive attack would be most effective if the spread in launch times were substantially smaller than t_B, for then the BMD system (which is constrained by finite dwell times t_D) would have the shortest possible time in which to operate. We have adopted the simple assumption that all missiles are launched nearly simultaneously; furthermore, we have assumed that all missiles are available as targets for the full duration of boost phase t_B, which, as we shall see, is some 50 to 200 seconds. In fact, the situation is less favorable to the defense than this implies, for a number of reasons. It will take some finite time to receive warning of the attack, to decide how to respond to it, and to activate the appropriate laser platforms. Moreover, the time over which missiles are available as targets is less than t_B by the time it takes missiles to rise through the atmosphere, where the laser beams are attenuated by water vapor, clouds, or both. This time is a significant fraction of t_B, especially for the fast-burn boosters discussed below. In accordance with our procedure, we ignore all these effects.

The effectiveness of the defense depends on the distribution of launch sites over the available area. At present, launch sites in the United States and in the Soviet Union are distributed over large areas. However, missiles launched from widely distributed sites tend to be vulnerable to attack by a space-based BMD system because the number of laser platforms within range of at least one site is greater than the number within range of any one site. The offense can deal with this by locating the additional missiles deployed to counter a BMD system within a relatively small area. This area need not be so small that mobile launchers would be vulnerable to attack, but only small enough that the separation between launch sites is considerably smaller than about 2000 km, a typical range at which a laser platform engages a missile. Because we are not aware of any additional cost to the offense for locating new launch sites within a small area, we assume that it will do so and therefore ignore the effect of geographical dispersal of launch sites in calculating the effectiveness of the BMD system.

We define the targeting time t_T as the time required by a laser platform to detect, track, and lock onto a missile target. Since the time spent engaging each target is $t_D + t_T$, during the time t_B, each effective platform can destroy N missiles, where

$$N = \frac{t_B}{t_D + t_T} \quad (4)$$

Here t_D depends on the position of the laser platform relative to the launch site.

Combining Eqs. 1 and 4, we can write N as

$$N = \left(\frac{Bt_B}{Hr_e^2}\right)\left(\frac{r_e}{h_{\min}}\right)^2\left(x^2 + \frac{R^2}{h_{\min}^2\cos\theta}\right)^{-1} \quad (5)$$

Here r_e is the radius of the earth; x is defined as the ratio of the tracking time to the minimum possible dwell time when R is set equal to $h_{\min}$, the minimum orbital altitude (see below), and θ is set equal to 0

$$x = \left(\frac{Bt_T}{Hh_{\min}^2}\right)^{1/2} \quad (6)$$

Note that we have implicitly assumed that the targeting instructions provided by battle management computers are completely effective, that each laser is pointed as accurately as required, that each laser beam is stabilized on the moving target over the entire dwell time, and that there are no malfunctions of the laser platforms because of improper maintenance, so that every laser platform can be regarded as typical.

We decompose the orbital motion of a laser platform relative to the launch site into two components: the motion in the fixed orbit and the rotation of the earth beneath the orbit. Let i be the orbital inclination, α the angular position along the orbit, and β the longitude of the launch site relative to the laser platform. Of course i is constant, whereas α and β vary with time. The launch site is assumed to be located at latitude 55°N; we find that our results are relatively insensitive to the exact latitude. The range R is

$$\begin{aligned} R(i,\alpha,\beta) = \{&[(r_e + h)\cos\alpha - r_e\cos(55°)\cos\beta]^2 \\ &+ [(r_e + h)\cos i \sin\alpha - r_e\cos(55°)\sin\beta]^2 \\ &+ [(r_e + h)\sin i \sin\alpha - r_e \sin(55°)]^2\}^{1/2} \end{aligned} \quad (7)$$

where h is the orbital altitude. We calculate the dwell time t_D (i, α, β) from Eqs. 1 and 7 for those platforms for which the launch site is above the horizon, and disregard all other platforms. The angle of incidence, θ, is computed under the assumption that the missile is launched due north at an elevation of 25°, appropriate for a minimum-energy trajectory between the Soviet Union and the United States.

In order to determine the total number of missiles, Γ, destroyed by the entire constellation of platforms, we sum the number of missiles destroyed by each platform, N, for a grid of platforms spaced evenly in α and β according to the integers p and s:

$$\Gamma(i,h) = \sum_{p=1}^{p_{\max}} \sum_{s=1}^{s_{\max}} N[h,i,\alpha(p),\beta(s)] \tag{8}$$

where $p_{\max}$ and $s_{\max}$ are chosen to be consistent with the total number of laser platforms L through

$$p_{\max}s_{\max} = L \tag{9}$$

and the positions of the platforms are found from

$$\alpha(p) = \frac{2\pi}{p_{\max}}(p + p_0) \tag{10}$$

and

$$\beta(s) = \frac{2\pi s}{s_{\max}} \tag{11}$$

Here p_0 is the phase of the constellation, defined so that as the platforms move along their orbits, p_0 varies between 0 and 1, causing fluctuations in the rate at which the system destroys missiles. These fluctuations can be made reasonably small by taking L large enough. We generally used $p_{\max} = s_{\max} = 20$, so that $L = 400$; calculations with other values of L in this general range showed that n, the number of missiles destroyed by a typical platform, is nearly independent of L, so that the actual value of L chosen is irrelevant.

In a real attack, p varies smoothly, and not only through integer values. The range R varies during an encounter according to Eq. 7, and t_D varies according to Eq. 1. Replacing the actual time-varying R by a value computed at a particular instant causes errors. These errors were shown to be negligible by comparing calculations made with integral steps in p with a calculation in which the steps in p were taken to be quite small.

The number of missiles destroyed by a constellation of platforms depends on its inclination i and altitude h, with smaller values of h favored because of the dependence of t_D on R^2 in Eq. 1. Varying i and h, we maximize Γ subject to the constraint that $h > h_{\min} = 400$ km, a value imposed by the requirement that atmospheric drag not be too large even at times of maximum solar activity, when the atmosphere is extended. The number of missiles destroyed by a typical laser platform is

$$n = \max_{\substack{0° < i < 90° \\ h > 400\text{ km}}} \left(\frac{\Gamma(i,h)}{L}\right) \tag{12}$$

Equation 5 shows that several parameters can be removed from the calculation by appropriate scaling. We can write Eq. 12 in the form

$$n = \frac{Bt_B}{Hr_e^2}y(x) \tag{13}$$

where $y(x)$, a dimensionless geometric factor that results from averaging Eq. 5 over all encounters, is given in Fig. 1. The optimum altitude depends on t_T and hence x; the optimum inclination i for the assumed 55° latitude of the launch sites varies between 57° and 70°; we estimate that the reduction in $y(x)$ resulting from the use of larger values of i—say 80°—in order to enable the system to attack SLBM's launched from submarines located at higher latitudes (a mission not discussed in this article) would be 30 percent for a system in which t_T equals 1 second. Approximate analytic calculations of the number of missiles destroyed by a constellation of laser platforms have been carried out under a range of different assumptions (*5*), and agree qualitatively with our results.

Let us consider what values of the parameters P, D, t_B, t_T, λ, and H are plausible. An infrared laser that has received much attention is a hydrogen-fluoride laser operating at a wavelength λ of 2.7 μm (*6*); in what follows we will assume that value for λ. If, for the same cost, laser systems can be developed that operate at shorter wavelengths, while at the same time maintaining the same laser power and optical aperture, then Eqs. 2 and 13 show that the higher system brightness will increase n and hence decrease the CER. Estimates of P, D, t_B, t_T, and H are very uncertain because no laser BMD system exists, and hence only design goals for P, D, and t_T are available in the literature, while estimates of t_B and H are at least as uncertain, because they are under the control of the offense and will probably evolve with time as the offense seeks to counter the BMD system. In what follows, we discuss estimates of the parameters found in the literature, and calculate corresponding values of n and the CER.

It is advantageous to the defense to attain the largest possible values for the laser power P and the mirror diameter D. In accordance with our procedure, we will therefore adopt the largest values of these parameters that seem plausible to us. Although infrared lasers with the required power do not now exist, it is planned to demonstrate the feasibility of an infrared laser design having $P = 2$ megawatts in 1987, and further, it is claimed that such a design should be scalable almost immediately to $P = 10$ MW (*6*). Drell *et al.* (*7*) envisage $P = 100$ MW as an ambitious and feasible goal. Worden (*8*) of the Strategic Defense Initiative Office and Bethe *et al.* (*9*) adopt a smaller figure, $P = 25$ MW. In view of the fact that we later assume that the costs of the laser generator and its power supply are negligible, we adopt $P = 25$ MW as the largest plausible value of P for a laser operating at a wavelength of 2.7 μm.

An optical system with $D = 4$ m is projected to be tested in 1988 (*6*); Drell *et al.* (*7*) adopt this value for D. In view of the fact that NASA plans to launch the Hubble Space Telescope, which has a 2.4-m diffraction-limited mirror, later this year, it seems reasonable to assume that it will ultimately be possible to develop diffraction-limited optical systems with effective mirror diameters greater than 4 m, although the problems in feeding such a system coherently with a high-power laser and maintaining diffraction-limited performance while the system is being illuminated with a power density equal to 30 W cm^{-2} appear to be substantial; presumably cooling systems will be required which are not part of the Space Telescope. If the Space Telescope achieves diffraction-limited performance at visible wavelengths, it seems reasonable that it would be possible to do the same at the wavelength of the HF laser (2.7 μm) with mirrors that are larger in proportion to the wavelength, that is, about 10 m. Bethe *et al.* (*9*) adopt $D = 10$ m, and Worden (*8*) adopts 15 m. The latter value seems unreasonably large to us from our acquaintance with the Hubble Space Telescope program, and in view of the testimony of Major General Donald Lamberson to the Senate Armed Services Committee on 23 March 1983 (*7*) that "a 4-meter optical system is a very large system that has not been constructed before, much less operated at or near its diffraction limit" (as is required for the present application). We adopt $D = 10$ m as a plausible estimate. We shall see later in Eq. 18 that per missile destroyed, the cost of a space-based optical system is almost independent of D in any case.

It is advantageous to the defense to reduce the targeting time t_T to the absolute minimum. The value that can be achieved is under study (*10*); planners are assuming that values less than 1 second can be obtained. One option for this purpose is to use active optics—that is, to introduce appropriate phase shifts into optical paths by suitable rapid-response electrooptical devices. Such an approach seems appropriate for moving the laser beam through small angles, but may prove difficult to implement for the large angles required to track targets through the degrees of arc which a missile moves in a dwell time and which are necessary to move in order to acquire new targets. A substantial improvement in performance over the Hubble Space Telescope (HST) is required, as the latter instrument, to which we will refer in making cost estimates, takes 20 seconds to move through 6° (200 km as seen from 2000 km) because of the long time required to settle if angular velocities are too large (*11*). In view of the uncertainties in this area, we have presented our results for three values of t_T: 0.1, 1, and 10 seconds.

It is advantageous to the defense if the offense is limited to boosters with large values of t_B and small values of H. In accordance with our procedure, we therefore use the largest values of t_B and the smallest values of H that seem plausible to us. Carter (*12*) gives values of t_B for various existing and planned U.S. and Soviet boosters. Generally speaking, the liquid-fueled boosters which today constitute the bulk of the Soviet ICBM force have t_B equal to about 300 seconds, while the solid-fueled boosters which constitute the bulk of the U.S. ICBM force have t_B equal to about 200 seconds. The next generation of Soviet boosters will reportedly be solid fueled (*12*). In view of the fact that it will take many years to develop a BMD system, it seems reasonable to assume that all boosters of interest are solid fueled, and therefore, that t_B is no larger than 200 seconds; Worden (*8*) adopts this value. A Martin Marietta study (*13*) shows that "fast-burn" boosters with t_B less than 60 seconds can be constructed at the cost of reducing the payload by 25 percent. Such boosters would burn out either within the atmosphere or soon after leaving it, and because the beam of the infrared laser under discussion is attenuated by the atmosphere, the time such boosters would be available as targets would be even less than t_B. We have calculated N for t_B = 50 and 100 seconds as well as for 200 seconds, but because of the attenuating effect of the atmosphere, the actual times over which the missiles are available as targets are less than these values by a considerable percentage at the low end of the range. In accordance with our procedure, we neglect this effect.

The hardness of current boosters is reportedly H = 0.4 to 2 kJ cm^{-2}, and Department of Defense studies have shown that the level of hardness that could be achieved by the Soviet Union is about 20 kJ cm^{-2} (*14*). The Soviet Union can reportedly achieve H = 5 to 30 kJ cm^{-2}, and even values as large as 100 kJ cm^{-2} (*15*). Drell *et al.* (*7*) state that missiles that carry multiple reentry vehicles can be hardened to H = 20 kJ cm^{-2} at the cost of deleting one out of ten reentry vehicles. In the light of this information, we regard H = 20 kJ cm^{-2} as the smallest plausible value of hardness with which a BMD system will have to contend. This value was also adopted by both Worden (*8*) and by Bethe *et al.* (*9*).

Using Eq. 2 and the value λ = 2.7 μm, we normalize Eq. 13 to the adopted values for laser power, mirror diameter, missile hardness, and duration of boost phase

$$n = 6.6\left(\frac{P}{25}\right)\left(\frac{D}{10}\right)^2\left(\frac{t_B}{200}\right)\left(\frac{H}{20}\right)^{-1}[y(x)] \qquad (14)$$

For use in Eq. 6, the values adopted for P (25 MW), D (10 m), and λ (2.7 μm), when put into Eq. 2 correspond to a laser brightness $B = 2.7 \times 10^{20}$ W $ster^{-1}$. Table 1 gives n for various values of t_T and t_B, with the values of the other parameters from Eq. 14.

Cost of a Laser Platform

Each laser platform would include a generator to produce the laser beam, an optical system to focus and direct the beam, systems for acquisition, pointing, and tracking, and a power supply, the whole weighing tens of metric tons (*1*). It is possible that substantial measures would be required to protect the platform against hostile attacks from ground- and space-based lasers, particle-beam weapons, direct-ascent antisatellite weapons, fragment clouds, and space mines. This would be difficult because the optics to direct the laser beam must be diffraction limited (accurate to about 0.02 wavelengths, or 5×10^{-8} m, over an aperture of 10 m) in order that the size of the laser spot on the missile be small enough to concentrate the energy to the required degree. Moreover, the support structure for the optical elements must be maintained in a fixed position to a high precision. In the HST, for example, alignment must be maintained within 3×10^{-6} m over the 5-m length of the telescope (*16*). However, neither the costs of countermeasures nor of the corresponding counter-countermeasures are estimated here.

In estimating the cost of a laser platform, it is consistent with our procedure to include the cost of only one major subsystem—the optical system consisting of the primary and secondary mirrors and the associated systems for acquiring targets, pointing the system at them, and tracking them long enough to enable the laser beam to be effective. We use as a basis for cost estimation the HST. Like the optical system of a laser platform, the HST has a diffraction-limited optical system that acquires, points at, and tracks distant targets. In keeping with our procedure, we will neglect the cost of the generator of the laser beam and the laser power supply (including fuel), as well as the cost of launching and maintaining the laser platforms and their fuel supplies in orbit, although there is no reason to believe that these elements will not be even more expensive than the optical system alone. The total cost of the HST is estimated to be 1.2 billion 1984 dollars (*17*). Its 2.4-m mirror weighs 0.83 metric tons, and the total weight of the HST is 11 metric tons (*18*).

One approach to building a 10-m optical system for a laser platform would be to scale up all the dimensions of the HST by a factor 4.2 (10/2.4). The weight of the resulting optical system would be 800 tons, which is unacceptably large. Confronted with a similar problem in constructing large ground-based optical-infrared telescopes, astronomers have designed telescopes which instead of a single monolithic mirror of diameter D use a number M of smaller mirrors having diameters $D_1 = M^{-1/2}D$, so that the total collecting area is the same. For example, the Smithsonian Institution–University of Arizona Multiple Mirror Telescope (MMT) uses six 1.8-m mirrors to form six separate images that are superposed at a focus to obtain the same collecting area as a single 4.5-m mirror (*19*). The Keck Telescope of the University of California and Caltech will use 36 1.8-m hexagonal mirror segments to achieve the collecting area of a single 10-m mirror by arranging the mirror segments to form a single optical surface (*20*).

A major advantage of MMT's and segmented-mirror telescopes (SMT's) is that because the individual mirrors (MMT) or mirror segments (SMT) have the same thickness as in a telescope of diameter D_1, the total weight of the mirrors, and therefore, of the telescope, scales as $M = (D/D_1)^2$, rather than as $(D/D_1)^3$ described earlier. As the costs of ground-based telescopes are nearly proportional to their weight (*21*), this represents a significant cost saving. Studies of MMT and SMT designs for a projected 15-m class ground-based telescope indicate that the two approaches each have advantages and disadvantages (*22*), so that for the present purpose, we will consider an MMT design for a laser platform optical system as representative.

We assume that the diameter of each individual mirror is

$D_1 = 2.4$ m, that of the HST mirror; this assumption enters the final cost estimates (Eq. 18) only very weakly. To achieve an effective diameter of $D = 10$ m, we require $M = (D/D_1)^2 = 17.4$ mirrors. (In practice, D_1 would be adjusted to give an integral number of mirrors.) Because the weight of such an optical system is proportional to M, we conclude that a 10-m space MMT based on the HST would weigh 17.4 times as much as the HST, or 191 metric tons. Note that although the BMD laser system would operate at a wavelength about four times larger than that for which HST is designed, so that one might suppose that less precise, hence lighter optics could be used, the diameter would also be four times larger, so that the relative precision required in the two cases would be the same. Moreover, the optical system of a laser platform would have to remain precise under far greater stresses than those to which HST is subjected, including the high-energy flux in the laser beam and far more rapid angular motion, as discussed above.

According to Teeter and Kuhner (*23*), costs of space systems tend to be proportional to their weight. From an analysis of about 40 spacecraft of various types in NASA's Explorer program, they conclude that in that program costs are proportional to the first power of the weight. In an early study of the cost of communications satellites, Kiesling *et al.* (*24*) conclude that costs are proportional to the square root of the weight. In a more recent study of communications satellites, Pritchard (*25*) considers nonrecurrent and recurrent costs separately, and represents each with a sum of power laws ranging from 0 to 1. These studies are based on spacecraft weighing less than 2,000 kg. Because HST weighs 11,000 kg and a laser platform optical system is estimated to weigh 191,000 kg, considerable extrapolation is necessary, and our results are correspondingly uncertain.

To test these cost models, we applied each to predict the cost of HST, using a standard inflator to express all results in 1984 dollars. Teeter and Kuhner's model predicts a cost of \$2.28 billion, 90 percent above the actual cost. Pritchard's model with his parameter u set equal to 0.22 (which is appropriate for communications satellites) predicts a cost of \$1.45 billion, 21 percent above the actual cost. Of this total, nonrecurring costs contribute \$1.05 billion and recurring costs contribute \$0.40 billion. Finally, the model of Kiesling *et al.* predicts \$0.51 billion, 42 percent of the actual cost.

On the basis of this information and the fact that Pritchard separates recurring from nonrecurring costs, we selected his model as the best one for extrapolating to a laser platform optical system. The dominant term in his formula for recurring costs is $114\ W^{0.81} + 56\ W^{0.87} \times 10^3$ 1984 dollars, where W is the weight in kilograms. The simpler formula, $159.6\ W^{0.84}$, agrees with this one to within 1 percent for W between 10^3 and 10^6 kg. With $W = 191{,}000$ kg, it gives \$4.36 billion. Recall that Pritchard's formulas predict a total cost for HST that is too high by a factor of 1.21; in accordance with our procedure, we divide 4.36 by 1.21, obtaining \$3.59 billion.

Note that recurring costs, which are of the greatest interest here because a large number of optical systems are required, have a quite different dependence on weight than does the total cost of a single unit, which includes both recurring and nonrecurring costs. According to Pritchard's formula, the latter cost, which is that often quoted, varies with an effective power law that increases with weight, starting at 0 for small weights, becoming 0.66 at 300 kg (typical of the range considered in studies), rising to 0.82 at 1,000 kg and to nearly 1.0 at 10,000 kg and above. This may account for the fact that power laws near 0.7 are suggested in informal discussions. As we have seen, a value near 0.84 is more appropriate for estimating recurring costs for heavy space systems.

We see from Table 1 that at least 200 platforms will be necessary to counter 1400 ICBM's (the size of the current Soviet force), even if we neglect, in accordance with our procedure, any requirement for platforms without lasers, which may be needed for tracking purposes alone. It is clear that recurrent costs will dominate our estimates, and furthermore, that substantial cost savings will result from mass production. The theory of experience curves (*26*) shows that for large production runs, the cost of the kth item produced, $c(k)$, fits the relation

Table 1. Number of missiles destroyed by a typical laser platform.

Targeting time t_T (sec)	Duration of boost phase t_B (sec)		
	50	100	200
0.1	1.7	3.5	7.0
1.0	0.8	1.6	3.1
10	0.2	0.4	0.9

$$c(k) = c(TFU)k^b \tag{15}$$

where $c(TFU)$, the cost of the "theoretical first unit," and b, the slope of the experience curve, are normally determined by fitting Eq. 15 to actual production data. The quantity b equals $\log_2 f$, where f, the "experience curve factor," is the factor by which the cost is reduced for each factor of 2 increase in production. In the 100 cases studied by Ghemawat (*27*), most f's are between 75 and 90 percent, 85 percent being average. We will assume for laser-platform optical systems that $f = 85$ percent, corresponding to $b = -0.23$.

In Eq. 15 we identify $c(TFU)$ with the estimated recurring cost of a laser platform optical system. Recalling that such costs scale with $W^{0.84}$, and that we have assumed that W scales with D^2, we estimate that the recurring cost of a laser platform optical system would be \$3.59 $(D/10)^{1.68}$ billion. According to Eq. 15, then, the cost of the kth laser platform optical system (in millions of 1984 dollars) is

$$c(k) = 3590\left(\frac{D}{10\text{ m}}\right)^{1.68} k^{-0.23} \tag{16}$$

The number of platforms k equals m/n, where m is the number of attacking missiles and n is the number of missiles destroyed by a typical platform. Hence the cost of destroying a missile is (in millions of 1984 dollars)

$$C = \frac{c(k)}{n} = 3590\left(\frac{D}{10}\right)^{1.68} m^{-0.23} n^{-0.77} \tag{17}$$

If we substitute n from Eq. 14, we find the cost (in millions of 1984 dollars) to be

$$C = 840\left(\frac{D}{10}\right)^{0.14}\left(\frac{P}{25}\right)^{-0.77}\left(\frac{t_B}{200}\right)^{-0.77}\left(\frac{H}{20}\right)^{0.77} m^{-0.23}\,[y(x)]^{-0.77} \tag{18}$$

Note the very weak dependence upon D referred to earlier. Recall that y depends upon P, D, λ, t_T, H, and h_{min} according to Fig. 1 and Eqs. 2 and 6.

Cost of Missiles and the Cost-Exchange Ratio

In order to compute the cost-exchange ratio, we need to compare the cost of destroying a missile to the cost of producing and deploying that missile. Because we are interested in the cost of producing additional missiles, development costs should not be included. Government documents give the cost of the second 100 operational MX missiles as \$2.2 billion in 1982 dollars, or \$22

Table 2. Cost-exchange ratio.

Targeting time t_T (sec)	Duration of boost phase t_B (sec)		
	50	100	200
0.1	8.8	5.2	3.0
1.0	16	9.5	5.6
10	46	27	16

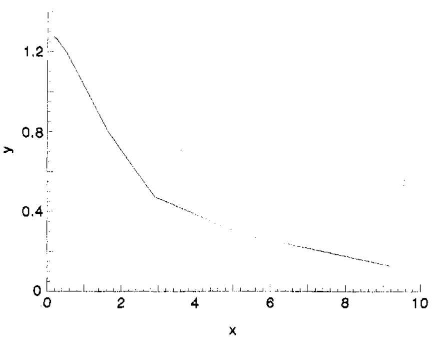

Fig. 1. The function $y(x)$ defined by Eq. 13 and used in Eqs. 14, 17, 18, and 19, calculated for h_{min} = 400 km and elevation = 25°. Here x is the ratio of the targeting time t_T to the minimum dwell time, and y is a dimensionless geometrical factor that results from averaging Eq. 5 over all encounters.

million per additional missile (*28*). We estimate that the cost of basing and operations will add $20 million to the cost of deploying an MX missile, bringing the total cost to $42 million per missile. Taking into account inflation since 1982, we adopt the somewhat larger figure of $50 million in 1984 dollars as the total cost per missile. Note that our estimates are based on procurements of relatively small numbers of missiles. In fact, a rather large number of missiles would be required to nullify a full-scale BMD system, and so additional cost savings associated with mass production would occur for offensive missiles, just as for laser platforms. In accordance with our procedure, we neglect this effect.

The cost-exchange ratio is obtained by dividing the cost of destroying a missile (Eq. 18) by the cost of deploying an additional missile ($50 million). The result is

$$CER = 16.8\left(\frac{D}{10\ \text{m}}\right)^{0.14}\left(\frac{P}{25\ \text{MW}}\right)^{-0.77}\left(\frac{t_B}{200\ \text{sec}}\right)^{-0.77}\left(\frac{H}{20\ \text{kJ cm}^{-2}}\right)^{0.77} m^{-0.23}[y(x)]^{-0.77} \quad (19)$$

For the case of an attack by 1400 missiles (m) and with the adopted values for D, P, and H, Eq. 19 yields

$$CER = 3.18\left(\frac{t_B}{200\ \text{sec}}\right)^{-0.77}[y(x)]^{-0.77} \quad (20)$$

Table 2 gives the CER for the indicated values of t_T and t_B, and the values adopted for the other parameters in Eq. 19. To find the cost of a laser platform optical system (expressed as the cost of a "theoretical first unit") that would be marginally cost-effective in the sense that the corresponding CER would equal unity, divide 3.6 billion 1984 dollars by the CER in Table 2.

Conclusions

The values in Table 2 suggest that the CER is likely to exceed unity for the proposed system, even if the defense achieves very short targeting times, while the offense fails to achieve shorter boost-phase durations. The values of the CER for other cases are even larger. The defense could reduce them by increasing laser brightness (Eq. 2) while the offense could increase them further by decreasing t_B and increasing H. It is not clear whether the net result of these activities would be to increase or decrease the estimated CER.

However, we should emphasize that we chose lower limits to costs to the defense and upper limits to costs to the offense; Eqs. 19 and 20 therefore represent an estimated lower limit to the true CER. A number of assumptions were made which, if violated, would increase the CER. They are: (i) the number of malfunctions of laser platforms because of inadequate maintenance is negligible; (ii) the time to receive warning of attack, to decide on a response, and to activate the laser platforms is negligible; (iii) the inaccuracy in targeting instructions received from battle management computers is negligible; (iv) the inaccuracy in pointing laser beams is negligible; (v) the loss of on-target time due to instability of the laser beams in spite of target motion is negligible; (vi) there is no loss in effectiveness because very high inclination orbits are used in order to deal with the threat of SLBM's launched by submarines in polar latitudes; (vii) the loss of efficiency in encounters at such large ranges that the energy of the beam is dissipated without damaging the target is negligible; (viii) the cost associated with a substantial reduction in targeting time from that of the HST is negligible; (ix) the effect of atmospheric attenuation in reducing the time over which targets are available is negligible; (x) the cost of launching laser platforms is negligible; (xi) the cost attributable to additional platforms that are needed as spares to facilitate on-orbit maintenance, and the cost of carrying out such maintenance are negligible; (xii) the costs of the generator and power supply for the laser beam are negligible; (xiii) the number or cost, or both, of platforms to be used only for tracking and battle management (but not firing) is negligible; and (xiv) the cost savings to the offense associated with large missile procurements are negligible.

It is possible that several of these assumptions would be violated, some quite significantly. If even a few were violated, a more realistic estimate of the CER would be an order of magnitude greater than is implied by Eqs. 19 and 20, and Table 2, and thus would be considerably greater than 1. If our estimates and methods are confirmed, a space-based laser BMD system would not be able to maintain its effectiveness against the offense at less cost than it would take to proliferate the missiles to overcome it. It is therefore not likely that such a system would satisfy the President's requirements (*2*) for an effective defense.

We have presented a method for estimating the CER of proposed BMD systems. Although we have illustrated the method by applying it to a space-based infrared laser system, it seems straightforward to extend the argument to other proposed systems. However, it should be kept in mind that cost-effectiveness is only one requirement to be met by a viable BMD system.

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Rates of DNA Sequence Evolution Differ Between Taxonomic Groups

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The mutation rates of DNA sequences during evolution can be estimated from interspecies DNA sequence differences by assaying changes that have little or no effect on the phenotype (neutral mutations). Examination of available measurements shows that rates of DNA change of different phylogenetic groups differ by a factor of 5. The slowest rates are observed for higher primates and some bird lineages, while faster rates are seen in rodents, sea urchins, and drosophila. The rate of DNA sequence change has decreased markedly during primate evolution. The contrast in rates of DNA sequence change is probably due to evolutionary variation and selection of biochemical mechanisms such as DNA replication or repair.

THE EVENTS OF SPECIATION AND THE TIMES AT WHICH THEY have occurred are of central interest in the study of evolution. Clear molecular evidence of systematic relationship is valuable both for the identification of these events and for interpolation of dates where the fossil record is incomplete. For example, the determination of DNA sequences of homologous regions for a series of species should disclose many nucleotide substitutions and rearrangements, and the pattern of occurrences can be used to establish the relatedness of the species. Even closely related species, such as man and chimpanzee, differ by almost 2 percent in their nuclear DNA sequences (*1–3*), and thus there are about 60 million sequence differences, most of which have little or no effect on the phenotypes. Human individuals probably differ from each other at as many as 5 million sites (*4*), and new genomic differences appear by the hundreds with every birth (*5*). The rate of occurrence, fate, and significance of these DNA mutations are of interest. As more sequences are measured and compared the differences should resolve questions regarding speciation and the process of evolution.

The constancy of the rate of DNA sequence change requires examination in order to make full use of the measurements and determine how many time calibrations are needed. In this article, many measurements of DNA sequence differences spanning the period since the mammalian radiation are examined. Although good time calibrations are difficult to find and the individual dates are relatively imprecise, clear conclusions can be drawn.

DNA sequence changes (substitutions, insertions, deletions, and rearrangements) are the likely source of phenotypic variation in evolution since they can affect genes or their regulation and influence biochemistry, development, morphology, and behavior. However, the majority of changes appear to be neutral; that is, they have little or no effect on the phenotype. The mutation rate (underlying or basal rate of DNA sequence change) may be estimated from the interspecies DNA sequence differences that result from the fixation of neutral changes in the genomes of different species.

Interspecies DNA Divergence

The number of interspecies comparisons of primary DNA sequences is rapidly growing but is still severely limited. Most of the comparisons are for gene regions in which only a small number of neutral substitutions can be identified, and the statistical uncertainty is large. However, there is a fair number of interspecies DNA hybridization measurements, and (as shown below) the two methods give closely similar results. The combination of the results of both methods is required for a full view of the pattern of interspecies

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