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Constellation Sizing for Modest Directed Energy Platforms

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Constellation Sizing for Modest Directed Energy Platforms

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CONSTELLATION SIZING FOR MODEST DIRECTED ENERGY PLATFORMS

by

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ABSTRACT

Discussions of boost phase directed energy constellation scaling have concentrated on tradeoffs for large lasers and mirrors, which require development. This report explores more modest lasers that could be deployed sooner, finding that for anticipated threats, performance and effectiveness are adequate.

I. INTRODUCTION

Recent discussions of the scaling of directed energy weapon (DEW) constellations on boost phase threats[1,2] have concentrated on the performance tradeoffs for large lasers and mirrors,[3] e.g., 20 MW lasers with 10 m mirrors, or "20-10" platforms.[4] Although their development is plausible and their projected performance and cost effectiveness favorable,[5] they require that several technologies be scaled together over significant ranges, which could require much of a decade.[6] This report explores the scaling of modest laser platforms that could be deployed sooner, finding that for the less stressing threats anticipated in the near term, their performance and effectiveness should be favorable.

II. BRIGHTNESS SCALING

A DEW platform's brightness, B, is the product of its laser power, P, and its transmitting mirror area, A, divided by the square of its wavelength, w, or

$$B = P\cdot A/w^2. \tag{1}$$

A platform of brightness B produces an energy flux of B/r^2 on an object at range r. Thus, brightness determines the rate at which the platform can kill targets, making it a useful parameter for characterizing a DEW's overall capability. "Nominal" 20-10 chemical laser platforms at $w = 2.7\ \mu m$ have a brightness of $20\ MW\cdot\pi(5\ m)^2/(2.7\ \mu m)^2 \approx 2.2\cdot10^{20}$ W/sr. That of a near-term 5-4 chemical laser platform is lower by a factor of $(5/20)\cdot(4/10)^2 =$ 4%, giving it about 10^{19} W/sr. The modest platform would take about 20 times longer to irradiate a given target, but for some applications that could be adequate.

III. LASER STATUS

After its first laboratory demonstration about 10 years ago, the chemical laser was scaled to about 100 kW with good beam quality in about 2 years.[7] Subsequent development has been paced by budget and mission uncertainties, but relevant infrared (IR) chemical lasers are argued to have demonstrated multimegawatt powers and resolved concerns about vibrations from the combusting flow and the radial exhaust of spent gases.[8] Not all laser technologies have been integrated fully, but there do not appear to be any insuperable technical barriers to doing so. Uncertainties in scaling are smaller for the 4-fold scaling needed for initial applications than they would be for the 20-fold scaling to advanced levels.

IV. MIRROR STATUS

The other major technology that determines the level of brightness attainable is that for the large primary mirrors that transmit the power. There is an active industry for casting light telescopes several meters in diameter using technologies applicable to larger mirrors.[9] Its largest scientific project to date was the Hubble Space Telescope (HST), a 2.4 m, near-perfect visible telescope for operation in space. The cost for producing, lightweighting, figuring, polishing, and coating the HST primary was about \$ 25 M. Since 80% of this cost was for tooling, subsequent mirrors could be produced for about \$ 5 M.[10] This mirror technology scales to at least 4 m, the limit for current launch vehicles and a size for which a developed space optics deployment capability exists.

A segmented aperture of area A made out of mirrors the size of the HST primary would require about $A/\pi(1.2)^2$ pieces and cost about \$ 5 $M \cdot A/\pi(1.2)^2$. The 10 m mirror for a 20-10 platform would thus require about 16 pieces and cost about \$ 80 M; with standard learning curves the average costs could drop to about half that. Such cost estimates for the mirror are consistent with current working estimates of the cost for fabrication and operation of a 20-10 platform.[11]

The maximum power, area, and wavelength demonstrated at any given time determine the maximum brightness that could be produced if all were demonstrated together. The parameters discussed above would thus produce a combined brightness of about $2\ \mathrm{MW} \cdot \pi(1.2\ \mathrm{m})^2/(2.7 \cdot \mu\mathrm{m})^2 \approx 1.3 \cdot 10^{18}$ W/sr, which is about two orders of magnitude below that of a 20-10 platform. If, however, that laser technology could be scaled another factor of 2-3 and the mirror technology to 4 m, this could support a 5-4 platform with a brightness of $\approx 10^{19}$ W/Sr, which roughly defines the integrated level of current technology.

V. PLATFORM COST SCALING

DEW costs are poorly known and will remain so until actual integrations at scale are executed. Some estimates of costs are useful, however, as a guide to how developmental effort should be allocated between the various components. This section gives an indication of platform cost scaling based on the optimization of platform component costs. If platform costs, C, are linear in power and aperture, i.e.,

$$C = p \cdot P + a \cdot A, \qquad (2)$$

where p and a are constants or weakly varying parameters, the platform costs are minimized by choosing

$$A = P \cdot p/a, \qquad (3)$$

which gives

$$P = w(B \cdot a/p)^{1/2}, \qquad (4)$$

and

$$A = w(B \cdot p/a)^{1/2}. \qquad (5)$$

Assuming that the 20-10 platform represents the proper combination of parameters for platforms of high brightness, the equations above can be used to scale to the most efficient platforms of lower brightness. Using the 20-10 platform's parameters in Eq. (3) gives a ratio of $a/p = P/A \approx 20\ \mathrm{MW}/80\ \mathrm{m}^2 = 0.25\ \mathrm{MW/m}^2$. Thus, according to Eqs. (4)-(5), the 5-4 combination at 2.7 μm discussed earlier has about the optimal combination for a brightness of 10^{19} W/sr, which is about 1/20th of a 20-10 platform.

The costs for various combinations can be scaled accordingly. Ratios are more reliable than absolute values at this point in development. From Eqs. (2)-(4), for optimal combinations the costs are

$$C = 2w(a \cdot p \cdot B)^{1/2}, \qquad (6)$$

which scale primarily as $B^{1/2}$ for fixed w. Thus, the cost of an initial 10^{19} W/sr 5-4 platform should be less than that of a 20-10 by a factor of $\surd 22 \approx 4.7$. A geometrically intermediate brightness level is about $5 \cdot 10^{19}$ W/sr. According to Eqs. (4)-

(5), a platform of that brightness should have $P \approx 20 \cdot (5/22)^{1/2} \approx$ 10 MW and $D = 10(5/22)^{1/4} \approx 7$ m. This 10-7 platform should then cost about $(5/22)^{1/2} \approx 1/2$ that of a 20-10.

The scaling in Eq. (5) takes optimal advantage of increases in power and aperture. In practice that scaling could be partially compromised by fixed structural costs and other inefficiencies. It is possible to aggregate some platform costs into fixed contributions from the satellite's structure, communication, and control systems, which are a significant overhead under current design practices. Fixed costs do not, however, shift the optimal P and A in Eqs. (4)-(5), they only add a fixed cost, C_F, to the right-hand side of Eq. (6), reducing the optimal brightness at total cost C to $B = [(C-C_F)/2w]^2/ap$ for suitable a and p. The effects of large fixed costs have been studied.[12] For various ratios of variable costs and, hence, power-diameter combinations, similar to those derived above, moderate fixed costs do not greatly change the overall scaling shown below.

VI. ADVANCED TECHNOLOGY

Because the cost in Eq. (6) is linear in w, it would be advantageous to use the shortest wavelength lasers available. Candidates are the free-electron, excimer, and visible chemical lasers, each of which has the potential to operate efficiently at large scale, although none has done so as yet. Free-electron and excimer lasers could apparently be developed for boost phase defenses on about the same time scale as the 20-10 chemical laser, with which they compete favorably on the basis of wavelength, efficiency, and the option of ground basing.

Visible chemical lasers do not exist, but if IR chemical lasers could be made to operate efficiently on overtones around 1.4 μm rather than the fundamental 2.7 μm, that would roughly quadruple a given platform's brightness, making a 5-4 platform at 1.4 μm about the equivalent of an 10-7 platform at 2.7 μm, and a

10-7 at 1.4 μm about that of a 20-10 platform at 2.7 μm. Free-electron and excimer lasers require, however, significant development, so IR chemical lasers are currently the only candidates for initial applications.

VII. SCALING

An essential question in determining the effectiveness of DEWs in the boost phase is the number of satellites the DEWs need to counter projected threats. Such estimates can be made most accurately by computer simulations, but analytic solutions give insight into the results, indicate sensitivity to the many parameters characterizing the attack, and produce scaling results that others can check and use.

A. Dimensional Relationships

The simplest scaling estimates use elementary dimensional relationships. A laser of brightness $B = 2 \cdot 10^{20}$ W/sr produces a flux B/r^2 at range r, so a target at 1 Mm hardened to a limiting fluence of $J = 200$ MJ/m^2 would be destroyed in a dwell time of

$$t = J/[B/r^2], \tag{7}$$

which is ≈ 200 MJ/m^2 $\div$ $[2 \cdot 10^{20}$ W/Sr$/(10^6\text{m})^2]$ = 1 s for a 20-10 platform. In a T = 100 s engagement, each such laser could destroy about $T/t \approx 100$ missiles, so about 10 lasers would have to be in range for the simultaneous launch of 1,000 fast missiles. The total constellation would have to be a factor of 5-10 larger, for a total of 50-100 satellites, to account for the "absenteeism" of satellites elsewhere in their orbits at the time of launch.

Early studies estimated much lower kill rates because of their assumption that all engagements took place at the maximum range possible, an error that affects kill rates quadratically.[13] A recent report by the American Physical Society (APS) estimated that the lasers would have to be an order of magnitude brighter to achieve these objectives, but did so on the basis of an arbitrary and inappropriate assumption that the kill time had to be 0.1 s rather than the 1 s calculated above for the conditions of the APS report.[14]

For 5-4 platforms, which are about 1/20th as bright, the kill time would be a factor of 20 longer. To first approximation about 20 times as many satellites would thus be needed. However, adding satellites decreases the average distance between them, which for current distributed launch areas, reduces the average range between the satellites and their targets, and with it the average kill time of each, reducing the number of additional satellites needed.[15]

B. Limiting Solutions

Refining these scaling estimates requires proper treatment of the interaction between satellite and target distributions. Two useful limiting analytic estimates are available. If retargeting the beam takes a time S, the total time per target at range r is

$$t = r^2 J/B + S. \qquad (8)$$

Each satellite is responsible for the targets in a zone of area Ω in the launch area, A_L. If $A_L \gg \Omega$, the dominant contribution is that from the interior satellites, i.e., those over A_L. Then Ω is approximately a circle of radius $R = 2R_E/(zN)^{1/2}$, where R_E is the earth's radius, N is the number of satellites, and $z \approx 3$ is the concentration possible if coverage is specialized to land based missiles.[16]

The kill time in Eq. (8) scales with area, so the average range for engagements is $\approx R_A = R/\sqrt{2} = \sqrt{2}R_E/(zN)^{1/2}$, so that for $N = 25$ satellites, $R_A \approx 1{,}000$ km, which is the value used in the estimates above. The time required to kill a typical target is found by averaging Eq. (8) over Ω, which produces[17]

$$\langle t \rangle = \langle r^2 \rangle J/B + S = (h^2 + R^2/2)J/B + S, \qquad (9)$$

where h is the constellation altitude. This average kill time $\langle t \rangle$ must be equal the the time available for killing each target, which is the engagement time T divided by the number of targets in Ω, or $T/(M \cdot \Omega/A_L)$. Equating that to Eq. (9) gives, for small h and S, a distributed launch constellation size of[18]

$$N_D = (8\pi R_E{}^4 JM/z^2 A_L BT)^{1/2}. \tag{10}$$

In this limit, which is appropriate for the current large distributed launch areas, the dominant scaling is contained in the single parameter $(JM/A_L BT)^{1/2}$. The individual attack parameters matter less than the generalized threat rate $JM/A_L T$, which the offense tries to maximize. As the threat increases, however, $N_D \propto \sqrt{M}$, so the exchange ratio, $M/N_D \propto \sqrt{M}$, increases, which favors the defense, until the effect saturates at $N \geq 5{,}000$.[19]

The complementary "exterior" solution treats only the contributions from satellites exterior to the launch area. It is strictly valid only for point launches, but represents an approximate limit for very large generalized threat rates. Point launch constellation sizes can be derived by summing the kill rates of each satellite, 1/t, over the constellation to give[20]

$$N_P = 4R_E{}^2 JM/\{zBT \ln [1+2R_E H/(h^2+SB/J)]\}, \tag{11}$$

which depends linearly on M but only logarithmically on retarget time and constellation altitude. The difference between the two limiting solutions is significant. Distributed launches scale on the threat rate as $(JM/BT)^{1/2}$, while point launches scale as JM/BT. Thus, as the number of missiles, their hardness, or deployment rates increase, constellations for distributed launch areas increase more slowly than those for point launches.

C. Combined Solution

Neither limit is completely appropriate. Current launch areas are too small for the interior solution to apply with much better than factor of 2 accuracy, but they are large enough for point launch estimates to err by about a factor of 4. Thus, the contributions from interior and exterior satellites must be integrated, which has been done in a near-exact, quasi-analytic "combined" solution, which reduces to the limiting solutions under appropriate conditions and has analytic solutions for conditions of interest.[21] It predicts constellations about a factor of 2 smaller than those from the interior solution for distributed launches. The combined solution is relatively insensitive to reductions of the launch area, so that DEWs usefully complement kinetic energy weapons (KEWs), which have a much stronger scaling.[22]

The combined solution agrees with numerical simulations to within 20-30% for nominal parameters,[23] so it is accurate enough for the scaling calculations below, for which few of the input parameters are known that accurately. For 20-10 platforms, combined constellations scale as

$$N = K(JM/A_L BT)^{\Gamma}, \tag{12}$$

where $\Gamma \approx 0.7\text{-}0.8$.[24] In Eq. (12), K is roughly constant; it can be evaluated as $\approx N/(JM/BA_L T)^{\Gamma} \approx 4 \cdot 10^{19}\ (m^4/sr)^{\Gamma}$ from the ≈ 50 20-10 lasers needed for the threat of M = 1,400 boosters hardened to $J = 200\ MJ/m^2$, launched from an area of $A_L = 10\ (Mm)^2$, and vulnerable for T = 100 s.[25] The scaling parameter $JM/BA_L T$ is fundamental. If only B varies, $N \alpha B^{-\Gamma}$, so that many small satellites would be required. Initial boosters could, however, have hardnesses an order of magnitude smaller than the limit assumed above and have burn times about an order of magnitude larger. If so, the constellation size, which scales as $N \alpha (J/BT)^{\Gamma}$, would be unchanged to first order, so that 40-50 platforms with brightnesses about 1% of a 20-10's could perform useful roles against initial threats. While stated in terms of chemical lasers, this result is true for any DEW of the same brightness.

D. Constellation Cost Scaling

Thus, boost phase constellation sizes could theoretically scale on platform brightness as anything from 1/B in unfavorable situations--point launch, slow retargeting, etc,--to $1/\sqrt{B}$ for favorable situations like distributed launch. Real cases lie in between and require the exact solutions below for detailed scaling predictions.

Platform costs are also largely unknown, but they should be bounded by the optimal $\sqrt{B}$ scaling derived in Eq. (6) and the linear scaling, $C \alpha B$, i.e., with no advantage to scale that are assumed by some.[26,27,28] While the cost-scaling combinations ultimately realizable are not now known, it is possible to give an expected value matrix using the extremes shown in Table I.

Table I. Possible Constellation Cost Scalings

		Cost per Satellite	
		B	$\sqrt{B}$
Number of Satellites	$1/B$	1	$1/\sqrt{B}$
	$1/\sqrt{B}$	$\sqrt{B}$	1

The total cost for any combination is the product of the number of satellites and the cost for each. Since the diagonal elements are independent of B and the extremes only scale on $\sqrt{B}$, small lasers might be useful if they were available early. For distributed launch and linear costs, the scaling could approach $\sqrt{B}$, making smaller satellites preferred, as discussed below.[29] Perhaps the most interesting observation is that for initial threats the cost could be relatively insensitive to B.

VIII. RESULTS

Using the brightnesses determined in Section V, the analytic solution produces the constellation sizes shown below, which were calculated for the limiting hardness of 200 MJ/m^2 and the current launch area of 10 Mm^2. The constellation altitude was fixed at 500 km and the retarget time at 0.1 s on the basis of earlier work that showed that constellation sizes were weakly sensitive to h and S for the parameters of primary interest here.[30]

A. Constellation Size

The results of constellation size vs threat are shown in Fig. 1. The bottom curve, which is for $B = 2.2 \cdot 10^{20}$ W/sr, was derived and discussed previously;[31] the middle curve is for

$5 \cdot 10^{19}$ W/sr; and the top for 10^{19} W/sr. For a launch of 100 fast missiles that are vulnerable for 100 s, which is the minimum consistent with the effective release of decoys,[32] the high, medium, and low brightness platforms require constellations of 8, 25, and 80 satellites, respectively; for 300 missiles those constellations roughly double; and for the 1,000 missile maximum initial threat, they need 45, 150, and 690 satellites.

The high brightness platform scales as $N \alpha M^{0.75}$ in accord with Eq. (12). A medium brightness platform scales as $N \alpha M^{0.75}$ below $M = 300$ and as $M^{0.85}$ above. The low brightness platform scales as $M^{0.88}$ below 300; above, it is almost linear.

B. Constellation Brightness

Figure 2 gives a crossplot of constellation size as a function of B. The bottom curve is for 100 missiles. Below $B = 5 \cdot 10^{19}$ W/sr, $N \alpha B^{-0.8}$; above it, $N \alpha B^{-0.7}$, i.e., the brighter platforms approach the distributed scaling of Eq. (10). On the middle curve for 300 missiles, below $B = 5 \cdot 10^{19}$ W/sr, $N \alpha B^{-0.85}$, and above it, $N \alpha B^{-0.73}$, i.e., smaller platforms degrade for larger threats, while brighter platforms retain their effectiveness. On the top curve for 1,000 missiles, the scaling on B is essentially linear below $B = 5 \cdot 10^{19}$ W/sr, and roughly $N \alpha B^{-0.8}$ above it. Thus, there is a continuum of scalings on B that lies roughly midway between the extremes used in Table I.

C. Constellation Costs

Figure 3 shows the constellation costs estimated by taking the constellation sizes from Fig. 1 and multiplying them by the normalized satellite costs of 0.2, 0.5, and 1.0 derived in Section V for the 1, 5, and $22 \cdot 10^{19}$ W/sr brightnesses, respectively, from the ideal $\sqrt{B}$ cost-brightness scaling of Eq. (6). The top curve is for the lowest brightness. It increases 5-fold as the number of missiles increases from 100 to 500 missiles. The middle curve is for the medium brightness; it increases at a significantly lower and decreasing rate by a total factor of about 7 by 1,000 missiles. The bottom curve is for the nominal $2.2 \cdot 10^{20}$ W/sr of previous studies, which increases by about a factor of 6 by 1,000 missiles, although it levels out at a much lower level than that of the lower brightnesses. Based on these cost assumptions and parameters, bright platforms would be preferred, if available when needed. That is particularly true for large threats where the low brightness constellations could cost about three times as much as bright constellations.

There is a penalty for small platforms at small threats. It is about a factor of 2 at 100 missiles, but the absolute cost difference appears to be small compared to the amount required to kill that many fast missiles with DEW of any of the brightnesses or with kinetic energy interceptors. The difference is about a factor of 3 at 300 missiles. The estimated cost of the low brightness platforms remains reasonable there, although for ≥ 500 missiles it is probably excessive. Note, however, that the costs of the intermediate platforms are only about 20% higher than those of the bright platforms, so that if they became available during the time interval when a fast threat emerged, they could be quite effective. Thus, intermediate levels of technology, which might be available 5-10 years earlier than that for 20-10 platforms, might be deployed earlier without significant penalty.

D. Cost-Brightness Relationships

Figure 4 is a crossplot of constellation cost vs brightness, which emphasizes that for large launches there is a great advantage for large platforms, although for small launches there is little. Indeed, if costs were linear in B rather than the optimal $\sqrt{B}$, platforms of lower brightness would be preferred. For small threats, low brightness constellations scale as $N \alpha B^{-0.8}$ so for platform costs linear in B, the constellation costs would increase as $B^{0.2}$, i.e., weakly.

IX. SENSITIVITY

The calculations above used varying numbers of missiles, all of which were assumed to undergo the most stressing performance the offense might ultimately provide. Thus, the nominal calculations are defense conservative, and it is useful to estimate how conservative they are.

A. Hardening

The nominal calculations above were hardened to the limiting value postulated by critics.[33] Further retrofit hardening would involve major penalties in payload.[34] Near-term missiles, which are not intentionally hardened, could be an order of magnitude softer than the limiting values assumed. Thus, the size and cost of the constellation needed to negate them would be be reduced from the estimate above. The results of Figs. 1-2 follow the scaling of Eq. (12): $N \propto J^{\Gamma}$ with $\Gamma = 0.7\text{-}1$ for high to low brightness. The impact of the lower hardness of initial threats is to scale constellation sizes and costs down by a factor of $(J/200\ \mathrm{MJ/m^2})^{0.7-1}$, which could amount to roughly an order of magnitude.

B. Engagement Time

The nominal calculations above were given the shortest burn and deployment times consistent with effective deployment, $\approx$ 100 s, which represents a physical barrier.[35] Existing missiles have engagement times of about $T = 600$ s. By Eq. (12) that would reduce the constellation sizes and costs roughly as $T^{-3/4}$. Figure 5 shows the combined calculations for low and medium brightness platforms. The former scale as $T^{-0.86}$; the latter as $T^{-0.78}$ over the whole interval. The modest numbers of satellites required are worth noting. About 45 low brightness platforms would suffice for 300 missiles vulnerable for 600 s; 13 medium brightness platforms would also suffice. If lasers were introduced as a supplement at a time when booster and bus times had been halved, giving an engagement time of about 300 s, then 80 and 22 platforms, respectively, would be needed.

C. Launch Area

The nominal calculations used the current distributed launch area of about 10 $\mathrm{Mm^2}$. Reductions in launch areas are possible, but could significantly penalize the attack's vulnerability, penetration, and flexibility.[36] It is interesting, however, to estimate the impact of reducing the launch area in order to compare the sensitivities of KEW and DEW intercepts to it.[37]

The present Soviet launch area extends from about 30° to 130° in longitude and 45° to 60° in latitude. It is partitioned into a symmetrical area west of the Urals, roughly 30°-60° longitude by 45°-60° latitude, and a string of fixed sites along the trans-Siberian railway from 60° to 130° longitude. The railway's meanders give the latter a latitudinal extent of 5-10°.[38] The western area is about 3.4 Mm^2 and the eastern about 5.6 Mm^2, which an early report rounded to the 10 Mm^2 used subsequently.[39]

The western region has about a third of the total launch area and about half the missiles, so the combined calculations for symmetric areas used as nominal are directly applicable to it.[40] Some discussions approximate the launch area by a line, but KEW and DEW constellations are more efficient for lines than for points. Thus, in reducing the area, in order to stress the defense the Soviets would presumably first eliminate the sites along the railway, which would reduce the area by about a factor of 2 to a symmetric residual. Further reductions would presumably be effected by gradually eliminating sites on the periphery of the current 20 distributed launch areas, ultimately producing either a single, compact launch area or a more expensive but more secure capability to cluster mobiles before launch. The combined solution is sufficiently accurate for all stages in the transition and essentially exact for either climax deployment. Since that transition could take 10-20 years, the application of modest lasers is appropriate.

Figure 6 shows the combined calculations for low, medium, and high brightness platforms for areas ranging from the 100 to 1% of the current 10 Mm^2, which are relatively insensitive to A_L. The high, medium, and low brightness constellations only increase by factors of 2, 2.8, and 3.5, respectively, when A_L decreases by a factor of 100. The scaling is strongest in the 1-10 Mm^2 region, where it is $\approx A_L^{-0.23}$. Thus, the factor of 2 reduction in area by eliminating the railway would only increase the constellation size by about $2^{0.23} \approx 17\%$. Decreasing A_L to 1 Mm^2 would increase the constellations by about a factor of 2. That would, however, require the elimination of about 90% of the launch sites, i.e., the completion of the transition.

D. Combined Constellations

Constellation costs would increase in proportion to their sizes, i.e., ultimately by factors of 2-3. By contrast, the costs for KEW intercepts would increase by a significantly larger factor, which would adversely shift their initial defensive cost margin.[41] For that reason, the introduction of faster missiles during the transition might best be met by the deployment of a modest, complementary DEW constellation, which could be available by about that time.

X. SUMMARY AND CONCLUSIONS

The brightness levels implied by the current technology levels in laser power and mirror fabrication are consistent with those required for useful applications in the near-term. Directed energy platforms could support cost-effective operations in the near and mid terms, and the constellations required would be significantly, but not prohibitively, larger than those required with high brightness platforms.

It is useful to note that for near-term threats, the costs for medium brightness constellations are not much greater than those for high brightness concepts. While low brightness concepts show the most sensitivity to cost-brightness relationships, if the actual scaling is intermediate between the linear and quadratic relationships used for illustration, the costs of low brightness combinations could be comparable with those for medium and high brightness concepts. The insensitivity of directed energy concepts to missile concentration before launch and other countermeasures to KEWs suggests a complementary role in the mid term, for which directed energy technology and development could be sufficiently mature.

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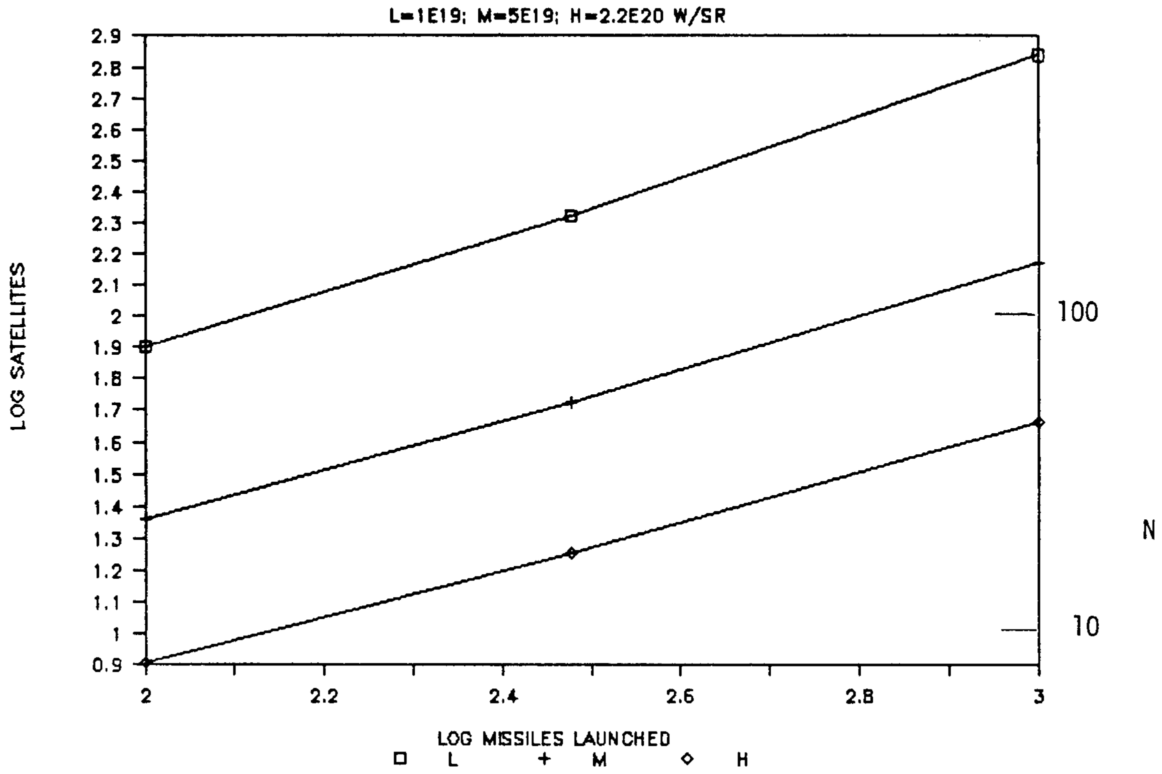

Fig. 1. Constellation size vs threat.

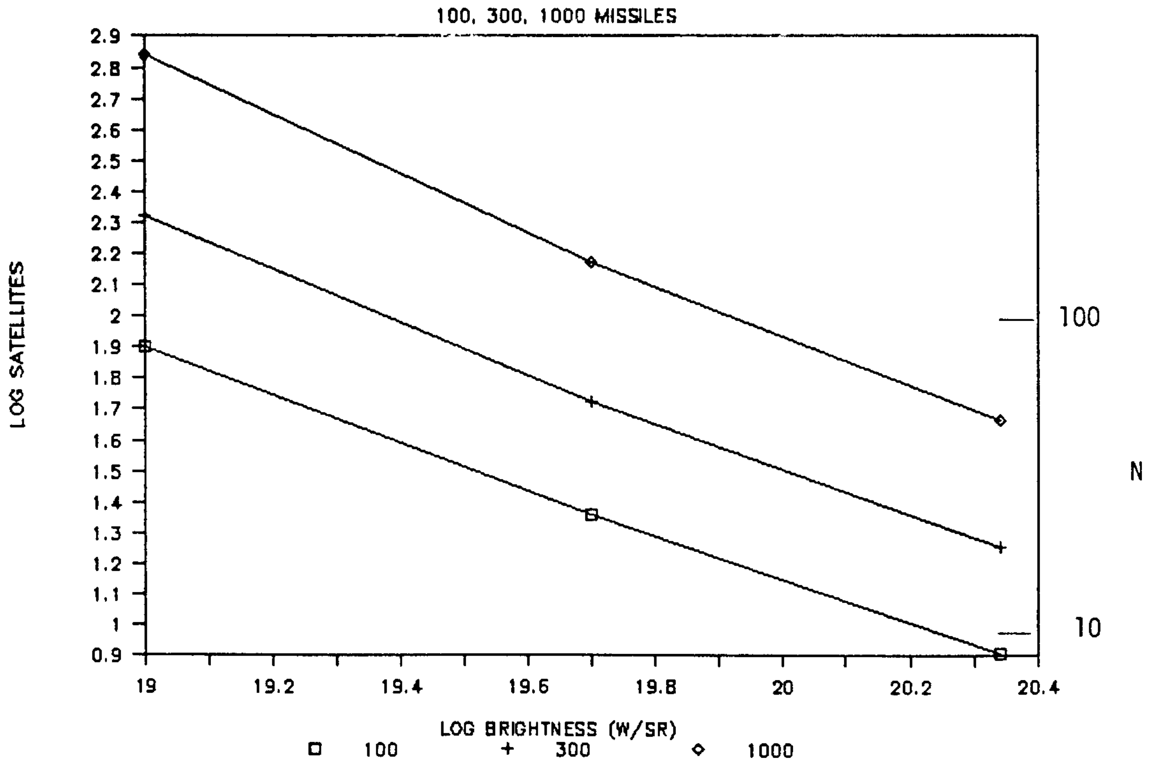

Fig. 2 Constellation size vs brightness.

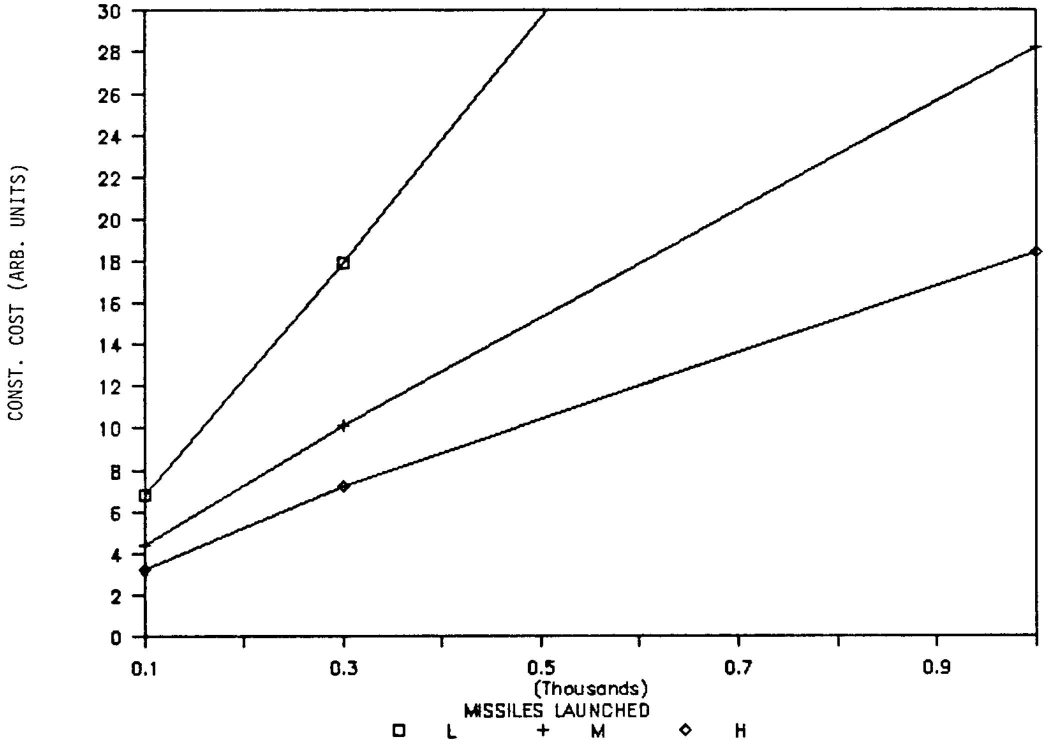

Fig. 3. Constellation cost vs threat.

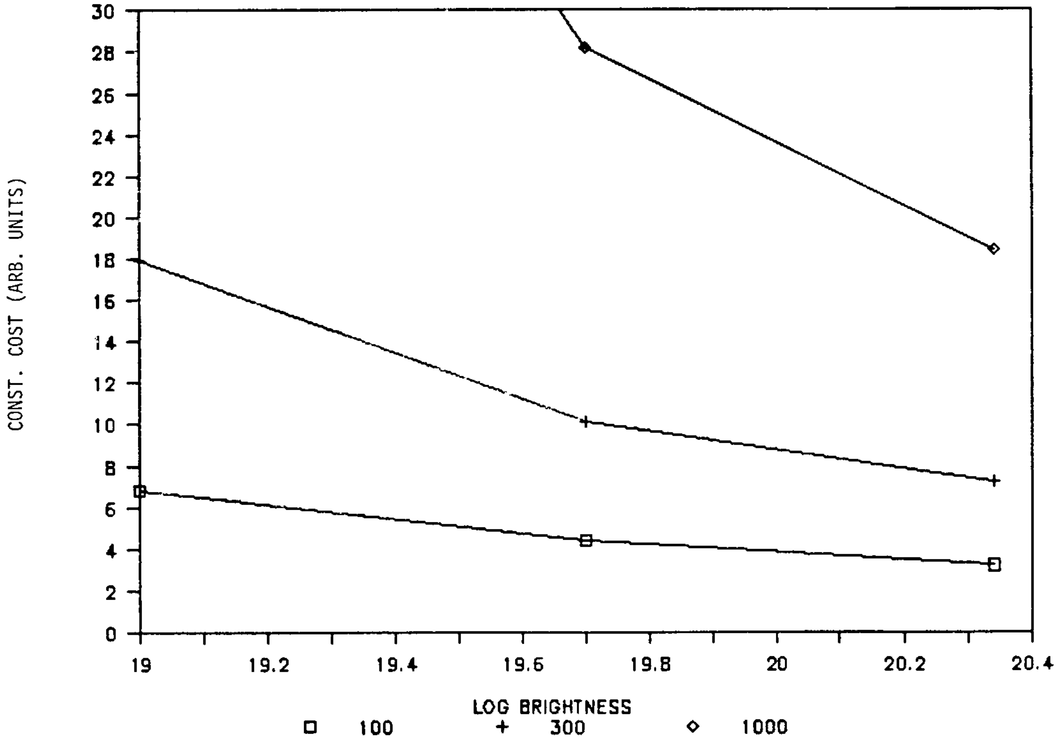

Fig. 4 Constellation cost vs brightness.

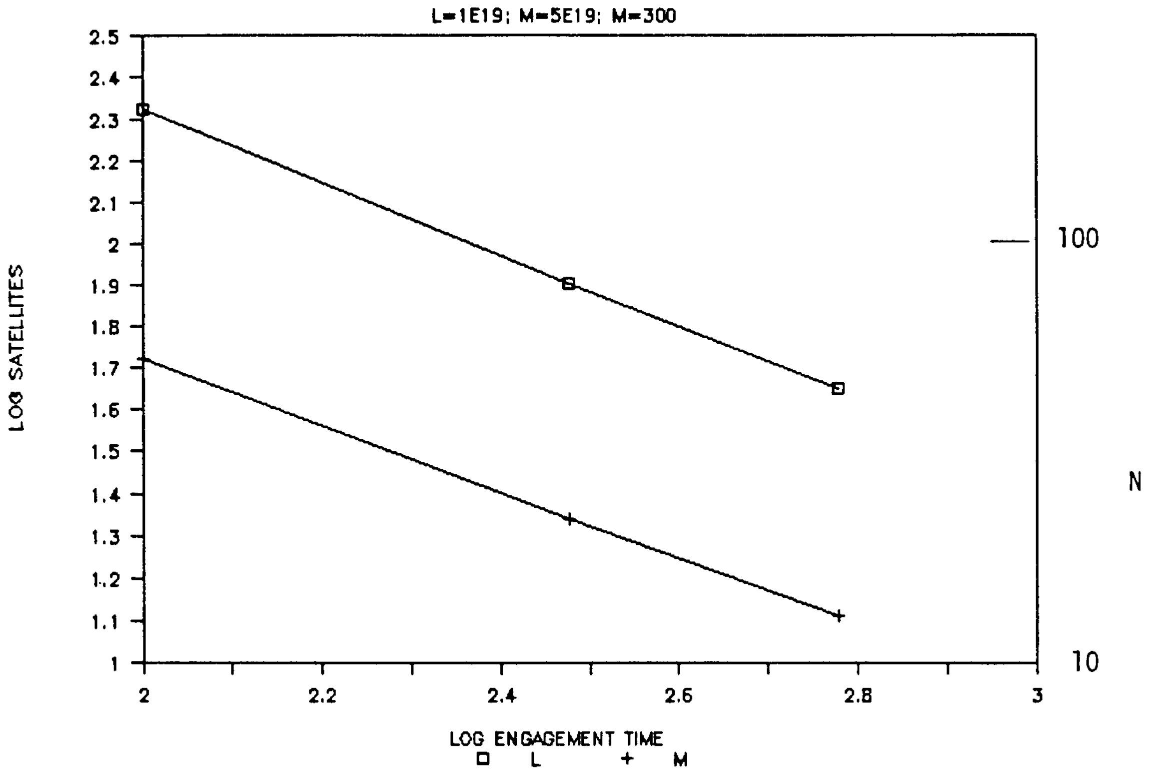

Fig. 5. Constellation size vs engagement time.

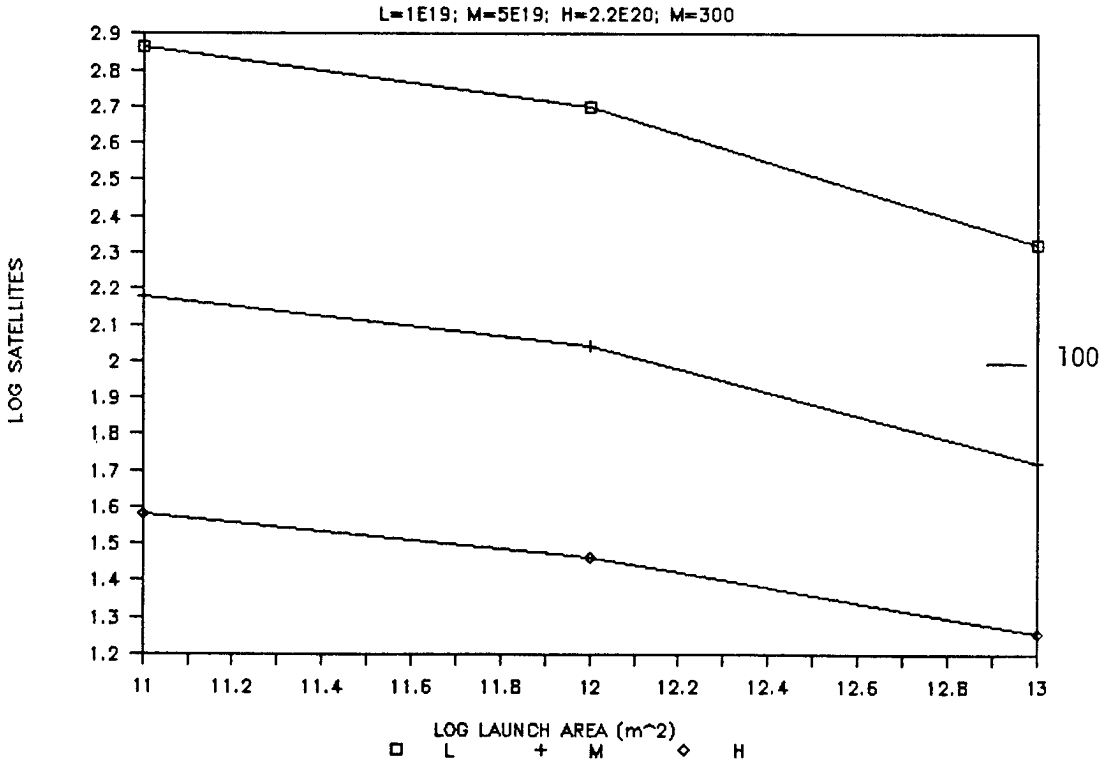

Fig. 6. Constellation size vs launch area.

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