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SURVIVABILITY OF SPACE ASSETS IN THE LONG TERM

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by

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ABSTRACT

This report discusses the threats to strategic defense satellites over the next 20-30 years. It describes the purposes and sizes of the satellites, the types of attacks on them, the counters to those attacks, and the likely outcomes of the encounters. It concludes that their survivability and contribution to stability should increase over the next 20-30 years because of the advanced technologies that should become available then.

I. INTRODUCTION

This report discusses the threats to satellites deployed in support of strategic defense over the next 20-30 years. It describes their purposes and sizes, the stressing attacks on them, counters to those attacks, and their likely outcomes. The discussion builds on previous reports. In the first report, an analysis was performed on the survivability of space assets in the near term, roughly the next 10-15 years, during which time the main satellites are likely to be kinetic energy weapon (KEW) homing, hit-to-kill space based interceptors (SBIs), their carrier vehicles (CVs), and supporting sensors.[1] During that interval the main problems appear to be direct attacks by conventional or nuclear antisatellites (ASATs).

The second report covered the midterm, when the mix of satellites could shift to include a significant fraction of directed energy weapon (DEW) platforms for the boost and midcourse, but in which those satellites would not have attained the brightness and performance levels required for full self-protection.[2] This report covers the long term, by which the U.S. and Soviet Union could deploy comparable numbers of large and capable satellites, lasers, and ground- and space-based ASATs, which introduce additional complications into the analysis of survivability and stability.

The impact of these features is thought to be destabilizing, but their overall impact on the evaluation of stability depends on the intrinsic and relative performances of the two sides' constellations. Near-term satellites have weakness in self-defense, because modest interceptor velocities limit the ability of CVs to defend themselves and others by boost-phase intercept, and modest DEW constellations are not bright enough to engage distant, hardened boosters. Advanced platforms could have enough range to defend themselves and other platforms, which could significantly improve their performance and survivability. This report explores, through a series of steps, the changes in satellite survivability that are caused by the deployment of the increasingly capable platforms possible on longer time scales.

Section II reviews near- and midterm survivability results from previous analyses. Section III discusses long-term ASAT threats, to KEW and sensor platforms from conventional ASATs, orbital ASATs, and ground-based lasers. Section IV discusses self-defense by DEWs; Section V treats DEWs' defense of other platforms; and Section VI evaluates DEWs as ASATs. Section VII reviews the problems raised by the significant and symmetrical co-occupancy of space in the long term. Section VIII uses these results to address the stability of joint deployments, which is stronger than generally thought.

II. NEAR- AND MIDTERM SELF-DEFENSES

It is useful to begin with a review of the main elements of self-defense in the near and midterms in order to identify their main sensitivities to improvements in ASATS over time.

A. Near Term

In the near term the main satellites are likely to be SBIs, their CVs, and their supporting sensors, whose main problems appear to be the direct ascent of nuclear or non-nuclear ASATs from the ground. Significant improvements have been made in the hardening of satellites; more are possible. Structures that do not need to reenter could be hardened far beyond the levels of current satellites, missiles, or even reentry vehicles (RVs) at moderate cost by strapping bulk shielding around them. That would force attackers to one-on-one attacks, precision guidance, and expensive sensors. The addition of modest propulsion could then make the intercepts even harder, particularly for ASATs with conventional warheads, which would not be well suited to attacking satellites with sensors to detect their approach and propulsion to evade them.

Combinations of hardening and maneuver could make small CVs survivable, in part because their value to the attacker decreases in proportion to the number of SBIs on them. It arguably reaches levels not worth attacking for singlet SBIs.[3] Figure 1 shows the mass penalties for various SBI CVs. The abscissa is the number of SBIs on board, and the ordinate is the penalty for the optimum combination of hardening and maneuver. The horizontal lines give the band for the effective masses of realistic nuclear ASATs. The bottom curve is for an imperfectly guided near-term ASAT, for which CVs with about 10 SBIs could break even with weapons of nominal expected masses. The middle curve is for improved ASATs, for which large CVs could only break even with the heaviest

ASATs. The top curve is for midterm ASATs with better guidance, against which only singlet to triplet CVs would be effective. Since the CV's mass penalty scales as the two thirds power of its mass, singlets with kill packages an order of magnitude smaller than current ones and low platform overhead would have a factor of ≈ 2-3 margin over the best ASATs shown.[4]

These arguments depend on unknown SBI costs. Thus, their conclusions weaken with time as better guidance and closer approaches become possible. Survivability could be extended further by providing satellites with self-defense missiles (SDMs). They could extract a favorable cost-exchange ratio from undecoyed ASATs, but in time, the ASATs could employ decoys. If credible, the decoys would force the satellites to intercept them all, which could be prohibitive. The defense's response could be to use decoys as well, taking advantage of the attacker's inability to discriminate them with on-board sensors in the short time of their approach. That step, though not an ultimate solution, could give CVs about an order of magnitude advantage over even capable midterm nuclear ASATs. Figure 2 shows the cost-effectiveness ratios (CERs) as a function of the number of decoys used for nominal offensive and defensive costs. For 20-40 decoys, the CER for a singlet would approach 5-10; that for a 10 SBI CV would be ≈ 2.

Their cost effectiveness should persist through the midterm into the long term, when capable space-based discriminators could begin to strip defensive satellite (DSAT) decoys of their effectiveness. In that time frame, however, the ASATs' decoys could also be discriminated, which would provide adequate survivability for defensive satellites through self-defense. There are residual concerns over the impact on such sensors of precursor nuclear bursts, peacetime attrition, and interference with command and control, but they seem modest for small SBIs and are bounded even for large satellites.

B. Midterm

In the midterm the two classes of satellites of primary concern are sensors satellites that support the SBIs, large DEW platforms, and other surveillance and reconnaissance missions. Sensors in the 1-10 ton range could be defended by extensions of the techniques discussed above. Their size and mass make them more difficult to harden and maneuver, but they could still make effective use of decoys. Figure 2 shows that they could achieve CER $\approx$ 2-3 with a few tens of decoys. Thus, midcourse satellites in low- and mid-earth orbit (LEO and MEO) gain enough from their higher altitudes to achieve roughly comparable levels of survivability as the CVs for LEO SBIs.[5]

High-earth or geosynchronous orbit (HEO or GSO) satellites tend to be large, so their positions could probably be determined prior to attack. During attack, however, direct ascent ASATs would be far from their support sensors, so the satellites could use a full range of deception and decoys. DEW satellites have a different concern. To perform well they must be in LEO, which is too low to hide effectively. High levels of performance are currently thought to require platform masses of 20-40 tons, which is too big to move or decoy. The CERs in Fig. 2 fall inversely with mass for satellites bigger than 4-6 tons,[6] so large DEWs would have CERs less than unity. Thus, these 20-40 ton DEWs must rely on their beams or others' ability to inspect or destroy attacking objects.

III. ASAT TYPES

Given the significant differences between the tactics and weaknesses of different types of ASATs, it is useful to define the main types and indicate how they could evolve in time.

A. Conventional ASATs

ASAT warheads can be conventional or nuclear. There is, however, little confidence that limited uses of nuclear weapons in non-war situations would remain controlled, so the use of nuclear ASATs is likely to be restricted to periods immediately preceding attacks. Non-nuclear weapons have less escalatory potential and hence much greater releasability. Their capability to directly attack and strongly suppress alert, active satellites is, however, limited in the near term and uncertain in midterm.

Conventional ASATs might have 10-100 kg kill package masses. If they hit an unhardened missile or satellite approaching at a relative velocity of 5-10 km/s, that would impart enough kinetic energy to kill it. A direct hit is, however, difficult to achieve against hardened, reactive platforms, so kill extenders could be used. They are useful against missiles and RVs, but satellites can affordably be hardened to reasonable areal mass densities, which the ASAT fragments' density must overcome. A CV with a 1-3 m^2 shield about 10 g/cm^2 thick, i.e., 100-300 kg, would devote 10-20% of its mass to hardening.

A conventional ASAT with a 10 kg kill package 10 cm across would have an areal density of about 10^4 g $\div$ $(10\ \mathrm{cm})^2 \approx$ 100 g/cm^2, which would penetrate the 10 g/cm^2 shield. For this example, if the ASAT could fragment its kill package into about 10 pieces of about that dimension, each could still penetrate the shield. If they were distributed about a satellite diameter $2R_S$ apart, the fragments could cover the kill area $\pi K_C^2 \approx 10 \cdot (2R_S)^2$. That would extend the ASAT's kill radius about a factor of $K_C/R_S \approx \sqrt{10} \approx 3$. The ASAT would, however, still have to maneuver to within $\approx 3R_S \approx$ 3-5 m of the evading satellite, so this extension would have only modest impact. Both sides could, however, vary these example parameters.

The general case is a simple extension of the example. If the satellite's shield has density μ_S, radius R_S, mass M_S, and only has to be shielded on the front, the attacking fragment must have an areal density of about $M_S/\pi R_S^2$ to penetrate it.[7] If a fragment has density μ_a and radius r, its mass is about $m_a \approx 4\pi\mu_a r^3/3$, and its areal density is $\mu_a r \approx (m_a \mu_a^2/4)^{1/3}$. Equating shield and fragment densities gives the penetration condition

$m_a \approx 4(M_S/\pi R_S^2)^3/\mu_a^2$, so that the required fragment mass increases as $m_a \propto M_S^3$, which favors the satellite. The attacker could increase μ_a by using high-density fragments, but that would lose the advantage of using the spent kill package to hit and kill the target.

The total mass needed for kill radius K_C is $M_A \approx m_a(K_C/R)^2$, so for a total kill package mass M_A, the extension is

$$K_C/R \approx (M_A/m_a)^{1/2} \approx \surd[M_A\mu_a^2/4(M_S/\pi R_S^2)^3] \propto \surd(M_A/M_S^3), \quad (1)$$

which for combat shield area strongly favors the satellite, whose shield mass should be less expensive than that of the ASAT and its extender. Thus, conventional ASATs appear to be primarily useful for producing peacetime attrition by very precise approaches, with defense suppression being executed largely by nuclear ASATs.

The significance of this point is that if only conventional weapons can be used in peacetime, and attrition is only useful in peacetime, since any reduction of the defenses must have occurred by the initiation of a large scale strike, neither conventional weapons nor attrition are first order problems for the defense. For that reason the discussion below largely concentrates on nuclear suppression attacks soon before launch.

B. Nuclear ASATs

Nuclear ASATs launched from the ground are likely to be hardened and guided. The attacker has considerable leeway in the choice of the ASAT's parameters, but there are some bounds. The kill radius of a nuclear weapon with a yield of $Y = 100$ kilotons against satellites hardened to 10-100 J/cm^2 is about

$$K = \surd(Y/4\pi J) \approx \surd[4 \cdot 10^{14} J/4\pi(10\text{-}100\ J/cm^2)] \approx 6\text{-}20\ km. \quad (2)$$

The kill radius increases as $K \propto \surd Y$ for higher yields, but given the paucity of data on high-altitude nuclear effects, the Soviets would want to minimize the number and yield of weapons used in suppression over their own territory.[8] Moreover, increases in Y could be offset by the defense's increasing the hardness J over time. Thus, yields in the tens to hundreds of kilotons might be more likely than megatons, and numbers of weapons in the tens to hundreds more likely than thousands. If so, nuclear ASATs would have much larger kill radii than conventional ASATs, but they would still require good guidance to attack hardened satellites, which they would have to address individually.

C. Orbital ASATs

In the mid- to long term, both nuclear or non-nuclear ASATs could be put into orbit. By treaty the latter are not allowed, and it is likely that the means to detect violations would be available to both sides by then. Apart from differences in their lethal radii, however, the two are quite similar in their impact, so they are treated together here. Orbital ASATs can be deployed in three essentially independent ways: interspersed with the defensive satellites, in counter-rotating orbits, and in co-rotating orbits, which are discussed below.

1. Interspersed Weapons

Although interspersing ASATs with the defensive platforms would appear to be the most threatening deployment, that is not necessarily the case, because of the distances involved in space-to-space intercepts. LEO satellites up to an altitude of $h \approx 1{,}000$ km could be spread over a volume

$$V_{LEO} = 4\pi[(R_e + h)^3 - R_e^3]/3 \approx 6 \cdot 10^{11} \text{ km}^3, \qquad (3)$$

excluding the first 100-200 km of the atmosphere. Moving at $V \approx 7$ km/s, a satellite with a keep-out radius of $K \approx 20$ km would sweep out volume at a rate $\pi K^2 V \approx 9{,}000$ km^3/s, at which it would sweep LEO in about $V_{LEO}/\pi K^2 V \approx 7 \cdot 10^7$ s $\approx$ 2 years, i.e., if there was one ASAT in LEO, the satellite should encounter it by chance in about 2 years. If there were 100 ASATs, the satellite should pass close enough to require one or the other of them to deflect about once a week. That time could of course be extended by increasing the hardness of the defensive satellite.

The deflections would be predictable, so they could be executed far in advance with small amounts of fuel. Executed a half-orbit ahead of time, the maneuver to generate a 20 km displacement would require a deflection of about 20 km ÷ 20,000 km ≈ 0.001, or 0.1% of its fuel, so for one deflection per week, the satellite would last ≈ 1,000 weeks ≈ 20 years, several times its expected lifetime. By performing the deflection 5 orbits (or 3 hours ahead) the time could be increased to about once a year. Unintentional encounters should not be a significant constraint on LEO deployments. For MEO, the volume would go up, and the rate of encounters down, by about an order of magnitude. For HEO encounters would go down as h^{-3}. Encounters there would only be a problem at GSO, whose special properties made it desirable for, and hence crowded with, earlier surveillance, warning, and communication satellites.

This phase space model can also be used to estimate the average distance to the nearest ASAT. For N_A ASATs it is

$$R_A \approx (V_{LEO}/4\pi N_A/3)^{1/3}, \tag{3a}$$

$\approx (1.5 \cdot 10^{11}/100)^{1/3} \approx 1.1$ Mm, which is useful for scaling the kinematics of suppression. If at the outset of attack each ASAT changed its direction and attacked the nearest defensive satellite, on the average it would have to traverse a distance $R_A \approx 1.1$ Mm, which is not much closer than the range from the ground to LEO defenses. The attack time $R_A/V \approx 150$ s is also about the same. Space ASATs would, however, on the average, have to deflect through about a right angle to attack the nearest defensive satellite, so it would have to expend an additional velocity ≈ V over and above the V ≈ 7.5 km/s expended to put it into orbit.

An ideal rocket with exit velocity c ≈ 2.5 km/s, or specific impulse of 250 s, would be $e^{V/c} \approx e^{7.5/2.5} \approx 20$ times larger than the kill package. Real ASATs would be closer to 30 times larger than the kill package. If the space-based ASAT's kill package mass is ≈ 500 kg, its total orbital mass would be ≈ 500 kg x 30 ≈ 15 tons, a factor of 2-10 larger than the masses of the defensive satellites they were attacking. Conventional warheads could reduce the kill package mass, but they would be at a disadvantage in attacking satellites with sensors, maneuver, and countermeasures.

Roughly similar factors govern attacks by ground-based ASATs, but their trajectory advantages, and the absenteeism of the defensive satellites, reduce the ASATs' effective kill package masses by a factor of $\approx$ 20, so a 500 kg kill package's effective mass would be $\approx$ 25 kg. That ASAT mass expenditure is stressingly low , but SBIs could apparently meet it. Putting ASATs in space would forfeit the absenteeism advantage and penalizes them by an additional factor of $e^{V/c} \approx 30$, which with the large divert velocities required, shifts the engagement by about a factor of 20 x 30 $\approx$ 600 in favor of the defensive satellite.[9]

The Soviets could shift their ASATs' trajectories to make close passages more frequent and the starting conditions for suppression attacks more favorable, but passages are predictable and subject to the establishment of statistics and rules of the road. If encounters came too frequently, that would constitute evidence of intent, representing a threatening act. To shift the starting conditions significantly from interspersed orbits, the ASATs' trajectories would have to be altered significantly to produce near-simultaneous conjunctions with each of their prey at the same future time. Since all of the satellites' trajectories are observable and predictable, it is only a problem in astrology for the defense to notice the approaching conjunction and take steps to avoid it. Overall, putting ASATs in space would appear to give the defense a significant advantage.

2. Contra-rotating Deployments

To overcome the large deflections needed for interspersed orbits it would be possible to put the ASATs into retrograde orbits where they would pass their prey regularly. Contra-rotating ASATs, or sweepers, are interesting, but fragile. Since each prey satellite could be put into a slightly different orbit, there would have to be at least as many sweepers as prey to gain any time advantage over attack from the ground.

The prey satellite could, however, make a small deflection when it was far from the sweeper and observed and move away from the sweeper in a short time. If the prey satellite made a transverse burn of half a degree when it was on the opposite side of the earth from the sweeper, by the time they passed, the sweeper and prey would be $\approx$ 10,000 km x 0.01 rad $\approx$ 100 km apart, enough to provide survivability. With a detection range of a few hundred kilometers, the sweeper would have to perform a $\approx 90^{o}$ maneuver to attempt an approach. After passing from sight, the prey could do another small burn onto a third plane, after which the sweeper would be lost in space.

These maneuvers could be performed with inexpensive, modest thrusters, but they should be effective unless the sweepers' support sensors had perfect coverage everywhere, which is unlikely. It would be too costly for the sweeper to chase its original prey or shift to another one in a different orbit promptly; its usefulness would be ended. The fractional mass required would be about $\delta M/M \approx \delta V/V \approx 1\%$, which is probably less than the mass required of a practical sweeper.

Fundamentally, sweepers have little advantage in the first place. They have to be capable to keep station precisely with the ASATs and large enough to accommodate the violent end game they face in retrograde orbits against maneuvering satellites. Even then for one sweeper per prey the coverage is about once every 45 minutes, which isn't much faster than direct ascent ASATs, and encounters would be less frequent in higher orbits of concern. It would be difficult for them to attack all prey satellites in less than 30-45 minutes, which is not stressing.

3. Co-rotating Deployments

These cost, evasion, and timeline problems could be overcome by co-rotating ASATs, generally called space mines, which could, without treaty violation, be co-orbited and keep station within tens or hundreds of kilometers of defensive satellites, i.e., at or within their nuclear keep-out distances. Trailing space mines would be in position all of the time, with the potential of being detonated simultaneously at any time. The most bothersome thing about them from the perspective of stability is the possibility that they might be able to disarm the defenses at the initiation of hostilities.

a. Characteristics

The space mines could fly simple pursuits with short-range sensors anchored on their prey. The mass required to pursue is less than that required of a heavier prey to evade by the ratio of their masses, which strongly favors light space mines. Thus, space mines could be difficult to negate, because satellites can neither afford to run away nor tolerate their presence nearby. They can, however, take a series of defensive steps.

b. Bare Space Mines

Maneuvering away from a bare, i.e., undecoyed, space mine would not be effective if the mine was lighter than the defensive satellite. The mass penalty is δM for a small velocity change $\delta M \approx M \cdot \delta V/V$, so if the satellite and the mine made the same maneuver, δV, the ratio of their mass penalties would be $\delta M_S/\delta M_A \approx M_S/M_A$, where the subscript S(A) refers to the satellite (ASAT). If $M_S \approx 10 \cdot M_A$, the maneuver is 10 times more costly to the satellite than the ASAT, and the ASAT would proliferate fuel and follow until the satellite's fuel was exhausted. Since the satellite might carry a 2-5 ton sensor while the ASAT carried a 200-500 kg weapon and pursuit sensor, the ratio of $M_S/M_A \approx 10$ is not inappropriate.

If there was a limited number of objects per satellite, and it could keep them beyond its lethal radius, it could use SDM to destroy the ASATs at the initiation of hostilities. The mass of such SDMs could be $M_{SD} \approx$ 20-50 kg, if the ASATs were unable to use flares or maneuver to avoid them. If so, destroying a $M_A \approx 200$ kg ASAT would favor the defensive satellite by a ratio of $M_A:M_{SD} \approx 200$ kg:20-50 kg $\approx$ 10-4:1, which would be enough margin to discourage the Soviets from proliferating bare ASATs. To achieve that ratio, however, the satellites would have to define keep-out radii of tens to hundreds of kilometers and reserve the right to disable or destroy trailing satellites that came within it, which could involve difficulty.

c. Decoys

Self-defense would become more difficult technically if the ASATs deployed large numbers of decoys. The prey would then not know what to shoot, and using SDMs to suppress $N_D \approx 100$ decoys with masses $M_D \approx 1\% \cdot M_A$ would give the defense an ASAT:satellite mass exchange ratio of

$$ER = (M_A + N_D \cdot M_D):(N_D + 1) \cdot M_{SD} \approx 400 \text{ kg:2-5 ton}, \qquad (4)$$

which would be 1:5-12 adverse to the defense, even if the defense was successful. For decoys, $ER \approx M_D/M_{SD} \approx 2$ kg/20-50 kg $\approx$ 10-4%, so light, credible ASAT decoys could reverse the leverage SDMs would have over bare ASATs. Such undicriminated decoys cannot be tolerated. While 1% decoys could be credible now, it is possible that by the midterm, passive or low power sensors could, by observing the decoys for long periods of time, force them to levels of fidelity in multispectral observations that their masses could approach 10% of the ASATs' to be credible. If so, the ratio above would drop to about

$$ER = (200 + 100 \cdot 20):100 \cdot (20\text{-}50 \text{ kg}) \approx 1:1\text{-}2.5, \qquad (4a)$$

which is greatly improved, but still marginal. For N_D large ER' $\approx$ 20/20-50 $\approx$ 1-0.4, which is useful, but sensitive to the decoys' unknown parameters.

Interestingly, against such decoys maneuver could have more impact than against bare mines, since 10% of the decoys could not be counted on to maneuver deceptively. The mass of the ASAT and its decoys is $M_A + N_D \cdot M_D$. If the decoys moved with the actual space mine in following its prey, the mass ratio would become

$$\delta M_S/\delta M_A \approx M_S/M_A(1 + N_D \cdot M_D/M_A) \approx M_S/2M_A \approx 5, \qquad (4b)$$

which is not fundamentally better than the bare maneuver result and is not as good as the self-defense of Eq. (4a). If, however, the decoys had to be discarded with and replenished after each maneuver, the ASAT's mass loss would be $\delta M_A \approx M_A \delta V/V + N_D \cdot M_D$, so the exchange ratio would become

$$\delta M_S/\delta M_A \approx M_S/M_A(1 + V/\delta V) \tag{4c}$$

for $N_D M_D \approx M_A$ as before, so that many small maneuvers could be used to magnify the mine's maneuver penalty and gradually strip the ASATs of their decoys. A bare mass ratio of $M_S/M_A \approx 10$ could be offset by $V/\delta V \approx 10$. This approach achieves a much better exchange ratio at the price of some sensitivity to maneuvering decoys. That sensitivity could be reduced if the satellites deployed decoys of their own, each of which maneuvered away in a different direction. If good offensive discrimination were absent, the ASAT as well as the decoys would have a high probability of being lost on a defensive decoy. The scheme would, however, remain sensitive to the ASATs' unknown discrimination capability. To do fundamentally better requires improved discrimination.

d. Decoy Discrimination

The best way to overcome the mass penalty from ASAT decoys is to discriminate them well, since doing so makes them a waste of mass for the ASAT. Passive means, which are well developed, could serve in the near term; lasers could be used to inspect a limited number of objects in an interim near to mid term discrimination role.[10] In the mid- to long term, however, neutral particle beams (NPBs) could provide a fundamental ability to discriminate decoys on the basis of mass, which is the hardest thing for the ASAT to simulate. The analysis of NPBs is treated in detail elsewhere;[11] this section summarizes the results.

NPBs discriminate by sending out a beam of neutral particles that can pass freely through space, penetrate the target, and produce particles and radiation that can escape and can be detected remotely. If the NPB transmits a current I, of particles of charge q, in a beam of divergence Θ, for time t, that produces a fluence $I \cdot t/q(\theta r)^2$ of particles on a target at range r. A target of area, $A_T < (\theta r)^2$ that produces τ neutrons per particle creates a neutron fluence

$$J_n = [It/q(\theta r)^2][\tau A_T/4\pi r_D^2] \tag{5}$$

on a detector at a range r_D from the object. A detector of effective area A_D would produce a signal $J_n \cdot A_D$. Equating that to the number of counts S_D required for detection gives

$$r \cdot r_D = (It\tau A_T A_D/4\pi q S_D)^{1/2}/\theta, \tag{6}$$

which shows the direct tradeoff between platform and detector ranges and beam divergence and their weaker dependence on beam and detector characteristics. For self-defense, detectors might be mounted on the NPB itself. That sets $r = r_D$ and produces

$$S_D = It\tau A_T A_D/4\pi q \theta^2 r^4, \tag{7}$$

which, like monostatic radar, scales as $S_D \propto r^{-4}$. NPBs whose divergences are limited by scattering scale as $\theta \propto 1/\sqrt{E}$, so

$$S_D \propto ItE/r^4 \propto Pt/r^4, \tag{8}$$

$Pt \propto r^4$, and $r \propto (Pt)^{1/4}$. The conversion efficiency τ is a nuclear cross section times the particles' interaction length, so $\tau \propto M_T/A_T$, where M_T is the target's mass and A_T is its area. The total signal is proportional to the product of τ and the number of particles that hit the target, so $\tau \propto (M_T/A_T) \cdot A_T \propto M_T$, the object's mass, the one parameter that best identifies a decoy. Equation (7) can be solved for the current-time product needed for interrogation

$$I \cdot t = (S_D 4\pi q/\tau A_T A_D)\theta^2 r^4, \tag{9}$$

whose dominant scaling is $\theta^2 r^4$. Figure 3 shows the $I \cdot t$ products required to discriminate as a function of beam divergence for ranges of 100-10,000 km. The lower range is the keep-out range needed for self-defense; the upper range is that needed to protect distant platforms. The parameters used are $S_D = 10^4$ counts, $\tau = 1$, and $A_D = 1\ m^2 = A_T$, which are attainable in the midterm. The beam divergence θ varies from a near term 10 μrad to a long term 1 μrad, producing $I \cdot t$ ranging from 10^{-6} to $\approx 10^3$ Amp-s.

According to the top curve, near-term NPBs would need $I \cdot t \approx 10^{-4}$ Amp-s to enforce a keep-out radius of 100 km. If the inspection was done in 1 s, that would require about 0.1 mA at a modest beam energy of 30-50 MeV. A 1,000 km range would require $\approx$ 1 Amp-s, which is practical because inspection could be performed over 10-1000 s at $I \approx 0.001$-0.1 A. Reducing the divergence to 1 μrad would reduce $I \cdot t$ to 0.01 Amp-s. The most bothersome co-orbiting objects are space mines and decoys, for which 10^3-10^4 s is available for inspections. That gives a range of currents of $I \approx 0.01$-1 Amp-s $\div$ 10^3-10^4 s $\approx$ 1 μA-1 mA, which are small compared to the currents required for weapon platforms.

In inspecting objects that threaten satellites thousands of kilometers distant, it is more efficient to put the detector on the satellite, which produces a bistatic geometry scaling

$$I \cdot t = (S_D q 4\pi/\tau A_T A_D)(r_D \theta r)^2. \qquad (10)$$

The curves of slope $I \cdot t \;\alpha\; r^2$ on Fig. 3 show the $I \cdot t$ products for various ranges and beam divergences for the parameters used earlier. The most stressing is a NPB at LEO protecting a satellite at GSO. A 1 μrad beam would require $\approx$ 1 Amp-s to interrogate objects at 30,000 km; a 3 μrad beam would take $\approx$ 10 Amp-s. Thus, $I \cdot t \;\alpha\; \theta^2 \;\alpha\; 1/E$, so $E \cdot I \cdot t = P \cdot t$ is roughly constant. NPB costs are roughly proportional to E in this region, so the appropriate scaling would minimize E and make it up on $I \cdot t$.

The dwell time t is set by the mission. If there were 10 satellites at GSO to be protected, with 10 objects around each, and it was necessary to inspect each once a day, that would give about 10^5 s $\div$ 10^2 objects = 10^3 s/object, or $I \approx 10$ Amp-s $\div$ 10^3 s = 0.01 Amp at 3 μrad or 100 MeV. The beam power would be $\approx$ 0.01 Amp x 100 MeV $\approx$ 1 MW. If the platform didn't have to survive, that amount of power might be generated with $\approx$ 1,000 m^2 of solar collector. This is not an optimization, just a point design to show that modest NPBs at LEO could inspect objects at

GSO, or more broadly that fundamental means of discrimination could be available earlier than generally thought.

The current-time products above are upper limits. Most large satellites would be at $\approx$ 2-4,000 km, for which $I \cdot t$ is less by a factor of 10-100. Given this performance, however, mass and cost trades would strongly favor the defense. If the NPBs derived their power from fuel, they might require several megajoules or about a kilogram of fuel to discriminate a kilogram-sized object. The fuel, however, would be at LEO and the object at GSO, so the NPB would still have mass and cost exchange ratios of $\approx$ 10:1 over decoys, and more over the ASATs.

e. ASAT and Decoy Kill

NPBs that discriminate can also be used to negate the weapons they find. For an object of hardness J at range r and a NPB of brightness $B \approx I \cdot E/\theta^2$, the dwell time required is

$$t = J \cdot r^2/B, \qquad (11)$$

which for a nominal $B = 10^{19}$ W/sr, electronics hardness of $J = 1$ MJ/m^2, and $r = 1{,}000$ km is $t \approx 1$ s. A nuclear weapon could require $J \approx$ (100-300 J/g)(10-30 g/cm^2) $\approx$ 10-100 MJ/m^2,[12] which would require $t \approx$ 0.1-1 s at 300 km. Since the same NPB platforms can interrogate, discriminate, and negate objects, there are advantages in performing the latter with NPBs as well, since that simplifies the overall engagement, produces speed-of-light kill, and eliminates some offensive countermeasures.

As the NPB's brightness increases, the range at which it could inspect unknown co-orbiting objects grows proportionally. An NPB with a brightness of about a percent of that needed for a weapon beam should be able to perform these defensive functions both for itself and for other satellites at ever increasing distances. That could provide the self-defense capability essential to constellation effectiveness It would also provide it in a way that could relieve the individual defensive satellites of the responsibility for performing interrogation themselves.

4. Summary

Interspersed and retrograde ASATs are interesting, but not necessarily threatening. The former impose less of a penalty on defensive satellites than would ground-based interceptors or lasers; the latter require only the ability to make modest, discrete maneuvers. Space mines are more challenging; they force the defense to efficient maneuvers, decoys, and discrimination, but all should be available in the mid- to long terms. With these counters, space mines should not be a severe threat.

D. Ground-Based Laser ASATs

In the mid- to long term, ground-based lasers (GBLs) could pose more of a threat than direct ascent ASATs to LEO and MEO satellites. This section discusses the metrics and economics of laser attacks. Such lasers would address satellites and decoys serially, taking 10-100 s to negate each object. Thus, in a conflict they would take 10^5-10^6 s to sweep space, during which time they would be exposed, vulnerable, and difficult to defend. They would have little ability to negate endoatmospheric RVs, including those attacking them. Thus, they would primarily be effective in attriting satellites and decoys in "peacetime," when they could operate unopposed for long periods of time.

1. Energetics

A laser of brightness B (W/sr) produces flux B/r^2 at range r, so targets hardened to a fluence J (J/m^2) would be destroyed in a dwell time $t = J/(B/r^2)$. A chemical laser operating at wavelength w = 2.7 μm, with power P = 10 MW, with a mirror of diameter 10 m, and a "10-10" design, would have a brightness[13]

$$B = P \cdot A/w^2 \approx 10^{20} \text{ W/sr}, \tag{12}$$

which would destroy targets at r = 1 Mm hardened to a limiting fluence $J = 100 \text{ MJ/m}^2$ in $t \approx 100 \text{ MJ/m}^2 \div [10^{20} \text{ W/sr}/(10^6 \text{m})^2] \approx$ 1 s. Smaller lasers would take correspondingly longer dwell times, but they would have $\approx$ 100 s to irradiate the object on each pass.

2. Laser Requirements

A lower limit to the useful brightness is set by the ability of hardening materials to reradiate the laser radiation as fast as it arrives. Such materials can operate up to fluxes of $F_c \approx 1\ kW/cm^2$; if the laser energy arrived at a lower flux, it could be reradiated passively. Thus, to defeat these materials the laser would have to produce a flux $F = B/r^2 \geq F_c$, i.e., it would need a brightness

$$B \geq r^2 \cdot F_c, \tag{13}$$

which is $\approx (1\ Mm)^2 \cdot 10\ MW/m^2 \approx 10^{19}$ W/sr for LEO. That is large, but it is an order of magnitude below the brightness of the 10-10 laser discussed above. The lower bound corresponds roughly to a 3 MW, 3 m laser at 3 μm. Lasers with that brightness or greater would pose a threat to LEO satellites. The required brightness increases with altitude; for GSO a brightness of $\approx (30\ Mm)^2 \cdot 10\ MW/m^2 \approx 10^{22}$ W/sr would be needed. These requirements are for CW lasers; those for pulsed lasers could be somewhat lower due to their coupling to the target.

Chemical lasers are efficient in space, but require cumbersome steam ejectors on the ground, so lasers at other wavelengths might be desirable. Chemical lasers of the 10-10 size discussed above have estimated costs of \$ 200-400 M in space.[14] For ground operation, launch and space qualification costs are removed, but pumps and auxiliary systems are added, so the system's cost might remain around \$ 200 M. Long wavelength lasers have been developed for a variety of DoD applications, in which they have achieved costs on the order of \$ 10/W at significant scale. By Eq. (12), a 10 μm wavelength laser would require a $(10\ \mu m/3\ \mu m)^2 \approx$ 10-fold larger P-A product than a 3 μm laser for the same brightness, roughly a 30 MW-20 m combination, whose costs should increase as $\alpha\ (P \cdot A)^{1/2} \approx$ 3-fold to about \$ 600 M.[15] Conversely, a 1 μm wavelength laser should reduce the P-A product an order of magnitude. Ideally, their cost should drop to \$ 100 M, but free-electron lasers (FELs), which are the leading candidates, require large electron accelerators, power supplies, and beam corrections, so their costs might not be reduced that much.

Overall, ground-based laser ASATs good to about 3,000 km with a brightness of $\approx 10^{20}$ W/sr might cost \$ 100-600 M. A nominal cost of \$ 300 M amortized over a period of a year would give about $\$ 300 \text{ M} \div 3 \cdot 10^7 \text{ s} \approx \$ 20$ /s for the GBL. Thus, if it took 100 s to destroy an object, the cost to do so would be $\approx$ \$ 2 K. If the GBL had a target in sight only 1% of the time, the cost would increase to \$ 200 K. The duty factor can be estimated from phase space arguments. The laser beam should be correctable to about 45^o from vertical, so at LEO its footprint should be about 1 Mm across and have area $\approx 1 \text{ Mm}^2$. Thus, it could see a fraction $\approx 1 \text{ Mm}^2/4\pi R_e{}^2 \approx 1 \text{ Mm}^2/4\pi(6.4 \text{ Mm})^2 \approx 0.2\%$ of the objects in orbit at any time. If there were $\approx$ 300 SBI CVs in LEO, the duty factor would be about 50%; for 30 CVs or DEWs, it would drop to about 5%. The periods without targets could impact the GBL's economics significantly for small constellations.

3. Beam Correction

The estimates above assume that the laser beam is diffraction limited. For lasers that are in space that is appropriate, but for lasers on the ground, irradiating targets in space requires the correction of atmospheric turbulence.[16] At $w = 2.7$ μm the turbulence's outer scale is $\approx$ 30 cm, so correcting a 10 m primary transmitter would require $\approx (10 \text{ m}/30 \text{ cm})^2 \approx 10^3$ actuators. Performing that correction against uncooperative targets is difficult, which is why lasers are described as a longer term threat.

Since the lasers are large, they could be destroyed. They would be on the other's territory, however, so one would not do that lightly. There are other ways of countering this threat. Some are based on the delicacy of beam correction, which could be interfered with. There are two control loops that might be interrupted. One is for pointing the beam. It is possible to use false return signals to cause beams to wander, which reduces the average flux at any point. If it is reduced below the level for passive reradiation, the satellite could survive indefinitely. The other loop is for correcting the atmospheric turbulence, which is difficult to perform even in the absence of interference.

4. Decoys

There are interim approaches to the defense against ground-based laser ASATs that use decoys and deception, using decoys that are released on warning, as described above, or deployed with the SBIs.

a. Deployment

Decoys deployed on warning were discussed in Section II. Their problem in this application is that the laser gives little warning for their release. The predeployed decoys' major issue is discrimination. Unless the decoys closely resemble the CVs, or vice versa, they might be discriminated, since they would be relatively close to ground-based sensors that could inspect them for years. They would need great fidelity, which usually means mass, but the decoy's mass must be well below that of the CV's if it is to be effective. Ideally, it should be possible for CVs to use light shells or disks with masses of 1-10 kg for altitudes above 500-1,000 km, since drag corrections are modest there and could be corrected or antisimulated.

Decoys could also be deployed just before the CV came into the laser's field of regard, much as those for a CV would be deployed on warning of a nuclear ASAT's launch. Such decoys could be hard, which would force the laser to high power. Light decoys would be quickly be burned away. A 10 μm laser with a 10 m mirror would produce a beam divergence of $\theta \approx 10\ \mu\text{m} \div 10\ \text{m} \approx 1\ \mu\text{rad}$, which at LEO would give a beam diameter of $\approx \theta \cdot 1\ \text{Mm} \approx 1\ \text{m}$, about the size of a CV. A 10 MW laser would give $\approx 1\ \text{kW/cm}^2$ over that area. Since spinning the decoys could average the irradiation over their whole surface, lasers with shorter wavelengths and smaller spots would not reduce the beam's area significantly. The laser's power could be increased, but its costs would increase proportionally, so its exchange ratio with the decoys would be the same, but at higher kill and launch rates.

b. Hardening

A 10 kg decoy the size of the beam would provide a hardening of roughly 20 MJ/kg$\cdot$10 kg $\div$ 10^4 cm^2 $\approx$ 20 kJ/cm^2, which gives a dwell time of 20 kJ/cm^2 $\div$ 1 kW/cm^2 $\approx$ 20 s. If the SBI deployed 100 such decoys, its chance of making one pass safely would be about 95%. If the remaining decoys remained credible on subsequent passes, and the CV replaced those lost, it could maintain roughly that probability of survival per pass for about 5 decoys x 10 kg/decoy $\approx$ 50 kg/pass. A 1 ton CV carrying 2-10 times its mass of decoys would give 2-10 ton $\div$ 10 kg/decoy $\approx$ 200-1,000 decoys. If $\approx$ 5 decoys were lost per pass, that inventory would last $\approx$ 200-1,000 decoys $\div$ 5 decoys/pass $\approx$ 40-200 passes $\approx$ 20-100 days.

Decoys might be deployed for about their launch cost of $\approx$ \$ 1 K/kg; the SBI's fabrication cost goal is 10-20 times higher. Thus, a CV with 10 times as much decoy mass as SBI mass would roughly double the CV's total mass, which should be about the optimal for this interaction. Note that this argument, as opposed to the earlier arguments on KEW threats, hardening, and maneuver, favors larger CVs, since the decoy masses and the number of decoys per CV are independent of the CV mass and cost so long as it survives. Thus, the use of decoys could provide some cushion at the initiation of an attrition attack.

c. Costs

For dilute mixtures of SBIs in decoys, the SBIs' cost would be spread over many decoys, reducing the ASAT's expected value per object killed. A reasonably current estimate of a SBI's cost in a 10 SBI CV is about $C_S \approx$ \$ 6 M/SBI, divided about evenly between kill package costs, prorated satellite costs, launch costs for the 100 kg SBI and satellite, and life cycle command and control costs.[17] It is straightforward to adjust estimates below for other SBI cost estimates, since the components of the SBI's cost should scale together. Plausible variations do not change the qualitative conclusions below.[18]

In these estimates the launch costs are about \$ 1.5 M ÷ 200 kg ≈ \$ 7 K/kg, which reflects current launch capacity. For the long term it is more appropriate to use Advanced Launch System (ALS) estimates of ≈ \$ 1 K/kg. The SBI cost is ≈ \$ 1.5 M ÷ 100 kg ≈ \$ 15 K/kg, about 10 times the ALS launch cost; the SBI kill package is ≈ \$ 1 M ÷ 10 kg ≈ \$ 100 K/kg, which is about the current cost of space hardware. It could, like SBI mass, decrease by about an order of magnitude in the mid- to long term, but the current cost is used as the baseline below.

For launch costs of ≈ \$ 1 K/kg, it would cost ≈ \$ 10 K to launch a 10 kg decoy. For the laser estimates above it would cost the GBL ≈ \$ 20 /s·20 s ≈ \$ 400 to kill a decoy in the beam. The cost might be increased by gaps in the constellation for a few tens of CVs with their decoys deployed compactly around them, but the costs typically shouldn't be more than about \$ 1,000 per decoy. That is a factor of 10 less than the cost to deploy them, so decoys cannot overcome the laser economically at projected launch costs; the best they can do is buy time for the CV. The numbers above are for a single GBL, but they scale. Two lasers would destroy decoys twice as fast, but they would cost twice as much, so the exchange rate would be the same.

If the CV carried one SBI costing C_S plus D decoys, its total cost would be about

$$C_D \approx C_S + \$\,10\ K \cdot D, \tag{14}$$

while the cost for the GBL to negate them is

$$C_G \approx (1 + D) \cdot \$\,1\ K, \tag{14a}$$

where it is assumed that the CV is about as hard as the decoys. It could be made harder, but if the laser must irradiate all targets, the CV is as well off to put any additional mass into more decoys, once the CV reaches ≈ 5 times the hardness of a decoy. The laser's optimization is already reflected in the \$ 1 K/decoy killed. The defender wants to maximize the ratio

$$C_G/C_D \approx [(1 + D)\cdot\$\ 1\ K]/[C_S + \$\ 10\ K\cdot D], \tag{14b}$$

which for the nominal $C_S \approx \$\ 6$ M is

$$C_G/C_D \approx (1 + D)/[(600 + D)\cdot 10] \approx D/6{,}000, \tag{14c}$$

for 1 << D << 1,000. For D = 100, $C_G/C_D \approx 1.4\%$, so the defense would pay about 70 times more than the offense. The cost ratio could, however, be reduced further by increasing D to >> 600, where it is ≈ 10%.

d. Effectiveness

Kill package and CV costs could possibly be reduced in time by an order of magnitude, for which Eq. (14c) would become

$$C_G/C_D \approx (1 + D)/[(60 + D)\cdot 10] \approx 10\%, \tag{14d}$$

for D >> 60. Thus, even for light SBIs, cost effectiveness favors the GBL by an order of magnitude. That gives a concrete measure of the beam degradation needed. If interference could increase the beam's diameter by a factor of 3, the laser's cost would increase by an order of magnitude to ≈ \$ 10 K/kill, against which combinations of decoys and light SBIs could just break even with the laser, which would allow continuing effective SBI coverage. Doing so would require replenishment. The laser could kill a decoy about every 20 s, or ≈ 50 ton/day, ignoring gaps. The defense would have to launch about as fast, i.e., 1-2 launches per day.

Thus, dilution helps, but the value of the average object killed is greater than the GBL's cost to kill it, absent beam degradation. The problem is often posed as one of logistics, i.e., a comparison of the cost to kill versus the cost to launch, and concluded with the observation that it costs more to launch mass than photons into space. When the laser's costs and lifetime are considered, the comparison is actually between the GBL's capital costs and the defense's launch costs. The ratio is uncertain because of the lasers' unknown costs, but it is unlikely that the launch costs could be reduced enough for decoys alone to offset this 10:1 advantage.

e. Delays

Decoys, like hardening, can buy time. For a SBI with D decoys, the time required for a laser to destroy all of them would be $T \approx 1/2$ day/passage x $(D/5 + 1)$ passages $\approx (D + 5)/10$ days. The ratio of the SBI's lifetime to the decoys' cost is

$$C_D/T \approx [C_S + \$\ 10\ K \cdot D]/[(D + 5)/10 \text{ days}], \tag{14e}$$

$\approx \$\ 100$ K/day$\cdot[600 + D]/(D + 5)$ for $C_S \approx \$\ 6$ M, decreasing as $\approx 1/D$ for $5 < D < 600$. For $D = 300$, or ≈ 30 days, $C_D/T \approx \$\ 300$ K/day, which means that a nominal SBI could be supported for ≈ 30 days for about a doubling of its cost. Equation (14e) can be solved for the time the SBI's life expectancy would be extended by a number of decoys whose cost was equal to its own, which is

$$T = (D + 5)/10(1 + D \cdot \$\ 10\ K/C_S). \tag{14f}$$

Figure 4 shows the times for which decoys could maintain a \$ 10 M SBI with decoys whose costs were 0.1, 0.3, and 1% of the SBI's.

The top curve is for decoys whose costs are $0.1\% \cdot C_S \approx \$\ 10$ K $\approx$ their launch cost. For 200-400 such decoys, the SBI's lifetime is 1-2 weeks. The curve rises to ≈ 30 days at $\approx 1{,}200$ decoys. The middle curve for decoys costing three times more than the lightest ones levels out at 8-12 days for 300-600 decoys. The bottom curve for decoys with costs 1% of an SBI's flattens at ≈ 4 days for $D \approx 200$ decoys. Given the short times and poor conditions available for discrimination by GBLs, something in between the top two curves should be appropriate. If so, delays of a few weeks to a month would be reasonable for a few hundred decoys that would roughly double the mass and cost of the SBIs.

For an SBI with 1/10 th of the nominal mass and cost, $C_D/T \approx \$\ 100$ K/day$\cdot[60 + D]/(D + 5)$, which for $D > 60$, T of a few months, would be close to the asymptotic \$ 100 K/day. The ability to protect SBIs for such a time before having to use them could give a useful amount of time for consideration before taking action against GBLs. Thus, decoys deployed ahead of crisis could reduce sensitivity to warning, and decoys deployed during periods of attrition could reduce vulnerability to exhaustion and buy time for decisions affordably.

5. Summary of GBLs

Lasers of modest brightness could be used to overcome passive measures and erode the hardening of low earth satellites. They could pose more of a threat to LEO and MEO satellites than would than direct ascent ASATs in the mid- to long term. Unless steps are taken to negate the laser or its correction loops, satellites at low altitude could be negated the first time they passed over the laser. Lasers throughout the infrared could be used; shorter wavelengths could be cheaper but more sensitive to countermeasures. All would have costs in the hundreds of millions.

Beam correction is delicate; either of two feedback loops could be interrupted. A simpler, interim approach could be to hide the satellites among decoys. Discrimination is a concern, unless the decoys resemble CVs closely, or vice versa, since the decoys would be relatively close to ground-based sensors and could be inspected for years. Decoys could also be deployed just before the CV approached the GBL. They would take tens of seconds to erode, so about five decoys would be lost per passage, but if a CV deployed $\approx$ 100 decoys, it would have a 95% chance of passing safely. Dilute mixtures of SBIs in decoys spread the SBIs' cost over many decoys, but the GBL retains an order-of-magnitude advantage. Decoys can, however, buy time. Nominal SBIs could be supported for weeks or months for a fraction of their cost, giving time for consideration before taking action.

E. Comparison of ASATs

Conventional ASATs have small kill packages, which could hit and kill unhardened missiles or satellites, but their agility would not necessarily be adequate against reactive satellites, so they would appear to be most useful for producing attrition in peacetime. If only nonnuclear ASATs could be used in peacetime, and if only attrition could be executed then, neither conventional weapons nor attrition would be first-order tools for the offense or problems for the defense.

Limited uses of nuclear weapons in non-war situations are not likely to remain controlled, so nuclear ASATs would probably be used only for suppression at the outset of hostilities. Nuclear ASATs launched from the ground would be hardened, guided, and directed towards individual defensive satellites. In the mid- to long term, ASATs could be interspersed with defensive satellites, put in contra-rotating orbits, or in co-rotating orbits. Interspersing them seems threatening, but the distances and maneuvers involved penalize them by an order of magnitude relative to ground-based ASATs. Accidental encounters are infrequent at LEO, less frequent at MEO, and fall by orders of magnitude in HEO. They could be predicted and avoided. ASATs in space forfeit the absenteeism advantage. That penalizes them by an additional mass ratio of ≈ 30, shifting the overall engagement by ≈ 600 in favor of the defense.

The Soviets could change their ASATs' trajectories to make encounters more frequent, but the result would be observable, so intended conjunctions could be predicted and avoided. Putting them into contra-rotating orbits, where they would encounter prey satellites more frequently, would overcome large deflections, but would require as many sweepers as prey, and could permit the prey to escape with modest maneuvers. The Soviet's putting their ASATs in space would give the U.S. a significant advantage.

Space mines overcome some of these problems. By coorbiting within tens or hundreds of kilometers they could keep defensive satellites at risk. The satellite could use SDMs and maintain a keep-out radius to discourage the proliferation of undecoyed ASATs. Light, credible ASAT decoys could reverse that leverage; maneuver and DSAT decoys could partially restrain it. The best way to overcome decoys is to discriminate them. NPBs could discriminate by irradiating the target and detecting the result remotely. Current-time products are modest, even for the protection of HEO satellites from LEO. Their beams could also negate the weapons found.

In the long term, GBLs could pose more of an attrition threat to LEO and MEO satellites than direct ascent ASATs. Modest lasers could overcome passive hardening and erode LEO satellites. Unless steps were taken to negate the GBLs, LEO satellites would be at risk. Light decoys could give SBIs a high probability of survival per overflight. Absent beam degradation GBLs would retain an order of magnitude advantage over small SBIs, but decoys could still buy time, supporting SBIs for weeks for a fraction of their cost and giving time for deliberation.

Overall, conventional ASATs could be effective against existing satellites, but not against properly hardened LEO and MEO defensive satellites. Nuclear ASATs' roles do not expand beyond those described in earlier reports. ASATs could be put into orbit, but the penalties for maneuver would eliminate the effectiveness of interspersed or contra-orbital ASATs. Space mines are more efficient but could be met by maneuver, decoys, and discrimination. Overall, putting ASATs in space would make them less effective than leaving them on the ground. GBLs are a potential threat. Decoys can delay their action, but the economics of satellite suppression favor the GBL, so some means of interfering with them or their beams is required.

IV. DEW SELF-DEFENSE

DEW self-defense is discussed in steps. The first considers the ASAT's approach to the DEW, which is the most stringent problem for the defense and which illustrates the strengths and weaknesses of the DEW's end game. The second step looks at the modification of those results by DEWs that can engage the attacker's booster. The third assesses the impact of decoyed and structured attacks. The fourth indicates their mitigation by discrimination, including that provided by the DEWs themselves.

Distinguishing between the two different scenarios in which these attacks might occur is useful. In one, the attacker attempts to attrit the satellites in a non-war environment by repeated or irregular attacks on each overflight. In the second, the attacker makes a determined, large-scale attempt to suppress all defenses strongly just before launch to allow his missiles to fly out through the holes created with minimal losses. The treatment below covers both.

A. DEW End Game

Interaction parameters are first discussed for lasers and then broadened to cover other DEWs. In the end game, the ASAT approaches the laser with a relative velocity $V \approx 7$ km/s, so the range decreases steadily during the engagement. The fluence a DEW platform of brightness B can deliver to the attacker as it approaches is the integral of the flux over time. For the laser to survive, it must deliver a lethal fluence, J, to the ASAT before it reaches its kill radius.

1. End Game Analysis

When the range from the DEW is r, the flux on the ASAT is B/r^2. The fluence deposited during its approach is the integral of the flux over time. The integral can also be taken over range, since $dt = dr/V$. Attaining the fluence needed to kill the ASAT before it reaches its kill radius K requires

$$J \leq \Sigma\, dt \cdot B/r^2 = \Sigma_K^{Ri}\, (dr/V) \cdot B/r^2 = (B/V)(K^{-1} - R_i^{-1}), \quad (15)$$

where the integral, Σ, extends from the initial separation R_i, the greatest range for effective irradiation, down to K, the shortest range of value. By Eq. (2), lasers whose large optical elements have the hardnesses $j \approx 1$ J/cm^2 typical of current coatings would have $K \approx 100$-200 km. R_i is typically $\approx 1{,}000$ km, so $R_i >> K$, and Eq. (15) reduces to

$$J \leq (B/V)(K^{-1} - R_i^{-1}) \approx B/VK. \quad (16)$$

The requirement for self-defense thus becomes

$$B > J \cdot V \cdot K. \tag{17}$$

A hardened attacker with $J = 1\ MJ/cm^2$, e.g., 30 cm of ablator with 30 kJ/g, is about the limit of the hardening achieved at scale. At a closing velocity $V \approx 10$ km/s, would require a laser hardened to $K = 100$ km to have a brightness of

$$B \approx 10\ GJ/m^2 \cdot 10^4\ m/s \cdot 10^5\ m \approx 10^{19}\ W/sr, \tag{18}$$

which is about that of a 5-4 chemical laser, to survive. While illustrated for lasers, this criteria is general. All DEWs can be described by a brightness B, so Eqs. (16)-(18) can be used for other DEW platforms on substitution of appropriate Js. NPBs are a special case. A 250 MeV beam can penetrate about 40 g/cm^2 of lead and it can kill the ASAT's electronics by delivering about 10 J/g to them, so a NPBs' survival criteria is

$$B_{NPB} \approx 4\ MJ/m^2 \cdot 10^4\ m/s \cdot 10^5\ m \approx 4 \cdot 10^{15}\ W/sr, \tag{18a}$$

which is about a factor of 1,000 less than the survivable brightness for lasers. NPBs could also kill warheads at 100-1000 MJ/m^2, which would give a sure-kill survival criteria of $B \approx 10^{17}$-10^{18} W/sr that is consistent with near- and midterm technology goals.

Heavily hardened attackers would require lasers to have $\approx$ 5-4 brightness, i.e., a 5-4 laser would draw with a heavily hardened attacker. The $\approx$ 20-10 lasers discussed for boost-phase missions could address such threats without detracting from their primary mission. By Eq. (16), the range over which a 20-10 laser would irradiate hardened ASATs is

$$\delta R = R_i - K \approx JVK^2/B \tag{19}$$

$\approx MJ/cm^2 10^4 m/s (10^5\ m)^2 \div 2 \cdot 10^{20}\ W/sr \approx 5$ km. The time required is $\approx \delta R/V \approx 0.5$ s, although the DEWs would be unlikely to reduce their margin that far. DEWs have considerable ability to defend themselves against ablatively protected ASATS.

2. Multiple Attackers

These results are readily extended to the case of multiple attackers. If n ASATs simultaneously are attacking a laser, which irradiates them sequentially, the interval over which the m-th ASAT is irradiated is determined by

$$J = (B/V)(R_{m+1}^{-1} - R_m^{-1}), \tag{20}$$

where R_m is the range at which irradiation of the m-th ASAT begins, and R_{m+1} is where it ends. A similar equation holds for each ASAT. If the laser's retarget time can be ignored, the ending radius for one ASAT is the same as the beginning radius for the next. Thus, when the equations are summed over m, the internal terms cancel, and the result is

$$n \cdot J = (B/V)(K^{-1} - R_i^{-1}), \tag{21}$$

or $B \approx n \cdot J \cdot V \cdot K$, so the requirement for surviving n weapons is n times greater than the requirement for one surviving weapon. For n = 10 the threshold for survival would be increased to about 10^{20} W/sr, about the level of a 10-10 platform. A 20-10 laser facing this number of attackers would irradiate them in the interval from twice K to K, which would take a time of about $K/V \approx 10$ s, which is about 5-10%.

3. ASAT Optimization

The brightness required for survival scales α J for fixed yield, about linearly with the ASAT's hardening mass. By Eq. (17), for fixed J, B scales as K α $\sqrt{Y}$ α $\sqrt{(\text{weapon mass})}$, so the ASAT mass for breakeven scales as B^2, and increasing yield isn't an effective use of weapon mass. Together these results suggest that optimized ASATs should be small weapons with a great deal of hardening rather than large weapons; there are indications that Soviet ASATs could be of this type. J and K's optimized product, which is a $\approx$ 2:1 ratio of hardening:weapon mass, scales as $(\text{mass})^{3/2}$, which would favor the attacker for very large weapons. For multiple weapons of total yield Y, the brightness for self-defense scales $n \cdot K$ α $n/\sqrt{n}$ α $\sqrt{n}$, which favors large n.

The ASAT can also be characterized by a "brightness" $B_W = Y/4\pi$, so the condition for survival can also be written as

$$B > JV(B_W/J)^{1/2}, \tag{22}$$

which shows explicitly that the DEWs' linear scaling on B dominates the more slowly scaling $\surd B_W$ at higher brightness levels.

The analysis above was stated in terms of space chemical lasers, whose key parameter is their brightness B, which scales as $P \cdot A/w^2$. Decreasing w by using short wavelength lasers would permit self-defense with smaller powers or apertures. For a 1 μm laser, the enhancement would be a factor of $(2.7/1)^2 \approx 7$. Pulsed lasers could also be less sensitive to countermeasures.

4. Advanced ASATs

The analysis of DEW effectiveness above is sensitive to the assumption that the laser is able to produce a small spot at short range and bore a hole through a small portion of the ASAT's ablator. The beam from a 3 μm wavelength laser with a 10 m mirror would illuminate a 1 m spot at the $\approx$ 3,000 km range of its defensive mission, but it would focus down to a 10 cm spot, 1% of the objects area, at a 300 km lethal radius for self-defense. The spot would be smaller, and the laser's leverage even higher, for smaller yields and closer end games.

It might be possible to negate the laser's advantage. If the laser always illuminated the center of the target, the ASAT's ablator could be redistributed to put most of the material there, forcing the laser to dwell longer. The laser could then move its aim point off axis, but the ASAT could be spun to continually bring new material into the beam. Ideally, the ablator could be applied to the entire exterior and the weapon rotated about several axes to attain roughly equal illumination over its full surface. Alternatively, heat exchangers could redistribute the heat load over the full amount of hardening material.

It is not clear which, if any, of these concepts could be implemented in practice, or what their penalties would be. To the extent that they could, however, they would force the laser to remove much of the ablator, rather than just a few percent of it. The energy to do that can be obtained from an energy balance

$$P \cdot T = j \cdot M_A, \tag{23}$$

in which M_A is the mass of the ablator, j is its ablation energy per unit mass, P is the laser power, and T the engagement time. $P \cdot T$ is related to the mass of fuel expended, M_F, by $P \cdot T = \sigma M_F$, where σ is the laser's specific efficiency, so the fuel required is $M_F = (j/\sigma)M_A$. For the j = 20-30 kJ/g of good ablators and σ = 300 kJ/km of current chemical lasers,

$$F = (30\ \mathrm{kJ/g})/(300\ \mathrm{J/g}) \cdot M \approx 100 \cdot M, \qquad (23a)$$

so the laser would have to launch about 100 times as much fuel as the attacker would hardening mass. Forced to defeat attackers with bulk energy, space lasers would face significant weight and cost disadvantages. This deficiency might not seem serious, since attriting fuel is an indirect way of reducing defensive forces before a surprise launch. In a crisis, however, even the possibility of exhaustion could create the type of attitude one would want to avoid, a degrading ability to negate the other's first strike. Defenses that so degraded would appear useful only against the other's second strike, making them destabilizing.

Hybrid concepts that use lasers on the ground to provide power for mirrors in space are a possible solution to this problem. A 10% efficient laser on the ground might have a specific efficiency of ≈ 300 kJ/kg, but that would correspond to ≈ 10 MJ/kg in space, which would negate the ASAT's ablation efficiency advantage. More importantly, hybrids would leave most of the expensive components on the ground. Against hybrids, both exhaustion attacks and advanced ASATs should be ineffective; against pulsed hybrids, other countermeasures could also be complicated.

B. Decoys

The ASAT warheads' parameters do not appear in the limit of Eq. (23a) above, since the laser is forced to treat as a weapon any object that it cannot discriminate, expending significant energy in negating it. In that situation, decoys could make space chemical lasers vulnerable to exhaustion, as discussed below.

1. Impact

The extent of the concern can be seen roughly from Eq. (21) by interpreting n as the total number of credible objects. If there was no unambiguous kill signal, the laser would be forced to irradiate all objects equally. For one weapon per ASAT and D decoys per weapon the number of credible objects would then be $n = D + 1$, so that

$$B \approx n \cdot J \cdot V \cdot K \equiv (D + 1) \cdot B_1, \qquad (24)$$

where $B_1 = J \cdot V \cdot K \approx 10^{19}$ W/sr is the brightness required for a single hardened weapon in the absence of decoys. Against non-discriminating lasers it might be possible to generate $D \approx 100$ decoys. If so, that would increase B to $\approx 10^{21}$ W/sr, which is greater than the brightness required for the demanding boost-phase missions themselves.

By attacking with larger boosters, or simultaneously with several boosters, the attacker could increase the requirement even further. Such attacks would be extreme, but would involve affordable weapons and numbers of decoys. The decoys could be deployed at range, and they would follow the same ballistic trajectories as the weapons over the intervals of concern. Such attacks could be worthwhile against high-value platforms.

2. Discrimination

Some ability to discriminate is needed. The ability that should evolve in the mid- to long term could permit the decoys to be discarded and the weapons negated with the same effectiveness as the bare threats discussed above. Their cost effectiveness would then be improved by the ASAT's pointless diversion of mass and effort into deploying ineffective decoys. Even short of that goal, however, lasers could give some interim ability to discriminate. Decoys would be light and thin, so powerful beams would burn through or heat them rapidly. If burn through produced an observable signal, the laser could switch to another target as soon as it was detected, using little energy. The energy to discriminate in that manner should be less than that to destroy the objects, perhaps by the ratio of the decoy and weapon masses, which is about $\phi \approx 1$ kg/100 kg $\approx 1\%$. If so, the energy to negate a decoy would be proportional to $\phi \cdot J$, and the brightness required to survive the weapon and decoys about

$$B \approx n \cdot J \cdot V \cdot K \approx (\phi \cdot D + 1) \cdot B_1, \tag{25}$$

which for plausible values such as $\phi \approx 1\%$ and D = 100 would only double the required brightness.

The ASAT could not greatly increase D, since much lighter decoys might be discriminated by auxiliary or passive means. The value of ϕ is less certain, since there are several different interactions and kill signatures possible; the value of 1% from the mass balance is reasonable on fundamental grounds. Achieving it would require good sensors to detect small return signals or decoy deflections.

The treatments of self-defense, multiple attackers, ASAT configuration, and decoys are summarized in Fig. 5, which shows the brightness required for a laser to survive as a function of the ASAT's yield. ASATs are assumed to be hardened to 10 GJ/m^2, and the laser coatings to 1 J/cm^2. The bottom curve is for a single attacker, which only requires about $2\text{-}5 \cdot 10^{18}$ W/sr. The middle curve is for 10 attackers or one with a number of decoys whose discrimination would require as much time and energy as 10 attackers. It requires $\approx 10^{19}$ W/sr at 10 kilotons and $\approx 10^{20}$ W/sr at $\approx$ 1 megaton. The top curve is for 30 objects, for which a yield of 100 kilotons would require about the brightness of a 20-10 laser. Thus, interim hardening and discrimination measures could provide a reasonable self-defense capability in the midterm against even highly decoyed ASATs.

C. Mixed DEW-KEW Defenses

The analyses above treated cases where the DEWs had to defend themselves with their own beams. In some cases there are more efficient means. For an ASAT to survive to approach the laser, it needs significant hardening. The survival criteria of Eq. (18) assumed $J = 1$ MJ/cm^2, e.g., a weapon with 30 cm of ablator covering most of it, since if the covering was uneven, another laser could see the vulnerable area and kill the ASAT. To achieve that level of hardness the ASAT would essentially have to close up and become inert for at least the last few hundred kilometers of its approach.

1. Undecoyed ASATs

The laser could irradiate and ablate the ASAT's shielding. By Eq. (19), irradiation near the keep-out range would take about 0.5 s, so the energy required would be $\approx$ 0.5 s·20 MW $\approx$ 10 MJ. The mass required for a laser of efficiency 300 kJ/kg would be 20 MJ ÷ 0.3 MJ/kg $\approx$ 65 kg. For an ASAT with a 400 kg weapon and a 2.5 ton shield, the exchange ratio would be $\approx$ 3,000:65 $\approx$ 46:1 in favor of the laser. Thus, the laser could defend itself effectively against hardened, inert ASATs, but countermeasures such as spinning could reduce its effectiveness, and the time for self-defense would detract from the laser's primary mission.

An alternative is to destroy the ASAT with a small SDM. For a single, inert weapon, a 25-50 kg SDM with 1-2 km/s propulsion could fly out and collide with the ASAT at a distance of few hundred kilometers from the lasers, which is an adequate keep-out distance for survivability. In such an engagement the ratio of the payload masses, which is a useful surrogate for cost, is $\approx$ 3,000:30 $\approx$ 100:1, which is even higher than the laser's, which favors the defense strongly.

This approach would involve developed, lethal KEW technology in a geometry where it should be effective, keep the laser from being diverted, and avoid the main countermeasures to each. Thus, it would make optimum use of their respective capabilities. For undecoyed ASATS, the optimal defense would be for the laser to irradiate the ASAT, passivate it, and then launch a SDM at it. If the passivation and launch were performed early, there should even be time for a shoot-look-shoot engagement, the second shot possibly coming from the agile laser, taking advantage of its speed of light flyout.

2. Decoyed ASATs

The situation becomes more complicated if the ASAT uses decoys. If it deploys D decoys per weapon, the effectiveness of mixed defenses, like that of the pure DEW defenses discussed above, would depend largely on the lasers' ability to discriminate. If it had no ability, the mass required for SDMs to negate the weapon and all $D \approx 100$ decoys would be $(D + 1) \cdot 30$ kg $\approx 3{,}030$ kg. The mass of the ASAT and decoys would be about $(D + 3{,}000)$ kg $\approx 3{,}100$ kg, so the SDMs and decoys would roughly break even, negating the effectiveness of the SDMs. The cost advantage could, however, be less favorable to the SDMs, since the attacker would only invest 200-400 kg in the sophisticated weapon, while the DEW would have $\approx 30 \cdot 100 \approx 3$ tons of equally sophisticated SDMs. The laser would take $\approx (D + 1) \cdot 65$ kg $\approx$ 6,600 kg, which is a bit more mass and hence even less effective. It is, however, only bulk fuel.

If, as in Eq. (25), DEWs can partially discriminate decoys by irradiating them with a fluence $\approx \phi \cdot J$, then the mass required for the laser to discriminate the decoys and the SDM to destroy the weapon found is $\approx \phi \cdot 65$ kg$\cdot D + 30$ kg ≈ 100 kg for $\phi \approx 1\%$ and $D = 100$. The exchange ratio would then be $\approx$ 3,100:100 $\approx$ 31:1 in favor of the mixed defense. If ϕ was 10% rather than 1%, the mass would increase to $\approx 0.1 \cdot 65$ kg$\cdot 100 + 30$ kg ≈ 680 kg, and the ratio would drop to $\approx$ 4.5:1. However, $\phi = 1\%$ is probably an overestimate of the required fluence, since it takes the discrimination energy to be a fraction of the weapon's 1 MJ/cm^2 hardness, rather than the lower hardness of practical decoys. The decoys above are assumed to require 10 kJ/cm^2, which would give 10 kJ/g ablators an areal density ≈ 1 g/cm^2 and a mass $\approx 4\pi(50 \text{ cm})^2 \cdot 1$ g/cm^2 ≈ 30 kg, which is ≈ 30 times the penalty assumed above for discrimination. Thus, modest levels of discrimination by DEWs could restore the effectiveness of SDMs in mixed defenses, and interim levels of discrimination could restore it almost fully.

D. Engaging Boosters

The sections above treated the DEW end game, which is demanding since the ASAT is closed up and approaching at high velocity. It is advantageous to the defense to engage the ASAT's booster, because it can only use a modest amount of hardening if it is to lift the weapon into space. The hardening of offensive missiles is treated elsewhere;[19] this discussion concentrates on the super hardening the boosters used to attack DEWs.

1. ASAT Booster Hardening

Since laser beams can reach the ground, direct ascent ASATs would have to be hardened more or less evenly over all stages, or the laser could kill the softest one inexpensively. The mass to harden the missile comes out of its useful payload. The hardening penalties are largest for small missiles, due to their large area to volume ratio, so large missiles would probably be used to launch ASATs. Liquid missiles would be preferred because of their high specific impulses. Thus, it is reasonable to use SS-18s, which are existing, highly developed, large liquid boosters with 8 ton payloads, as examples. Tradeoffs between payload and hardening are intricate, but for SS-18s the results are known, simple, and typical of that class of boosters, including its variations under development. The studies are for retrofit hardening, but SS-18s have a modest structural fraction, so the gains from integral designs should not be great.

The main result of the studies is that if the SS-18s were retrofit hardened uniformly over their whole exterior, their payload, P, would decrease approximately linearly with the shielding mass, M_S, as

$$P(M_S) = P_o(1 - M_S/M_o), \quad (26)$$

where $P_o \approx 8$ is the maximum payload with only the SS-18's intrinsic shielding, which is negligible, and $M_o \approx 16$ tons is the value of shielding at which the payload would reach zero. The SS-18 is about 32 m high and 3 m in diameter, so it has an area of $\approx 300\ m^2$. The maximum shielding possible is thus $M_o/300\ m^2$ = 16 ton/300 m^2 = 0.05 ton/m^2 = 5 g/cm^2. That is about 15% of the hardening assumed for the ASAT's payload in the previous section, but that shielding only had to be applied over the weapon's few square meter surface.

2. Penalties

For a good ablator, the maximum shielding of 5 g/cm^2 might correspond to a hardness of $\approx$ 5 g/$cm^2 \cdot$20 kJ/g $\approx$ 100 kJ/cm^2, but that would leave no payload. The nominal ASAT treated above had a weapon mass of about 0.5 ton and a shielding mass of 2.5 tons, which is roughly optimized for the laser end game it must face, so it would be necessary to retain about 3 tons of useful payload for the weapon. The current SS-18 bus has a structural mass of about 2 tons, so the net payload left for hardening would be about 8 - (3 + 2) = 3 tons. If it is assumed that the bus's structural and control functions could be reduced to 1 ton, the residual payload would be $\approx$ 4 tons, half the maximum, which would support roughly 50 kJ/cm^2 = 500 MJ/m^2, about 2-5 times the limiting hardness assumed for offensive missiles.

The scaling of offensive missile hardening has been studied extensively for parameters in this range, as have the defensive constellations required to address them, which scale as[20]

$$N = K_D(JM/BA_LT)^{\Gamma}, \qquad (27)$$

where $\Gamma \approx 0.7$-0.8, and the constant $K_D \approx N/(JM/BA_LT)^{\Gamma}$ can be evaluated as $\approx 4 \cdot 10^{19}\ (m^4/sr)^{\Gamma}$ from the N $\approx$ 50 chemical laser satellites of 20-10 performance needed for the nominal threat[21] 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. Variation of constellation sizes with the various parameters are discussed in the references; here the concern is the variation of constellation size with booster hardening.[22]

The nominal case above assumed a total time of 100 s for booster burn and bus deployment. Current SS-18s have about 600 s, divided about equally between the booster and bus burn times. For the super-hard ASATs of interest here, the bus is eliminated, so the time of concern is the booster. Its 300 s burn time is a factor of 3 longer than that of the 100 s fast solid assumed for the nominal offensive missiles above, but there are programs to reduce liquid burn times to 225-250 s. Solids could be used, but their lower engagement time could be lost in the shielding penalty due to their much lower specific impulses.

3. Tradeoffs

About 200 MJ/m^2 is thought to be limiting for offensive missiles; the 500 MJ/m^2 used for super-hard ASATs is comparably limiting for ASATs. The key scaling parameter for both is the JM/BA_LT in Eq. (27), which in going from offensive missiles to super-hard ASATs changes by a factor of

$$(500/200)(M_A/1400)/(1)(1)(2.5) = M_A/1400, \tag{28}$$

i.e., the changes are offsetting, so that the same size DEW constellation could negate about as many super-hard ASATs as hardened, faster offensive missiles. By Eqs. (27)-(28), boost-phase defensive constellations would be indifferent to combinations of hardened offensive missiles and ASATs with the same value of $(JM/T)_O + (JM/T)_A$, where the subscripts O and A refer to offensive missiles and ASATs, respectively.

Since $(J/T)_O \approx (J/T)_A$, ASATs could be substituted for offensive missiles on a 1:1 basis for the parameters used above. The substitution is not without penalty to the attacker, however, since the offensive missiles are subtracted from the attack on a 1:1 basis. Thus, if the ASATs were retrofitted from the offensive missile force, the defense would require no adjustment, and the net effect would be the reduction of the offensive strike by one missile for each ASAT converted.

4. Higher ASAT Yields

There are several variations on this discussion. One is the use of a very large weapon that is lofted just above the atmosphere and detonated before the SBIs can get to it in an attempt to kill all of the defensive satellites in sight. The simplest example would be the super-hardened booster, discussed above, with a lightly hardened weapon inside it. If most of the weapon's 2.5 tons of shielding were converted to fissile mass, its yield could increase by about a factor of (0.5 + 2.5 tons) ÷ 0.5 megatons ≈ 6 to ≈ 3 megatons. For the DEW platform hardening used above, the weapon's lethal radius would then increase by a factor of $\sqrt{6}$ to 200-400 km, which would not even require the raising of the operating altitude of a 500 km constellation. The Soviets could attempt to reduce the hardening on the missiles, but then they would not survive transit to the altitude at which their radiation could leave the atmosphere and reach the satellites.

The yield of the weapon could be increased further at the price of burnout velocity. That would reduce the missile to a sounding rather than an attack trajectory, but that is acceptable as long as it can reach 50-100 km reasonably quickly. To reach a kill range of 1,000 km the weapon would need a yield of about $(1{,}000/400)^2 \cdot 3$ megatons ≈ 6.3·3 megatons ≈ 19 megatons, which could require a mass of ≈ 19 tons. The payload would then be 1 ton structure + 4 ton missile hardening + 19 ton weapon ≈ 24 tons. Including structure and losses, SS-18s have effective specific impulses of about 220 km/s, so that such an increase in payload would decrease its velocity by ≈ 2.2 km/s·ln (24/8) ≈ 2.4 km/s, which is large but acceptable. The Soviets have detonated devices of this size at about that altitude, although their devices did not have to be lofted against defenses.

This combination could impact DEW satellites at 1,000 km. It would also impact SBIs at lower altitudes out to a radius determined by their greater hardening, but if they were hardened to ≈ 100 J/cm^2, that radius would only be ≈ 100 km. To impact satellites at 2,000 km the weapon's yield would have to increase to $2^2 \cdot 19$ megatons ≈ 75 megatons. If the weapon's mass was

$\approx$ 75 tons, the velocity degradation would be ≈ 2.2 km/s$\cdot$ln (80/8) $\approx$ 5 km/s, i.e., the missile's burnout velocity would be about 2 km/s. That would be enough to loft the weapon to a few hundred kilometer, but it would do so slowly, which according to Eq. (27) makes the defenses more effective. Thus, a moderately hardened weapon on a very hard booster could use a very large weapon to impact 1,000-2,000 km DEW satellites of current hardening.

That is about as far as this analysis can be carried usefully at this level of detail. Larger yields are more efficient, but the boosters to carry them could be somewhat less efficient, so before drawing conclusions, the estimates above should be reviewed. A reoptimization would increase ASAT booster hardness, the weak link in the configuration above, which would detract from its payload. Some hardening would also be required to keep the weapon from being vulnerable to selective, direct attack, so that it could survive to detonation.

These points are less critical than the extent to which DEW hardness could be increased over the near-term values used in the mid- and long terms. In the midterm, lasers could control their orientation and use baffles and shields to prevent their coatings from being exposed to direct irradiation by these obvious, transient, and miss-timed precursor threats. DEWs other than lasers would be less affected; lasers other than those with the ASATs directly in their field of view could thereby increase their hardening by a factor of 10-100, which would reduce the impact of even high-yield devices to moderate levels.

5. Initial Deployment

The initial deployment of the defensive constellations involves slightly different issues, whose resolution depends on the order in which concepts are deployed. In the current scheme, the better developed KEWs would be deployed first.[23] Because of their limited range, each would essentially have to defend itself as soon as it was deployed, which KEWs appear to be capable of doing.[24] DEWs would be deployed later. In the process they would initially be protected by the SBIs during deployment, although DEWs could apparently be deployed and readied for self-defense by their first pass over the Soviet Union.

Even if SBIs could be bypassed, there are reasons for retaining them. Once both capable SBI and DEW layers were in place, a useful synergism between them would be possible. SBIs are highly lethal against the missiles they can reach, and DEWs are effective against fast missiles that are moderately hardened, but affordable SBIs are not fast enough to reach all missiles, and some missiles could be very highly hardened in the absence of SBIs. That combination of strengths could permit SBI and DEW constellations to bootstrap off one another by using DEWs to kill ASATs directed towards SBIs, which would then survive to kill slow, hardened offensive missiles that DEWs could be less efficient at killing. The combination of SBIs, on-board SDMs, and their own directed energy beams would then permit the DEWs to use a 2-3 shot sequential defense, which would make them highly survivable against ground-launched threats. It would also add an additional layer to the SBIs' own hardening, maneuver, decoys, and self-defenses, which could make them adequately survivable for as long as they remain useful.

E. Summary

Large but appropriate DEWs can usefully self-defend against determined attackers. Their end game analysis reduces to a comparison of brightness and masses that generally favors DEWs. Entry-level 5-4 platforms should be able to survive direct attacks by large, highly hardened nuclear ASATs, but if ASATs could take advantage of preferential hardening, rotation, or heat dissipation, the energy balance could shift to favor them, and hybrid lasers would become favored over space-based lasers. NPBs' ability to penetrate practical shieldings and kill the warhead could reduce the brightness required for survival by several orders of magnitude. Multiple attackers increase the brightness required for survivability directly. DEWs that cannot discriminate could be overwhelmed, but those with interim levels of discrimination should only be impacted by a factor of 2-3. DEWs that passivate ASATs and then dispatch them with SDMs should be effective against undecoyed and decoyed ASATs; plausible ASAT variations do not alter these results.

If DEWs can engage ASAT boosters, defenses are simplified because boosters can use only modest hardening. If all payload was converted into shielding, the boosters' hardness could be increased ≈ 5-fold above that of hardened offensive missiles. The weapon reduces the hardening further. The overall result is that DEW constellations would be roughly the right size to negate arbitrary combinations of boosters and ASATs, in which case the conversion of offensive missiles to ASATs would subtract from the attack on a 1:1 basis. High-yield ASATs popped up just above the atmosphere are interesting, but not stressing.

In the current deployment sequence, SBIs would be deployed first and DEWs later, protected by SBIs or by their own beams. That makes possible a synergism in which DEWs would kill ASATs, and SBIs would use their lethality to kill slow, hard, offensive missiles. That type of cooperation could make both adequately survivable against ground-based threats throughout their useful lifetimes. Long-term results depend on the outcome of incomplete technology trades; if they ultimately favor the DEWs, self- and mixed defenses should remain effective into the long term.

V. DEFENSE OF OTHER PLATFORMS

Previous sections discussed the DEWs' ability to defend themselves singly or in concert with other platforms. DEWs can also defend other platforms at significant distances, including other constellations such as SBIs, which is reviewed below. The main difference is that in self-defense, the threats converge on the DEWs, while in defending other platforms the weapons can attack other constellations without having to approach the DEWs.

That leads to less saturation, but it does so at the price of greater range, different geometries, and less favorable scaling.

A. Analysis

When other constellations are defended, the range between the DEWs and ASATs is large and slowly varying, which permits the requirements to be established with some simple but accurate scaling estimates.

1. Scaling Estimates

The DEW constellation might be at altitudes of h_D = 1-2 Mm. When DEWs defend SBI constellations at altitudes that vary from $h_S \approx 1$ Mm in the near term to 250 km in the long, the vertical separation between the constellations would be 0.75-1 Mm. DEWs would, however, have to irradiate missiles all the way from the ground, so the range from the DEWs would vary from h_D to $h_D - h_S \approx 2$ Mm to 1 Mm. Thus, the effective, average vertical separation is roughly $h_E \approx h_D - h_S/2$. There is an additional separation that comes from the granularity of the DEW constellations. For N satellites constellation at LEO, the satellite areal density is

$$N'' \approx zN/4\pi R_e^2, \tag{29}$$

where R_e is the earth's radius, with respect to which h_D is ignored, and z is the satellite concentration possible over the launch area.[25] Each DEW's immediate area of responsibility is $\approx \pi R^2 \approx 1/N''$, whose radius is

$$R \approx 2R_e/(zN)^{1/2}, \tag{30}$$

which for $z \approx 3$ and $N = 50$ is $R \approx 1$ Mm. If the transverse separation between a target and the nearest satellite is denoted by x, the mean square separation is

$$\langle x^2 \rangle = (\pi R^2)^{-1} \Sigma_0^R \, 2\pi x \cdot dx \cdot x^2 = R^2/2, \tag{31}$$

so the rms separation is about $R/\surd 2$, which is ≈ 0.7 Mm for the conditions above, and the average range is

$$\langle r \rangle \approx (h_E^2 + R^2/2)^{1/2}, \tag{32}$$

which for h_E = 1-2 Mm is $\langle r \rangle \approx$ 1.2-2.1 Mm, so that a range of 1-2 Mm covers most cases of concern. The time it takes a DEW of brightness B to kill a target of hardness J at that range is

$$t = J\langle r\rangle^2/B \approx J(h_E^2 + R^2/2)/B, \tag{32a}$$

so in the engagement time T = 100-200 s it takes the ASATs to reach the SBIs, a laser could negate a total of about $T/t \approx T \cdot B/J\langle r\rangle^2$ targets. If N_A ASATs were distributed over a launch area A_L, each satellite would expect to face about R^2N_A/A_L ASATs. Equating this number to that killed determines the number of satellites required for closure, which for $h_E << R$, e.g., early, low constellations, approaches

$$N = (4\pi R_e^2/z)N'' \approx (4R_e^2/z)(N_AJ/2B \cdot A_LT)^{1/2}, \tag{33}$$

which is related to the $N \alpha \sqrt{M}$ limit in boost-phase defense.[26] For h_E large, i.e., later, denser, and higher DEW constellations,

$$N = (4\pi R_e^2/z)N_AJ \cdot h_E^2/\pi B \cdot A_LT, \tag{34}$$

which is rarely approached. Both limits can be improved.

2. Exterior Contributions

Equation (33) includes only the contributions from the satellites overhead. When the contributions from those outside the launch area but within sight of if are included, the result is the scaling of Eq. (27). If ASATs are distributed widely along with the offensive missiles, the number of satellites required is $N \alpha (N_AJ/BA_ET)^\Gamma$, which scales more strongly on N_A than Eq. (27), although it gives roughly a factor of 2 smaller N because of the inclusion of the external contribution. The scaling parameter is still N_AJ/BA_ET, so as noted earlier, for nominal hardening and engagement times, retrofit ASATs would displace offensive missiles and degrade the threat on a 1:1 basis. Unless the ASATs were a significant fraction of the total, they would have little impact on the constellation size or performance required. Given the close relationship between boost-phase defense and the defense of other constellations, all of the sensitivity studies performed for the former can be used directly for the latter.[27]

3. Compact Launch Areas

Offensive missiles could be concentrated in a small area to overwhelm the defensive satellites locally. ASATs could also be concentrated, although it would not be useful to concentrate them in a smaller area than that occupied by the offensive missiles, since the ASATs have to fly out beyond the offensive missiles to protect their launch corridors. If both the missiles and ASATs were concentrated in a small area, an approximate expression for the total ASATs killed for given defenses can be obtained by summing the kill rate

$$t^{-1} = (Jr^2/B)^{-1} \approx [J(h_E{}^2 + x^2)/B], \tag{35}$$

over the transverse separation, x, between the satellite and the missiles in the launch area. If satellites are approximated as uniformly distributed in the constellation plane, the result is

$$N \approx 4R_e{}^2 N_A J/\{zBT \cdot \ln[1+2(R_e/h_E)/(1+T_S B/Jh_E{}^2)]\}, \tag{36}$$

which resembles the limit of Eq. (34), except that the constellation's altitude appears as a logarithmic correction in conjunction with the beam's retarget time, T_S.[28] For h_E = 1 Mm, N_A = 10% of the missiles ≈ 140, J = 50 kJ/cm^2, B = $2 \cdot 10^{20}$, and T_S small, then N ≈ 75. Since $N \alpha N_A J/BT$, and B is divisible, the total brightness required is

$$B_D \approx N \cdot B \ \alpha \ N_A J/T. \tag{37}$$

Since the parameter $N_A J/T$ was shown earlier to be the same for super-hard ASATs and offensive missiles, ASATs again substitute on a 1:1 basis for offensive missiles, and the defense has wide latitude in the choice of the platform sizes to meet them. The cost of an optimized satellite increases approximately as $C_B \ \alpha \ \sqrt{B}$, so the cost of the DEW constellation for a compact or point launch should decrease as

$$C_D \approx N \cdot C_B \ \alpha \ 1/\sqrt{B}, \tag{38}$$

so high brightness DEWs would minimize the cost of the defense against both super-hard ASATs and large attacks.[29] Since J cannot be increased much further and T cannot be decreased significantly from the values used, the total brightness of Eq. (37) scales approximately as $N \cdot B \ \alpha \ N_A$, and the cost per ASAT as

$$C_D/N_A \ \alpha \ N\sqrt{B}/N_A \ \alpha \ (N_A/B)\sqrt{B}/N_A \ \alpha \ 1/\sqrt{B}, \tag{39}$$

which is insensitive to the ASAT threat size and favors the defense for large DEWs. Thus, for large or small launch areas and ranges, the scaling for the negation of super-hard ASATs by large DEWs favors the defense, and the defense of other constellations does not detract from the DEWs execution of their primary mission.

B. Defensive Variations

Several variations of these arguments could enhance DEWs' performance as DSATs or boost-phase defenses. A concern in the self-defense of SBI and sensor constellations is their ability to deal with decoys released by ASATs. Small SBIs could use decoys and maneuver efficiently enough to survive; large CVs and sensor satellites apparently could not. If decoys could be suppressed or discriminated, even large LEO and MEO satellites could become survivable.[30]

1. Decoy Negation

DEWs could irradiate ASAT's buses and attempt to negate their ability to deploy decoys, or they could destroy the decoys as they were released. The former is preferred, since it would produce an inert, unitary threat that the satellites' SDMs could handle effectively. In the latter, if all decoys came out of the same port and the DEW maintained a modest flux on the port, the decoys would be destroyed as they emerged. Decoys could, however, be destroyed or discriminated later. Deployment might last tens of seconds; flying out to the satellites might take the ASATs hundreds of seconds. During the latter there could be leverage in lasers cutting or discriminating holes in the decoy clouds approaching the SBI trajectories. If the lasers could negate the ASATs' maneuver and homing, the SBIs could close up to achieve high hardnesses, pass through the ASATs, and then reopen to execute their primary defensive mission once clear--another example of the KEW-DEW synergism discussed earlier.

The use of lasers for self-defense, mutual defense, or discrimination has leverage. It should produce reasonable survivability whether the lasers are long or short wavelength, continuous or pulsed, space based or hybrids, and conventional or nuclear. What is fundamental is the DEWs' ability to deliver energy rapidly at long ranges. The brightness and sizes of defensive constellations are similar to the combined constellations sized to meet the offensive threat, so the survivability benefits discussed above should evolve naturally in developing the best mixes for their primary defense missions.

2. Observation and Illumination

The applications above have stressed the DEWs' lethal capabilities, but even at low power they would have the ability to illuminate the offensive buses' deployment and watch it either actively or passively at the high resolution afforded by their large primary optics. A 10 m mirror with a 2.7 μm beam has an angular resolution $\approx$ 2.7 μm/10 m $\approx$ 0.3 μrad, which would resolve an object on a bus 1 Mm away that was $\approx$ 0.3 μrad x 1 Mm $\approx$ 30 cm across. With that resolution it would be difficult or impossible for buses to release RVs and decoys deceptively.

This point is fundamental. At present the most difficult challenge in strategic defense is to deal with the many decoys possible in midcourse. If that could be accomplished by close observation during deployment, the decoys could be ignored and the RVs killed efficiently by near-term, ground-based KEW interceptors. Given the leverage implicit in the DEWs' large optics, it is natural that they would be priority targets for the ASATs. As demonstrated above, however, DEWs have considerable ability to defend themselves in the mid- and long terms, so their surveillance and reconnaissance capabilities could have a fundamental impact on the defense.

If irradiating the ASATs' buses at sub-lethal levels could disrupt communication and control, this could be as effective as killing them, since delaying deployment could allow KEWs to reach the bus before deployment. Disruption could best be accomplished with NPBs, since they can reach the bus's electronics rather than simply depositing their energy on its surface. The requirements for doing so in the near to midterm are modest.[31] If it proved difficult to correct that susceptibility, the disruption of buses could be a high-leverage mode of negation in the long term as well as the near, and be against both ASATs and offensive launches. If multiple RVs and decoys could be negated by preventing deployment, the defenses' leverage would increase by $\approx$ 10 RVs/missile x 10-100 decoys/RV $\approx$ 100-1,000:1. It could be somewhat higher, since the NPBs used would be absentees from midcourse, where their primary discrimination function would lie.

VI. DEWs AS ASATs

DEWs function as DSATs by negating threats approaching other space platforms. Thus, they can also act as ASATs and irradiate the other's space platforms and constellations. This section reviews their capability to do so and its limitations. The discussion is divided into separate treatments of suppression and attrition because of the fundamentally different requirements they place on the DEWs and the significantly different priorities they place on the various types of lasers.

A. Suppression

The suppression of defenses before attack is a critical ASAT function, which according to the arguments of Section III, is best served in the near term by nuclear ASATs. In the mid- to long term, however, suppression could arguably be served more effectively by DEWs. The following sections review their scaling in that role and compare them to other approaches.

1. Scaling Estimates

Suppression must be rapid to be useful. The boost phase lasts a few hundred seconds; midcourse a few thousand. Those two times roughly bound the interval within which DEWs would have to attrit the defenses to be significant. On a time scale of 100 s, a satellite would move $\approx$ 100 s x 7 km/s $\approx$ 700 km $\approx R_e/10$, so that to first order the motion of the platforms can be ignored and their kills evaluated for their location at the outset.

a. Geometric Analysis

By Eqs. (11) and (32a) it takes a time $t = Jr^2/B$ for a platform of brightness B to kill a target hardened to J at range r. Since the DSAT and ASAT constellations would be intermingled, their vertical separation can be ignored and the separation between satellites taken to be in the constellation plane. If there is an areal density, N_D'', of DSATs in the plane, there should be about $N_D'' \cdot 2\pi r \cdot dr$ satellites in a ring of area $2\pi r \cdot dr$ a distance r away from the ASAT. It should take $\approx (Jr^2/B)N_D''2\pi r \cdot dr$ for the ASAT to kill them. Thus, during the engagement time T, an ASAT should kill the DSATs out to a range

$$R = (2BT/\pi JN_D'')^{1/4}, \tag{40}$$

which grows slowly with T. Figure 6 shows the variation of R with T for a laser brightness of $2 \cdot 10^{20}$ W/sr and $N_D = 100$ target defensive satellites of various hardnesses. The top curve is for $J = 100$ kJ/cm^2, about the level to which existing boosters could be retrofitted. For the current 300 s engagement time, such a laser could kill all defensive satellites within about 3 Mm; for a fast burn missile's 50-100 s, it could reach ≈ 2 Mm. For DSATs hardened to the level of an ASAT, 1 MJ/cm^2, the maximum near-term range would be cut to ≈ 1.5 Mm, roughly the effective radius of the current launch area. In the long term the radius would drop in time to about 1 Mm. The bottom curve for a satellite 10 times harder would start at 800 km and drop to 600-700 km, about the distance between the defensive satellites. The area cleared is $\approx \pi R^2$, so a phase space estimate of the number of DSATs killed is

$$N_K \approx N_D''\pi R^2 \approx (2\pi BTN_D''/J)^{1/2} \approx (zBTN_D/2JR_e^2)^{1/2}, \tag{41}$$

which grows as $\sqrt{T}$. For $B = 2 \cdot 10^{20}$ W/sr, $T = 100$ s, $J = 100$ kJ/cm^2, and $N_D = 100$, $R \approx 2$ Mm and $N_K \approx 8$ satellites. Figure 7 shows the number of satellites killed for engagement times and hardnesses of interest. The top curve shows that for retrofit hardening, the number would start at ≈ 15 in the near term and drop to ≈ 6 in the long term; for moderate hardening it would drop from ≈ 5 to 2; and for heavy hardening it would drop from ≈ 1.5 to ≈ 0.5.

Thus, the fraction of a hardened constellation that a DEW ASAT could cover is modest. It could achieve a ≈ 8:1 exchange ratio for near-term conditions, but most of the DSATs would then be far from the launch area, making the local exchange rate about even. The number of ASATs required to kill all N_D DSATs in T is

$$N_A \approx N_D/N_K \approx (2JR_e{}^2N_D/zBT)^{1/2}, \qquad (41a)$$

which is shown in Fig. 8 for ASATs with the brightnesses of 20-10 lasers, i.e., ASATs about as large and bright as the defensive satellites they attacked. The bottom curve is for retrofit hardening, which would require ≈ 10-20 satellites; the middle curve is for 10 GJ/m^2, which would require 20-50; and the top curve is for 100 GJ/m^2, which would require 80-160 ASATS, which is larger than the number of DSATs attacked. Thus, in the near term, DEW ASATs, if available, could achieve a favorable ratio, but by the long term of the top curve, ASAT constellations would be as large as the DSAT constellations. Plausible increases in B would not change these results, but further variations in J are possible, as discussed in the next section.

The derivation of Eqs. (40)-(41a) treated the satellites as if all of them were in a plane, i.e., that the constellation thickness obeyed $h << R << R_e$. The latter approximation is only approximately valid for the top curve of Fig. 6 at long engagement times, although it is a small correction. The former is marginal on the bottom curve for small times. For $R \leq h/s$, the derivation of Eq. (40) should be replaced with that for a three-dimensional distribution of satellites $N_D' \equiv N_D''/h$. For it there would be $\approx N_D' 4\pi r^2 dr$ satellites in a shell of thickness dr a distance r away, which would take the ASAT $\approx (Jr^2/B)N_D' 4\pi r^2 dr$ to kill. Thus, in an engagement time T, the ASAT could clear DSATs out to range $R \approx (5BT/4\pi JN_D')^{1/5}$, killing $\approx N_D' 4\pi R^3/3 \approx N_D' 4\pi (5BT/4\pi JN_D')^{3/5}/3 \propto (BT/J)^{3/5}$ of them in the process.

N_k would thus decrease more rapidly with B, T, and 1/J than Eq. (41). If $N_D'4\pi R^3/3 < 1$, this result would have to be further corrected for the probability that no satellite is present in the volume swept. That is a small correction here, but a larger one in the analysis below of attrition.

b. Hardness

The nominal value of J = 100 kJ/cm^2 used in the previous section is harder than that used in the self-defense arguments of earlier sections. The reason for using it is that space-based DEW ASATs should not be able to approach from within the field of view of the DSAT's optics. Thus, the ASAT should have little opportunity to see or directly irradiate the DSATs' coatings, which could be shielded from stray radiation. Thus, for laser ASATs, the optics limits used earlier against ascending nuclear ASATs are replaced by the DSATs' structural hardness, which is governed by the strength of their structures and the amount of shielding material added. The value J = 100 kJ/cm^2 used above is $\approx$ 5 times the limiting fluence for practical hardening of offensive missiles, which can only afford a few gm/cm^2 of added shielding. It is less by an order of magnitude than the heavily hardened ASATs treated above, which do not represent a physical or economic limit either.

So long as the defense can lift more shielding material, the DSATs' hardening can be increased significantly without encountering fundamental constraints. For a 20-30 kJ/g ablator, a hardness of 100 kJ/cm^2 = 1 GJ/m^2 would amount to 3-5 g/cm^2 = 30-50 kg/m^2 of shielding. Thus, a 10-20 m^2 shield would have a mass of $\approx$ 0.3-1 ton, which is $\approx$ 0.5-5% of the 20-50 ton satellite protected. Since the shield material's cost is about that of launching it, which is 1-10% of the satellite's internal components, the shield thickness could be increased effectively to 10-100 x 0.3-1 ton $\approx$ 10-50 tons, at which the satellite's hardness would be increased by a factor of $\approx$ 100 to $\approx$ 100 GJ/m^2.

Figure 7 shows that at that hardening N_K would drop to ≤ 1, and there would be more ASATs than prey.

While a shield 300-500 g/cm^2, or ≈ 1 m, thick could be fabricated and attached to the DSAT effectively, it is not necessary to do so. From a distance of 1 Mm, a laser with $B = 2 \cdot 10^{20}$ W/sr could deposit, during the $R/V \approx 100$ s of closest approach, about $100\ s \cdot 2 \cdot 10^{20}\ W/sr \div (10^6 m)^2 \approx 20\ GJ/m^2$ on a single spot. Thus, a shield thicker than $\approx 2 \cdot 10^6\ J/cm^2 \div 2\text{-}3 \cdot 10^4\ J/g \approx 60\text{-}100\ g/cm^2$, or 20-40 cm, could not be penetrated on one pass. Moreover, since the deposition of the energy takes place over a time of ≈ 100 s, there is adequate time to rotate new material under the beam. For a 5 m radius shield, rotating new material into a ≈ 1 m beam each second would require a rotation rate of about $(1\ m \div 1\ s)/5\ m \approx 0.2$ rad/s, or a period of ≈ 30 s, which could be generated with little stress. The portion of the shield nearer the axis could be make thicker to compensate for its lower velocity.

In contrast to the high rotation rates required to increase the effective hardness of offensive boosters, the ASAT's greater distance and the DSAT shield's greater thicknesses would allow much more time for new material to be brought into the beam before that within it was eroded. Alternatively, the shielding could be placed on a detached shield or ring that was moved quickly under the beam. All of the tactics that the advanced ASATs of Section IV could use to protect themselves from DSAT beams are also available to the DSAT in negating the laser ASAT's beam, although the design constraints would be significantly relaxed.

The converse is not true. DSATs could use SDMs to destroy advanced ASATs' shields and heat exchangers, but laser ASATs could not use SDMs to attack the DSATs. A DSAT that could sense the approach of a SDM could use decoys or flares to confuse the ASAT or generate enough of a viewing angle to destroy the SDMs without exposing itself to the ASAT. That forces the ASAT to attack the DSAT's shield with its own beam, which appears prohibitive.

To the extent that DSATs can force ASATs to erode most of the shield, the ASATs' brightness becomes irrelevant, power becomes dominant, and the result is the balance of Eq. (23), which indicates that for good ablators with j = 20-30 kJ/gm and current chemical lasers σ = 300 kJ/km, the ASAT would have to launch $\approx F/M_A \approx j/\sigma \approx 100$ times more fuel mass than the DSAT would shield mass. Moreover, the time required for an ASAT to kill a DSAT would be

$$T \approx jM_A/P, \tag{41b}$$

$\approx$ 30 kJ/g·20 m^2·1 m·2 ton/m^3 ÷ 10 MW $\approx 10^5$ s. Thus, in a single pass, an ASAT could erode $\approx$ 0.1% of the DSAT's shield, so that significant attrition would require about a day. Space laser ASATs would not, however, have enough fuel for such periods of irradiation, so they could not attrit heavily shielded DSATs at all. Hybrid lasers might be able to; the discussion of that possibility is delayed till the related discussion of that hybrid exhaustion.

c. Cost Trades

According to the above, 100 ASATs could kill 100 hardened DSATs in time T =100-300 s. Thus, the average number of DSATs active during T would be $N_D/2$, so the defense's effectiveness would be degraded by about a factor of 2 over the course of the engagement. Since the ASATs postulated are about as large as the DSATs, the cost to the attacker would thus be about twice the defense's in extended engagements, since the ASATs would have exhausted themselves in the process. ASATs could be effective initially, but high levels of hardening and shorter boost phases would cause them to become ineffective over time. For advanced DSAT hardening, the ASAT's effectiveness would be reduced by another factor of 10-100, at which time the ASATs would be cost ineffective by a like amount.

By Eq. (41), if the ASATs' objective is killing a fixed number of satellites in a given amount of time, they must compensate for increases in hardness by increasing their brightness, so that $\delta B \alpha \delta J$. Note, however, that the hardening is bulk mass, which could be added for the bulk launch cost of ≈ $ 1 K/kg, while the laser has sophisticated hardware that currently costs $ 10-100 K/kg. Thus, if the ASAT's brightness was roughly proportional to its mass, the ASAT would have to add high technology on a kilogram-for-kilogram basis to offset the low technology shield, a trade that favors the defense strongly.[32]

That argument also applies to the DSATs themselves. It would be effective for the defense to add ≈ 10-100 times the mass of the DSAT in shielding, since it is 1-10% as expensive as the DSAT's functioning components. The DSAT's hardness would then be 100 MJ/cm^2, at which the ASATs would be unable to kill a single DSAT. In that limit the DSATs marginal cost trade is particularly simple. The ASATs would have to add laser and fuel fuel mass to offset hardening, losing by a factor of ≈ 100 on every increment. Even if the cost of the laser was ignored, the fuel balance would still be unfavorable. From each kilogram of fuel the laser produces ≈ 300 kJ of beam, which could erode ≈ 300 kJ/30 kJ/g ≈ 10 g of shield. Thus, the ASAT loses by about a factor of 1,000 g:10 g ≈ 100:1 on each kilogram of fuel, even ignoring the laser's cost and its fuel's bulky tankage.

d. NPB ASATs

The argument above is cast in terms of lasers, but it also applies to NPBs with slight modification. A 250 MeV NPB can penetrate 40-50 g/cm^2 of shielding, which would increase the DSAT's mass by ≈ 10%. The NPB's penetration increases as the square of its energy, so increasing its energy 500 MeV would force the DSAT to ≈ 200 g/cm^2, which would quadruple the DSAT's shielding, perhaps doubling its mass and increasing its cost by about 10%. Since the NPB's costs are roughly proportional to its energy, they would also roughly double. The NPBs would then be be so large, expensive, and rare, however, that the DSATs could shield critical components to high levels in only the direction from which the attack would obviously come.

e. Implications

What emerges from the sequence of arguments above is the transformation of the constellations of today's light, delicate satellites into a fleet of space battleships. Economics clearly point to the satellites being heavily armored and hence relatively impervious to one another, somewhat like earlier periods when naval battleships were so heavily armed relative to their attackers' cannons that they could literally "dread nought"--save running into one another, which is unlikely for space defenses according to the earlier estimates. That satellites could armor themselves does not mean that they would have to do so at the outset. Brightness cannot readily be retrofitted, but hardness can. DSATs could be launched with 50-100 kJ/cm^2 shielding, and then as much more hardening as was required by the evolving threat could be added later. Since the leverage strongly favors DSATs, there should be adequate time to do so.

The arguments above went into some detail, but the main point is simple. Shielding against DEWs is relatively cheap; it could be deployed for about its launch costs, which are likely to remain 1-10% of DEW hardware costs. Offensive missiles are hard pressed to throw useful payloads between continents, which requires about as much thrust as insertion into orbit, so their payloads must be optimized and little can be diverted for shielding, so DEWs can remain useful in their primary defensive roles. To defend themselves, however, DSATs can afford large amounts of shielding, which could be cheap and upgraded as needed. The additivity and relative inexpensiveness of defensive shielding should make it a dominant feature of space-to-space DEW engagements.

2. Satellite Allocation

Previous paragraphs discussed the basic trades for space-to-space DEW interactions using a geometric model that is accurate to factors of 1.5-2 but whose scaling is the same as that of the exact solutions. It is possible and useful, however, to treat certain factors more carefully, specifically the contributions from satellites exterior to the launch area.

a. Exterior Satellites

In defense suppression prior to launch, the interior DSATs that are directly over the launch area, plus the exterior satellites that are outside but in sight of it, make large contributions. Thus, rather than suppress the nearest DSATs, ASATs that could see the interior and nearby DSATs could direct their fire towards them instead. Then, rather than producing a uniform attrition of DSATs everywhere, the ASATs could leave some exterior DSATs alone in order to produce a greater kill rate over the launch area itself. The treatment of this effect is an extension of the combination of interior and exterior satellite kill rates derived earlier for boost-phase defenses, whose solution, given in Eq. (27), scales as

$$N_A = K_D(JN_D/BA_ET)^{\Gamma}, \tag{42}$$

where N_A is the number of DEW ASATs, N_D the number of defensive satellites, and the other symbols are as before. The scaling exponent $\Gamma = 0.7-0.8$ is weaker than the $\surd N_D$ of Eq. (41); the scaling parameters are otherwise the same.

b. Interpretation

In the $J = 10^9$ J/m^2, $N_D = 100$, and $T = 100$ s example above, the geometric model requires $N_A = N_D/N_K \approx \surd(2JR_e{}^2N_D/zBT) \approx 12$ satellites. For those conditions and an approximate DSAT density of $N_D/A_E = zN_D/4\pi R_e{}^2 \approx 3\cdot 100/4\pi(6.4\cdot 10^6\ \mathrm{m})^2 \approx 6\cdot 10^{-13}/\mathrm{m}^2$, the combined model requires

$$N_A \approx 4\cdot 10^{19}\cdot(10^9\mathrm{J/m}^2\cdot 6\cdot 10^{-13}/\mathrm{m}^2\div 2\cdot 10^{20}\mathrm{W/sr}\cdot 100\mathrm{s})^{\Gamma} \approx 3, \tag{43}$$

which would be a significant reduction, were it not that 6-10 satellites are needed to maintain coverage at all times. This represents a significant extrapolation of the combined results from their scaling base near 1,400 missiles and ≈ 50 satellites, but it indicates that the geometric model could underestimate the size of ASAT constellations by factors of ≥ 2. For either the geometric or combined estimates, however, the number of ASATs required is modest. The combined solution changes the specific size of the constellation and the value of the scaling exponent, but not the key combination of parameters, JN_D/BA_ET, which governs the trade between brightness and hardening.

B. Attrition

In suppression, the key issue is the relative effectiveness of shielding and power generation. For DEWs that carry their fuel with them, much the same result holds for attrition. For hybrids that constraint is relaxed, making them more flexible.

1. Space-Based Lasers

The previous section presented the basic results for space-based lasers used for suppression when their performance was driven by the available engagement time. This section treats the opposite limit in which lasers have a long time to engage, but only a limited amount of fuel.

a. Sweep Analysis

Section III treated KEW ASAT sweepers, which were severely hampered by the difficulty of changing orbits to stalk their prey. Lasers have an advantage over KEW sweepers in that they can fire at satellites in other orbits without transferring to those orbits. The analysis below shows, however, that the difficulty of irradiating targets at long cross ranges can still make combinations of maneuver and irradiation preferable to either alone.

If a DEW drifts at velocity V through the volume occupied by its prey, restricting its fire to satellites at their closest approach, for ranges R less than the thickness of the constellation, the rate at which it sweeps out area is $\pi R^2 V$. That is the same form as Eq. (3)'s sweep rate for nuclear ASATs, but DEWs' ranges are typically 1-2 orders of magnitude larger. A N_D satellite LEO constellation of thickness h has an average satellite density $N_D' \approx N_D/4\pi R_e^2 h$. In moving a distance δz it would encounter $\approx N_D'\pi R^2 \delta z$ satellites out to range R. If the time for retargeting can be neglected, the time required to kill them would be

$$\delta t = \Sigma_0^R\ 2\pi r dr(N_D'\delta z)(r^2 J/B) = \pi N_D'\delta z J R^4/2B. \quad (44)$$

The ASAT moves at speed V, so $\delta z = V\delta t$, which with Eq. (44) produces the estimate

$$\pi R^2 = (2\pi B/VN_D'J)^{1/2}, \quad (45)$$

for the radius within which an ASAT of brightness B could kill all DSATs found. The number of DSATs killed is thus

$$N_K = \pi R^2 VTN_D' = \sqrt{(2\pi VN_D'B/J)}T, \quad (46)$$

which scales approximately like Eq. (41), although its scaling on T is stronger. That is shown below to be a deficiency of space-based DEW ASATs. There are two corrections to Eq. (46) that must be discussed: satellite statistics and constellation geometry.

Irradiating satellites only during their nearest passage, which is implicit in taking the length of the threat cylinder δz to be infinitesimal, is not valid if the volume irradiated, $\pi R^2\delta z$, becomes so small that there is little probability of finding a satellite in it. Thus, δt and δz must be replaced by finite dimensions to treat satellite statistics. If the irradiation volume is a cylinder of half height Z and radius R, at any time it should contain $n \approx \pi R^2(2Z)N_D'$ satellites, which would have to be ≥ 1 for continuous operation. The time for targets to pass through the cylinder is $t = \Sigma\ dt = 2Z/V$, which must also be the time required for the laser to negate them all. The time to negate the targets within a differential cylinder $dr2\pi r(2Z)$ is

$$dt = dr2\pi rN_D'2\Sigma_0^Z dz(r^2+z^2)J/B = dr4\pi rN_D'(r^2Z+Z^3/3)J/B, \quad (46a)$$

so the total time to sweep all cylinders is

$$t = \Sigma\ dt = \Sigma_0^R\ dr4\pi rN_D'[r^2Z+Z^3/3]J/B$$
$$= [4\pi N_D'J/B][ZR^4/4+(Z^3/3)(R^2/2)]. \quad (46b)$$

For Z small this reduces to

$$t = 2Z/V = (\pi N_D'J/B)ZR^4$$

$$1/V \approx (\pi N_D'J/2B)R^4, \tag{46c}$$

which reproduces Eq. (45). For Z large

$$t = 2Z/V \approx (4\pi N_D'J/B)Z^3R^2/6,$$

$$\pi R^2 \approx 3B/\pi VN_D'JZ^2. \tag{46d}$$

Superficially this result is quite different than Eq. (45), but the solution to the quadratic of Eq. (46b) is

$$2R^2 = -4Z^2/6 + \sqrt{[(4Z^2/6)^2+8B/\pi VN_D'J]}, \tag{46e}$$

which reduces to Eq. (45) for Z << R.

The search radius of Eq. (46e) only holds when there is a target within the search volume. The expected number is

$$n \approx \pi R^2(2Z)N_D' \propto R^2Z. \tag{46f}$$

If Z is chosen too small, $n \leq 1$, irradiation is frequently interrupted, and the effective sweep rate falls. Equation (46b) can be rederived for this restriction, but an equivalent correction for interruptions is to multiply the sweep area of Eq. (46e) by n < 1, smearing out the satellites, to give the number of satellites killed in engagement time T as

$$N_K = \pi R^2VN_D'T \cdot p, \tag{46g}$$

where $p = 1$ for $n \geq 1$, and $p = n$ for $n < 1$. For V = 7 km/s and h = 1,000 km, $N_K \approx 1.3 \cdot 10^{-4}N_D \cdot R^2(\mathrm{Mm}) \cdot T(\mathrm{s})$; R = 1 Mm and T = 300 s, the nominal boost time, give $N_K/N_D \approx 4\%$ attrition. R^2 is shown in Fig. 9 for $B = 2 \cdot 10^{20}$ W/sr and $J = 100$ GJ/m^2. The top curve is is the $\delta z \approx 0$ limit of Eq. (46); the middle curve is the solution from Eq. (46e); and the curve at the lower left is corrected for n < 1. The correction for n is ≈ 50% for these parameters, and unity for Z > 1 Mm; for smaller B it is large and significant for all Z. The curve at the lower left is the small n limit of Eq. (46g), which scales as $N_K = \pi R^2VN_D'Tp \propto p \propto Z$.

The peak of the curve is determined by the intersection of the increasing n and decreasing R for increasing Z. Figure 10 shows N_K as a function of Z for $B = 2 \cdot 10^{20}$ W/sr on top, $5 \cdot 10^{20}$ W/sr in the middle, and 10^{20} W/sr on bottom. The top gives ≈ 0.85 kills per $2\cdot10^{20}$ W/sr DEW in a 150 s midterm engagement; the middle curve drops to ≈ 0.15 kills for $5\cdot10^{20}$ W/sr; and the bottom produces about 0.02 for 10^{19} W/sr. These N_ks are down by factors of ≈ 2/3, 1/4 and, 1/12 from the maxima of Eq. (46).

The maxima in Figs. 9 and 10 occur at Z ≈ 1 Mm, which is greater than the half height of typical constellations. Thus, Eq. (46b) overestimates of the area swept out. R should be restricted to R ≤ h/2; when that is imposed, the boundaries at h/2 force the ASAT to irradiate targets to the sides at longer ranges which take longer times. If the search volume is taken to be a rectangle of height h, half width W, and trackwise half length, Z, the time to irradiate the targets within it is

$$t = 8\ \Sigma_0^{h/2}\ dx\ \Sigma_0^{W}\ dw\ \Sigma_0^{Z}\ dz\ N_D'(x^2 + w^2 + z^2)J/B, \qquad (46h)$$

where the integral is over one octant of the volume, giving

$$t = 8\ (J/B)\ N_D'(WZh^3/3 + hZW^3/3 + WhZ^3/3)$$

$$2Z/V \approx 8/3\ J/B\ N_D'Z(Wh^3 + hW^3 + WhZ^2), \qquad (46i)$$

a normal form cubic that defines W as a function of Z, h being determined by the defense. The sweep rate is then $2WhVN_D'\cdot p$, where p = 1 for n ≥ 1 and p ≈ n = 4hWZ otherwise. Figure 11 shows that n peaks at ≈ 1 at Z ≈ 1 Mm at for B = $2\cdot10^{20}$ W/sr and at ≈ 0.4 at 600 km for $5\cdot10^{19}$ W/sr. The resulting N_ks of Fig. 12 have peaks of about 0.8 and 0.1 kills, respectively, which are not reduced greatly from the peaks of Fig. 10 for cylindrical search volumes.

For a typical 1,000 km thick constellation, ASATs would be able to operate near the peak. For thinner constellations, however, they would have to work to the left of it, which would be less efficient. The observation that the DSATs should be deployed in a shell to be survivable is valid, but does not lead to a zero sweep rate, as suggested by the figure, since for h → 0, the right-hand side of Eq. (46i) α $N_D''Z(W^3 + WZ^2)$, which remains finite. For the parameters chosen, particularly

$J = 100\ GJ/m^2$, at a brightness of $2 \cdot 10^{20}$ W/sr the corrections are $\approx 10\%$; at higher B/J ratios they would be even smaller; but at lower B/J they are much larger. Advanced shielding approaches have effective Js much larger than those used above, which produce large degradations of ASAT performance even at $B >> 10^{20}$ W/sr.

b. Fuel Exhaustion

The $N_K \alpha T$ scaling of Eq. (46) works against space laser ASATs. Their brightness is proportional to power, P, as $B \equiv B'P$, where $B' = A/w^2 \approx 10^{13}/sr$ for a $w = 2.7\ \mu m$ laser with a 10 m mirror. P depends on the rate at which fuel is burned, so the product of power and run time is constrained by

$$P \cdot T \le \sigma M_F, \tag{47}$$

where M_F is the mass of laser fuel carried, and $\sigma \approx 300$ kJ/kg is its specific efficiency. Thus, N_K reduces to

$$N_K = (2\pi V N_D' B' \sigma M_F T/J)^{1/2} = (2\pi V N_D' B'^2 \sigma^2 M_F{}^2/BJ)^{1/2}, \tag{48}$$

dropping the Z and n corrections of the previous section for transparency. Since $N_K \alpha (M_F T)^{1/2}$, the mass exchange ratio, which scales as $N_K/M_F \alpha (T/M_F)^{1/2}$, is fixed for $M_F \alpha T$, i.e., fixed P or B, and decreases as $1/\surd B$.

c. Interpretation

Equation (48) shows that $N_K \alpha 1/\surd J$, so strong shielding, which is applicable against attrition, can also be used to degrade space laser ASAT effectiveness in attrition. If $N_D = 100$, $h = 1$ Mm, $J = 1\ MJ/cm^2$, $P = 1$ MW, $T = 3{,}000$ s, and $M_F = P \cdot T/\sigma \approx 1\ MW \cdot 3{,}000\ s/300\ kJ/kg \approx 10$ tons, then Eq. (46) gives

$$N_K = \surd[2\pi 10^4 m/s \cdot 2 \cdot 10^{-19}/m^3 \cdot 10^{19} W/sr/10 GJ/m^2](3 \cdot 10^3 s)^2, \tag{49}$$

≈ 10, which shows that a constellation of

$$N_S \approx N_D/N_K \approx (2R_e{}^2 hJN_D/VB'\sigma M_F T)^{1/2} \approx 100/10 \approx 10 \tag{50}$$

modest space lasers could be effective sweepers against strongly hardened satellites for the conditions above.

d. Brightness

Equation (48) shows that for fixed fuel mass and mirror area A, the number of satellites killed scales as $1/\surd B$. The optimal satellite would thus be small, and its sweep rate would also be slow, since $\pi R^2 \propto \sqrt{B}$. In this small laser limit, ASATs have the option of using their fuel to maneuver closer to their targets. The laser then degenerates into essentially an illuminator, which is not interesting for prompt defense suppression or attrition. Overall, DEWs appear marginal when they must carry their fuel with them. They face the same shielding versus laser competition discussed for suppression, ultimately having the same drawback: shielding is cheaper than laser power.

2. Hybrid Lasers

Hybrids are a useful variant because they relax the restriction on the product of power x run time that limits space lasers in attrition. The principal hybrids of interest are ground-based FELs[33] and excimer lasers,[34] whose short wavelengths are also an advantage because they minimize the sizes of the relay mirrors needed in space. Particle beams are not of interest as hybrids because they can neither be transmitted from the ground nor redirected effectively in space. Lasers powered by solar panels would have many of the characteristics of hybrids, but they would be limited by the size and survivability of the panels. Lasers pumped by nuclear reactors would also have many of their characteristics when run closed cycle. At present they are heavy and limited in power, but it is not excluded that bright, visible, reactor-pumped lasers could be developed, in which they could eliminate the hybrids' potentially vulnerable uplink.

a. Impact of Hybrids

The analysis of hybrid laser ASATs is essentially that leading to the N_K vs T scaling of Eq. (46). The power-time limitation of Eq. (47), however, does not apply since the fuel, like the laser, remains on the ground. The Z and n corrections of the previous section are suppressed for clarity, since for hybrids they have the same form and magnitude as those derived earlier. Since by Eq. (46) $N_K \propto T$, the number of DSATs the ASAT could kill is not bounded; it continues to grow linearly with time. Against this secular growth of N_K, even hardness, the DSAT's ultimate advantage over space lasers, is not dominant. Ablation is more efficient than lasing, but leaving the fuel on the ground provides the ASAT a ≈ 30-fold advantage in mass ratio, which compensates for that difference. Leaving the laser on the ground also reduces the ASAT's capital costs, although space optics could still be large and expensive, possibly moreso than those for space lasers.

By continuing to erode DSATs' hardening over many passes, the hybrid ASAT could, if unopposed, eventually and affordably break down any level of shielding. At best, additional shielding would buy time, but the increase in the time to reach a given number of kills would only increase as $T \propto \sqrt{J}$ in the uncorrected analysis. There are several time scales of interest. $T \approx 300$ s characterizes the boost phase; ≈ 3,000 s the midcourse; ≈ 30,000 s exchanges over several hours; ≈ 300,000 s a few days for replenishment; ≈ 3,000,000 s the month needed to respond to space initiatives; and ≈ 30,000,000 s a year, which is essentially full survivability on the time scale treated here. These rough time scales are used below to interpret quantitative results.

b. Analysis

The number of hybrid space platforms, N_H, needed to negate N_D defensive satellites in time T is given by Eq. (46) as

$$N_H = (2R_e^2 hJN_D/VB)^{1/2}/T, \tag{51}$$

≈ 29 for the conditions of Eq. (49)-(50): $N_D = 100$, $h = 1$ Mm, $J = 1$ MJ/cm^2, $B = 10^{19}$ W/sr, and $T = 1{,}000$ s. For those conditions the number of hybrid mirrors would be larger than the number of space lasers needed to achieve the same sweep rate. Hybrids could, however, use larger lasers on the ground. For a 20 MW laser, or $\approx 2 \cdot 10^{20}$ W/sr brightness, N_H would drop to $29/\sqrt{20} \approx 6$ platforms. For larger B, N_H would become smaller still. The ratio of hybrid and space platforms is

$N_H/N_S \approx \surd(B'\sigma M_F/BT)$, (52)

$\approx \surd(10^{13}/\text{sr}\cdot 3\cdot 10^5\text{J/kg}\cdot 10^4\text{kg}\div 10^{19}\text{W/sr}\cdot 3\cdot 10^3\text{s}) \approx 1$ for the conditions of Eq. (50), for which $N_H \approx N_S \approx 10$, as shown above. Figure 13 shows N_H and N_S as functions of T. Breakeven is at $T \approx 3{,}000$ s, as indicated by Eq. (52). At 100 s the hybrids are at an order of magnitude disadvantage; at 100,000 s they have an order of magnitude advantage. Hybrids are preferred if long times are acceptable and high brightnesses are affordable. Space lasers' advantages are large mirrors, short wavelengths, and the ability to provide large amounts of fuel for each laser. In general, hybrids are useful when there is an extended period in which they can attrit the defense, and space lasers are preferred for times of $\leq 1{,}000$ s.

c. Advanced Shielding

In the previous section's analysis, as in that of earlier sections, DEWs' self-defense benefits greatly from the leverage that lasers are assumed to gain by irradiating only a small fraction of the approaching target's shielding. It was noted, however, in Section IV.A that if satellites could spin about one or more axes, use heat exchangers, or other advanced shielding techniques, this leverage could be negated. That is more likely for interactions with hybrid laser. The interaction ranges are typically several thousand kilometers, so the spots irradiated are much larger than those in the nuclear ASAT end game, which reduces DEW's leverage directly. Moreover, the interactions take place on longer time scales. Irradiation of an ASAT at ≈ 100 km might take less than a second; irradiation from 1 Mm would take $\approx$ 100 times longer. The period of close passage during which irradiation is effective is about $t \approx R/V \approx 1$ Mm $\div$ 10 km/s $\approx$ 100 s, during which a beam of brightness $B \approx 2\cdot 10^{20}$ W/sr could deposit $\approx Bt/R^2 \approx B/RV$, which would erode an ablator with $j \approx 20$ kJ/g about

$$d_A \approx B/RVj \approx 2\cdot 10^{20}\ \text{W/sr}/(10^6\text{m}\cdot 10^4\text{m/s}\cdot 2\cdot 10^7\text{J/kg}) \approx 10^3\ \text{kg/m}^2 \approx 100\ \text{g/cm}^2. \quad (53)$$

Targets hardened more than that could not be destroyed on a single pass. Several revisits would be required, so there would be hours or days for the ablator to be repaired or rearranged. Even during one pass there is the possibility of using moving shields. They would be impractical on offensive missiles, particularly within the atmosphere, but they could be manipulated rapidly in space. Even if the ASAT moved its beam to avoid the shield, that would still average its deposition over most of the shielding. The ASAT would lose its geometric advantage, and would have to erode all of the DSAT's shielding, which is costly in mass and time.

The analysis is analogous to that in Section IV.A.4. When the laser ASAT must ablate all of the DSAT's shielding its brightness is irrelevant; only its power matters. If the DSAT has hardness J over a shield area A_S, the energy the ASAT must supply is $J \cdot A_S$. The time to ablate it is $J \cdot A_S/P$, and from Eq. (44) the average time to sweep targets within R is about

$$\delta t = \Sigma_0^R \, 2\pi r dr (N_D' \delta z)(JA_S/P) = \pi R^2 N_D' \delta z J A_S/P, \qquad (54)$$

so that by Eq. (46)

$$N_K = \pi R^2 V T N_D' \approx PT/JA_S, \qquad (55)$$

which is independent of N_D and B. The correction for finite Z is suppressed for clarity. The generalization of Eq. (54) is obviously $t = 2\pi R^2 Z N_D' J A_S/P = nZN_D' J A_S/P$, whose scaling is like Eq. (55) for large B. N_K is the ratio of the energy delivered in time T to that required to kill a satellite, so the size of the hybrid ASAT constellation is

$$N_{HA} = N_D/N_K \approx N_D J A_S/PT, \qquad (56)$$

which also scales as T^{-1}, although with a smaller coefficient. For the conditions of the example of Eq. (51), this number is

$$N_{HA} = 100 \cdot 10^{10} \mathrm{J/m^2} \cdot 10 \mathrm{m^2} \div 10^6 \mathrm{W} \cdot 3 \cdot 10^3 \mathrm{s} \approx 3{,}000, \qquad (57)$$

which is a rather unwieldy number of ASATs. Increasing P to 20 MW would only reduce N_{HA} to about 170. To reduce the constellations further it would be necessary to increase T. $T \approx 1$ day, would give 10 satellites, but would surrender any impact on prompt exchanges, impacting only longer term replenishments.

Space lasers rarely have an advantage when substantial shield erosion is required. Their number is given by Eq. (56) with $PT = \sigma M_F$, so that

$$N_{SA} = N_D/N_K \approx N_D J A_S/PT \approx N_D J A_S/\sigma M_F, \quad (58)$$

$\approx 100 \cdot 10^{10} J/m^2 \cdot 10\ m^2 \div 3 \cdot 10^5 J/kg \cdot 10^4\ kg \approx 3{,}300$. It is also quite large, but for space lasers, unlike hybrids, there is no simple way to reduce it.

d. Cost Effectiveness

The cost-effectiveness ratio (CER) of these interactions can be estimated. If an ASAT's cost is about that of a defensive platform, C_D, the ratio of offensive and defensive costs is

$$CER_H \approx C_D \cdot N_{HA}/C_D \cdot N_D \approx JA_S/PT, \quad (59)$$

$\approx 10^{10}\ J/m^2 \cdot 10\ m^2 \div 10^6\ W \cdot 3 \cdot 10^3\ s \approx 3$, so that for $T << 10{,}000$ s or $P << 3$ MW, CER_H favors the defense. Figure 14 shows the variation for $100 < T < 16{,}000$ s. The top curve is a hybrid with a 1 MW laser, which has $CER_H \approx 10$, advantageous to the defense, at 10,000 s. The lower curve is for a 10 MW hybrid. It has a $CER_H \approx 10$ disadvantage at 100 s, which it offsets by 16,000 s, as shown by Eq. (50). For longer times, hybrids have an advantage. The defense's cost effectiveness against space lasers, evaluated as for the hybrids in Eq. (58), is

$$CER_S \approx JA_S/\sigma M_F, \quad (60)$$

$\approx 10^{10} J/m^2 \cdot 10 m^2 \div 3 \cdot 10^5 J/kg \cdot 10^4 kg \approx 30$, which is not subject to modification other than increasing the ASAT's fuel mass to 10-30 times the laser's. The top horizontal line on Fig. 10 is for 10 tons of fuel; the bottom curve for 30 tons.

e. Alternative CERs

Unlike hybrids, space lasers cannot enforce success by extending the duration of the interaction. If the DSAT survives, its cost is only that to replace the shielding eroded. The cost to the attacker, however, includes that of the failed ASAT, $C_D \cdot N_{HA}$, unless it has some salvage value, so the CER is

$$\mathrm{CER_S}' \approx C_D \cdot N_{HA}/C_L(JA_S/j)N_D \approx C_D j/C_L \sigma M_F, \tag{61}$$

$\approx \$ 400\ \mathrm{M} \cdot 2 \cdot 10^7\ \mathrm{J/kg} \div \$ 1\ \mathrm{K/kg} \cdot 3 \cdot 10^5\ \mathrm{J/kg} \cdot 10^4 \mathrm{kg} \approx 2{,}700$, based on platform costs of $\approx \$ 400$ M and ALS launch costs of $\approx \$ 1$ K/kg.[35] $\mathrm{CER_S}'$ is $\approx 100 \times \mathrm{CER_S}$, reflecting that in unsuccessful attacks the attacker would essentially be putting expensive platforms into space to chip cheap paint off the DSATs.

This argument also applies to hybrids. They can always be effective if they are allowed to operate long enough, but if their objective is to sweep all of the DSATS by some time T and they cannot do it, their platform costs are properly attributed to the cost of the attack, but the defense would again only be charged for the shielding eroded, since DSATs that survive the attack are still useful to provide defense later. The ratio of hybrid platforms to DSATS would then be

$$N_{HA}/N_D \approx JA_S/PT, \tag{61a}$$

$\approx 10^{10}\ \mathrm{J/m^2} \cdot 10\mathrm{m^2}/20\mathrm{MW} \cdot 3 \cdot 10^3\mathrm{s} \approx 2$, so the CER would be

$$\mathrm{CER_H}' \approx C_D \cdot N_{HA}/C_L(JA_S/j)N_D \approx C_D j/C_L \sigma M_F, \tag{61b}$$

$\approx 2{,}700$, about that of the space lasers of Eq. (61). When the ASATs fail in their missions, space lasers and hybrids fail about equally, since both must pay the costs of their space platforms, which are comparable. Either accounting of cost effectiveness indicates space lasers are unacceptable as ASATs, and that hybrids might be acceptable for very long times, but not for short engagements.

f. Analogy to Ground-Based Lasers

There is a close analogy between hybrids and ground-based laser ASATs. Both leave the laser and its fuel on the ground to reduce the cost of attacking space objects. Ground-based ASATs attack targets directly as they fly overhead; hybrid ASATs use several mirrors to redirect the beam in space to reach DSATS more quickly and farther from the laser. At the first level, the main difference between the two is beam redirection and the improved timeline it produces.

At the next level the differences are more serious. The direct and indirect cost of putting hybrid optics into space can be large. There is no reason to believe or experience to show that hybrid platforms should cost significantly less than space lasers of the same brightness. Related to that is vulnerability. The hybrids' final focusing or "fighting mirrors" should have about the same self-protection as other lasers of the same brightness, but the large relay mirrors would not. They would have to be protected by the fighting mirrors, which leads to a situation in which the whole beam line from the laser to the relays to the fighting mirrors must be active all of the time. Even an ≈ 100 s interruption would allow relay or fighting mirrors to be attacked.

In addition to the interruption of their beams, hybrids could be vulnerable to attacks executed at times favorable to the defense, which, given the hybrids' long-term capability, should have high priority. In discussing them, another asymmetry is significant. Hybrid space optics, relays, fighting mirrors, sensors, and command platforms would not be in sanctuary. Either side would be reluctant to attack the others' GBLs because they would be on his sovereign territory, but that would not be the case for hybrid space elements. Their components could be disarmed, possibly unobtrusively, elsewhere in their orbits without violating strong sanctions. This difference between GBLs and hybrid ASATs is fundamental. Whether lasers or space elements would be simpler to attack is unclear, but to the extent that space optics and beams are easier to interfere with, the hybrids' loss of sanction could be significant.

The key is what the hybrids would gain. If direct irradiation from the ground was effective, a few GBLs could access all critical satellites in about a day. Hybrids could shorten that time to hours, but they would prefer economically to do so over weeks or months. Thus, mission considerations drive hybrids to very short times, but economic considerations drive them towards times, days or more. Presumably there is an overlap in which hybrids are economically viable relative to the DSATs, but in it, it is unclear from the analysis above that hybrids would be preferable to space lasers or that either would be superior to GBLs.

g. Vulnerabilities

The vulnerabilities of ground-based lasers discussed earlier carry over directly to hybrids. An additional concern is the physical vulnerability and sensitivity to interruption of the relay and fighting mirrors. In the long term, both sides should be equally capable of building hybrid lasers and optics. Thus, as ASATs drift about irradiating DSATs, the DSATs could well have an equal capability to irradiate them back. One implication is that if two lasers with comparable hardnesses of optics and coatings entered a duel, the brighter one should be able to destroy the smaller one without suffering much degradation. Thus, hybrids could become subject to extremes in offensive as well as defensive capability. There is, however, little incentive for a shielded laser to enter such a duel; a more logical outcome would be for the smaller laser to look away, seek ways to block the other's relays, and erode the other's beamline, rather than fight a pointless duel. The implication is that duels would be rare, and both sides would instead spend their time searching for weaknesses in the other's beam and guarding against the other's finding a weakness in his.

C. Assessment

DEWs' can act as DSATs by negating threats to their own space platforms or they can act as ASATs by irradiating the other's platforms. This section has reviewed their capabilities and limitations in the latter role. To be useful, suppression must be rapid; ideally it should be extended on a time scale short compared to the boost phase, for which a geometric analysis of their performance suffices. Kill rates grow modestly with engagement time and brightness. Increases in satellite hardness could eliminate the effectiveness of ASATs in suppression; the masses required would be 10-20% corrections. Cost trades favor the DSATs, so suppression by DEW ASATs does not appear promising, none of which impacts DEWs' ability to negate offensive missiles, which cannot afford such hardening.

Attrition is a more likely mission. Lasers have an advantage over KEW sweepers because they can fire in any direction without changing orbits. The key issue is the relative effectiveness of shielding and lasing. DEWs that carry their fuel with them face much the same problems for attrition as for suppression: hardening can degrade their performance and eliminate their effectiveness. Advanced hardening could make them inferior to ground-based KEWs and nuclear ASATs. A space lasers' power-time product is fixed at levels inadequate to produce favorable cost exchanges. For hybrids that constraint is relaxed. Hybrids should ultimately dominate, given enough time, but hardening can buy a great deal of time and force ASATs to large sizes. Even then they would only be effective if attrition over weeks or months was acceptable.

There is a close, useful analogy between hybrids and GBLs. Both leave their lasers and fuel on the ground to reduce the cost of attacking space objects. Ground-based lasers attack satellites directly as they fly over; hybrids use mirrors to reach DSATs faster and further away. Their main differences are cost, the risk of space optics, timelines, and vulnerabilities. It is not clear that hybrid gains would justify their expense. They could shorten engagement times to hours, but hybrids would be better suited to operation over weeks or months. It is not clear that there is a niche where hybrids are economically viable relative to the defense, or even that there they would be preferable to space lasers or GBLs.

VII. CO-OCCUPANCY OF SPACE

This section reviews the long-term survivability of the different defensive platforms and discusses the adequacy of survivability in light of the requirements for crisis and arms control stability under conditions of significant co-occupancy of space.

A. KEW Self-Defense

KEW platforms' survivability should shift from near- to long-term. As discussed in Section II, near-term SBIs can harden and maneuver to achieve useful cost effectiveness against ground-based KEWs and nuclear ASATs. The addition of decoys and self-defense provide higher effectiveness, which should be adequate against midterm threats. Decoyed attackers could have more impact, but could be offset by entry levels of discrimination provided by other DSAT platforms.

Midterm DEW threats would have limited impact. Space-based DEWs could be negated by heavy but economical hardening. Good space mines would probably be too expensive to use on SBIs. The greatest threat to them could be ground-based laser ASATs, whose impact would be gradual. Hardening could buy significant time to respond, but it would be necessary to negate the laser or degrade its beam in a matter of days or weeks. Both look feasible; the former involves greater political sanctions.

In the long term, higher-power DEWs could offset the SBIs' hardening. Their gradual erosion by space-based DEW ASATs would be slow and ineffective, actually working to the advantage of the defense. GBLs could grow in brightness, which would reduce the time for response, but not the fundamental susceptibilities of the lasers' control systems. A larger issue is attrition by hybrid laser ASATs, which can operate faster and cover larger areas. They could be addressed by interrupting their uplinks, and there are possibilities for interfering with their relay and fighting mirrors. That would probably have to be accomplished by DSATs; SBIs alone would not have the flexibility.

B. Sensor Defense

Sensor defense issues are closely related to those for SBIs. Sensors are intermediate to high value targets with some mobility that are worth shielding heavily. Given good discrimination and SDMs, their survivability should be adequate. Proliferated sensors should be as survivable as modest SBIs; larger sensors could lose mobility and survivability, and could be valuable enough to attract space mines. Discrimination and DSAT support should remove those susceptibilities. If the sensors became too large to decoy effectively, ground- or space-based laser ASATs could gradually have a large impact on them. Hardening could buy time, but the defense would again have to respond in days or weeks.

At worst, the sensors could degrade slowly toward the current situation, in which sensor satellites critical to defense are unshielded and susceptible to rapid suppression, which acts as a source of potential crisis instability. Shielding them adequately would remove that source, which is arguably the defense's greatest current weakness. Hybrid laser erosion adds at worst a gradual, secular contribution to arms control considerations, which could arguably be removed by adding defenses and removing or negating GBLs.

C. DEW Self-Defense

Initial low-brightness DEWs could, like SBIs and sensors, perform their missile defense roles adequately before they would have enough offensive capability to represent a threat to other objects in space. DEWs are generally too large to harden, maneuver, self-defend, and use decoys; they must be able to recognize threats and defend themselves and their fellows. In the midterm they should be able to kill attackers effectively with their beams or possibly in concert with SDMs. Their interim ability to discriminate should support adequate self-defense against hardened, decoyed attackers. KEWs, nuclear ASATs, or DEW attacks from space should not present a technical or economic challenge. Space mines would require an interim level of discrimination. Hybrids would present the same attrition problem to DEW platforms as they would to others.

D. Summary of Co-occupancy Susceptibility Issues

In the near to midterm, space should be relatively opaque, which should act to the benefit of the defense. Limited sensors and brightnesses and good decoys would enable SBIs and DEWs to harden, hide from much of the threat, detect, and negate the rest with SDMs or modest beams. Both sides could field useful defenses that would present little threat to the other. In the long term, deployment of defenses with good discrimination would reverse the situation, making space transparent. Paradoxically, that would also act to the benefit of the defense, since DSATs could then detect the approach of threats at large distances, discard decoys, and negate the rest. Their keep-out distances could be continental, so the only useful attacker could be a DEW beam, and even DEW platforms would have to keep their distance.

DEWs in space could evolve an excellent capability to defend themselves against these threats. Their beams would be bright, and the other's decoys should be ineffective, which would make it possible to engage the entire offensive launch in midcourse, if necessary. Meanwhile, DEW platforms would present no prompt suppression threat to one another, and little effective attrition threat apart from hybrid lasers, which could be degraded by shielding. If so, the defensive constellations could co-occupy space for extended periods of time without either seeing any significant incentive for initiating an interactions that could only disarm himself at significant expense.

Given this disincentive to initiate suppression attacks, joint occupancy should also be stable under noise, probing, or false sensor signals. There would be no reason for erroneous or mixed signals to trigger a prompt attrition attack, which would degrade the attacker. If one started, considerations of his declining capability and increasing expense should end it promptly. The situation would be analogous to the offensive configuration of single RV missiles in very hard silos, which is also stable for the same reason: attacking would draw down one's own forces faster than those of the opponent. Each side would see at most an incentive to probe the other's weaknesses in space, not one to duel. The largest issues remain development of good discrimination in the near to midterm, and proper handling of attrition and hybrids in the long term.

VIII. STABILITY CONCERNS

Even if strategic defenses could reduce the damage from exchanges, they would also have to reduce the likelihood of such exchanges to be fully stabilizing. At a minimum, their introduction should increase rather than decrease international stability. The two dimensions to that reduction are crisis and arms control stability. Crisis stability treats the impact of their introduction on each side's preemptive calculus in a crisis. Arms control stability examines whether the introduction of defenses by one side would induce offensive or defensive counter moves by the other side. Improved capabilities to defend against attacks are crisis stabilizing, so long as the deployment of defenses by one side does not threaten to eliminate the utility of the others strategic reserves prematurely, leaving only irrational options in a crisis. Those conditions can be met by either or both sides' roughly symmetrical offensive-defensive deployments and arms reductions.[36]

A. Crisis Stability

General discussions of crisis stability is complicated, but the main result is simple. Defenses essentially enter the calculus of crisis stability as negative offenses. The disincentive for one side to strike first in a crisis is not altered if each reduces his offensive forces proportionally when defenses are deployed. If the defender destroyed an offensive missile each time he deployed a defensive interceptor, each side's net offense would be reduced equally: the defender's directly by the offensive missile destroyed; the attacker's by the equal number of missiles the defender could then destroy in flight. The net potential damage in a strike or retaliation would be unchanged, and the incentive to strike in a crisis would not increase, so long as the defenses could not be suppressed, which appears to be the case. What would change is the damage possible should an exchange occur, which would decrease in proportion to the defenses deployed.

The analysis becomes more complicated when multiple-weapon missiles, probabilities, air-breathing threats,[37] etc., are introduced,[38] but the logic is unchanged and leads to counting rules analogous to those familiar in offensive arms talks.[39] The central advantage of such negotiations is that they could lead to reductions in net offensive forces of both sides, which could reduce damage to both societies should exchanges occur. That advantage persists to small levels of offensive forces, below which defenses are essential to avoid involvement.

In the long term, there are no major sources for crisis instability in defensive space satellites. Ground- or space-based KEWs or nuclear ASATs should retain little prompt anti-sensor or anti-interceptor capability, and the action of space-based DEWs against other satellites is too slow and ineffective to be destabilizing. DEWs would, in attacking another hardened DEWs, disarm themselves without significant damage, in which case their interaction should be positively stabilizing. In progressing from the near to the long term, current susceptibilities should be eliminated, so the overall situation, including large and comparable joint occupancies of space, should become more crisis stable than it is today. The principal requirement is hardening, which has no offensive impact, and at worst leads to harder and modestly more expensive satellites.

The increase of crisis stability should be true even in the presence of imperfect sensors and noise. Given the above estimates of ASAT performance and effectiveness, no signal should set off an attempt at suppression because it would be both ineffective and self-emasculating. The initiation of an exchange would thus cause DEWs to address their primary defensive functions rather than each other. The situation is analogous to earlier offensive configurations in which singlet missiles faced hard silos. Given the weakness of prompt incentives for conflicts in space, defensive constellations should be able to cohabit space indefinitely without serious incident.

B. Arms Control Stability

Defenses are arms control stabilizing so long as they induce the other side to build defenses, or at least not to build more offenses.[40] If defenses are effective for both sides, they should induce successive rounds of defense increases and offense reductions, which could ultimately reduce the offenses to levels that limited defenses could handle. The process should produce a sequence of balances at ever-decreasing levels of offenses, possible destruction, and actual cost.[41] This feedback loop is stabilizing so long as defenses are effective, which should obtain if they are survivable. This description of the internal dynamics of combined crisis and arms control stability is largely theoretical, but it is consistent with the initiation and evolution of the current strategic arms discussions linking defenses and deep offensive reductions.

Defenses and arms reduction appear to be compatible in a fundamental way, in which offensive forces and arms control have not been.[42] Ideally, both sides should prefer eliminating offensive forces altogether, which has been the stated goal of arms control discussions for the last four decades. Those discussions have, however, been only marginally effective. There is still about a factor of 1,000 between the threat that each side faces and what either could currently defend himself against. That margin could be overcome by reducing offenses by a factor of 1,000, by improving defenses by a factor of 1,000, or by changing each by a factor of 30. Such offensive reductions have not proved possible, and such defenses have not yet been shown to be feasible, but their joint modification has a chance.

Reducing offenses makes defenses more effective, and developing defenses would make major reductions in offenses less risky. Thus, there is a feedback mechanism between defenses and offensive reductions that creates an incentive for the reduction of overall force levels and that is stabilizing so long as the defenses are cost effective and survivable.[43] Whether that criteria can be met can only be settled by research and development. The estimates above, however, indicate that space-based defenses could become both more cost effective and survivable with time. The mechanism described here is consistent with the catalytic role of strategic defenses in initiating current arms control discussions.

The cost effectiveness of offensive missiles against KEW,[44] laser,[45] and NPB[46] defenses has been discussed extensively. In the near- to mid-term defenses should be effective against programmed missiles and countermeasures, given expected survivability against projected suppression.[47] The underlying balances in those technologies should largely carry over into the long term. Their cost effectiveness was calculated and discussed above.

The space basing of KEWs or DEWs has little impact. The principal addition to the analysis in the long term is the performance and economic impact of hybrid lasers, which could make a gradual, expensive contribution to the degradation of the space-based defenses. Their contribution would not be explosive; it would evolve over days or months. The interaction would be analogous to the gradual attrition of ships at sea. If one side or the other had a distinct advantage, it could gradually draw the other down, but over a wide range of conditions that would not happen on time scales of concern.

Both sides' costs should be comparable for lasers and replacement shielding. Thus, their interaction would basically use one's lasers to erode the other's shielding, and one's lift capacity to replace the shielding eroded by the other's laser. The costs could be calculated from the constellation sizes, brightnesses, and launch costs above, but there is no need for a calculation to see that the optimal solution is for both sides to stop, or never start, eroding one another. That would maximize residual defenses and minimize the potential damage and cost.

This is a clear case in which each side could benefit and save money by not interacting. If that concept could not be grasped, stability could be too subtle. Even irrational acts, however, should not upset the intrinsic stability of their interactions. Should, however, interaction continue, the hybrid lasers and links that are the most troublesome feature would no longer be inviolable, and either's defenses could remove them physically or by interrupting their beams.

C. Summary

This section reviewed the stability issues for space defenses. In the near term, space should be opaque, and defenses could hide to survive. In the long term, space should become transparent, so the defenses could see the real threats and negate them. Space-based DEWs are poor ASATs, which do not generate significant suppression. Thus, crisis stability should increase with their deployment. Hybrids could provide an uncertain attrition threat on a long time scale, but there are strong, mutual technical and economic incentives for not using them against the other's satellites. Thus, in the long term--as well as in the near and midterms--defensive constellations should have a strong incentive to peacefully cohabit space and jointly perform their primary, parallel defensive functions.

IX. SUMMARY AND CONCLUSIONS

This report has reviewed ground- and space-based threats to defensive satellites in the mid- and long terms. It discussed the main concepts for conventional, nuclear, KEW, and DEW ASATs, self-defense of KEWs, DEW defense of other platforms, and DEWs as ASATs in suppression or attrition modes, for which fundamental responses exist. Attrition can apparently be moderated enough to remove any source of prompt instability.

There is a contrast between the defenses' greatest concerns over time. In the near term the problem is mostly suppression, i.e., the possibility that the attacker could punch a hole in the defensive constellation by killing the defensive satellites over the launch area, which would give a large launch window at low cost due to the absenteeism of the defensive satellites. The possibility of strong degradation of SBIs and small sensors could, however, be offset through hardening, maneuver, and decoys. The attacker's putting the ASATs in space would present little additional challenge--and possibly some advantage--to the defense. The attack timelines are not changed significantly, space-based ASATs are put at an order of magnitude cost and performance disadvantage relative to ground based ASATs, and space-based ASATs forfeit the advantage of absenteeism.

Known defensive countermeasures appear adequate in the midterm. The complications are the introduction of ground-based lasers, which could require disruption, and the deployment of large sensors and DEW platforms, which would require some interim discrimination ability to survive direct attacks. With their addition, survivability should also be adequate later. In the long term the threat shifts towards attrition. Space-based DEWs could engage in limited attrition, but the primary threat would be from hybrid lasers operating for long times. While shielding could delay their action, the hybrids' cost advantage should eventually prevail.

Direct attack by a hardened nuclear ASAT on DEWs is essentially settled by comparing their brightnesses, which favors the DEWs under most conditions. If the attacker could use advanced shielding, the outcome could be less favorable, but combined DEW and SDM defenses still resolve that ambiguity in the defense's favor. For mutual defense or the defense of other constellations, DEWs' economics appear favorable. For most threats the constellations required for defense are about the right size for boost-phase defense as well. DEWs can enforce a 1:1 substitution of ASATs for offensive forces, which reduces the threat correspondingly. Killing decoys and negating the attacker's command system could reduce the offensive threat to simple, single, inert weapons, which would greatly improve the performance of any level of defenses.

The use of deception is subject to compromise by the attacker's discrimination, but none of the attacker's passive options look threatening in the near- to mid-term. In the long term, active options such as lasers and particle beams could improve the defenses of both. Thus, dense constellations of smaller, hardened satellites with an admixture of DEW defensive satellites that can take full advantage of decoys, deception, and shielding could produce robust self- and mutual-defense constellations with adequate survivability at relevant altitudes in the near-, mid- and long-term. Under those conditions defensive constellations should be able to co-occupy space and be stable for long periods of time.

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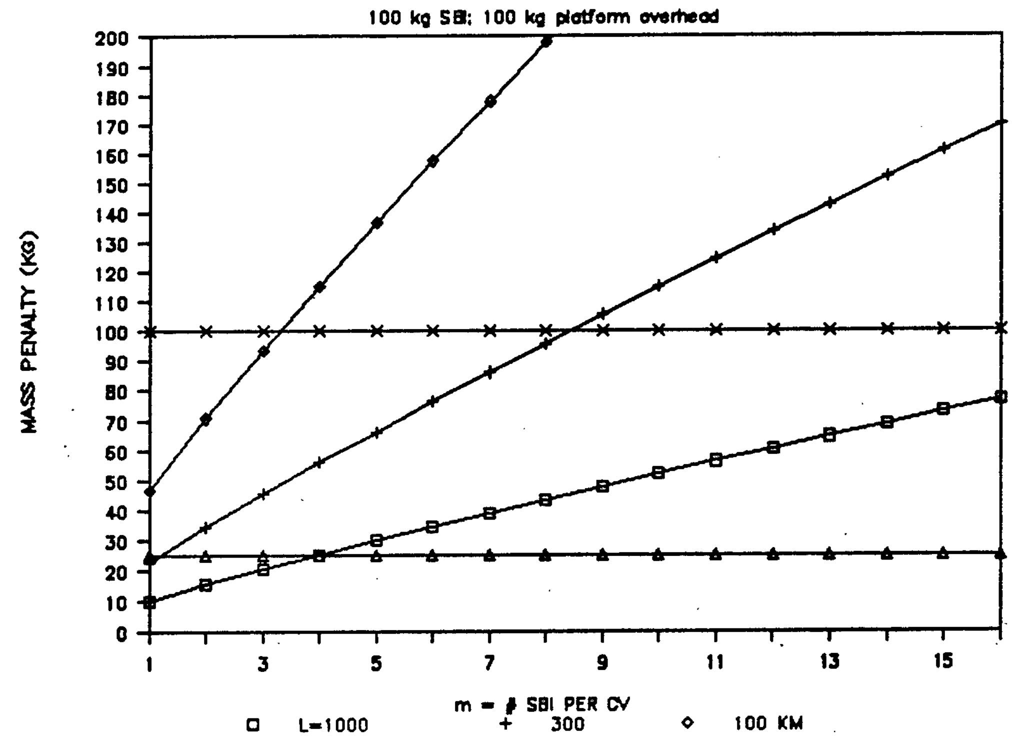

Fig. 1. Penalty for optimal hardening and maneuver against real and ideal nuclear ASATS.

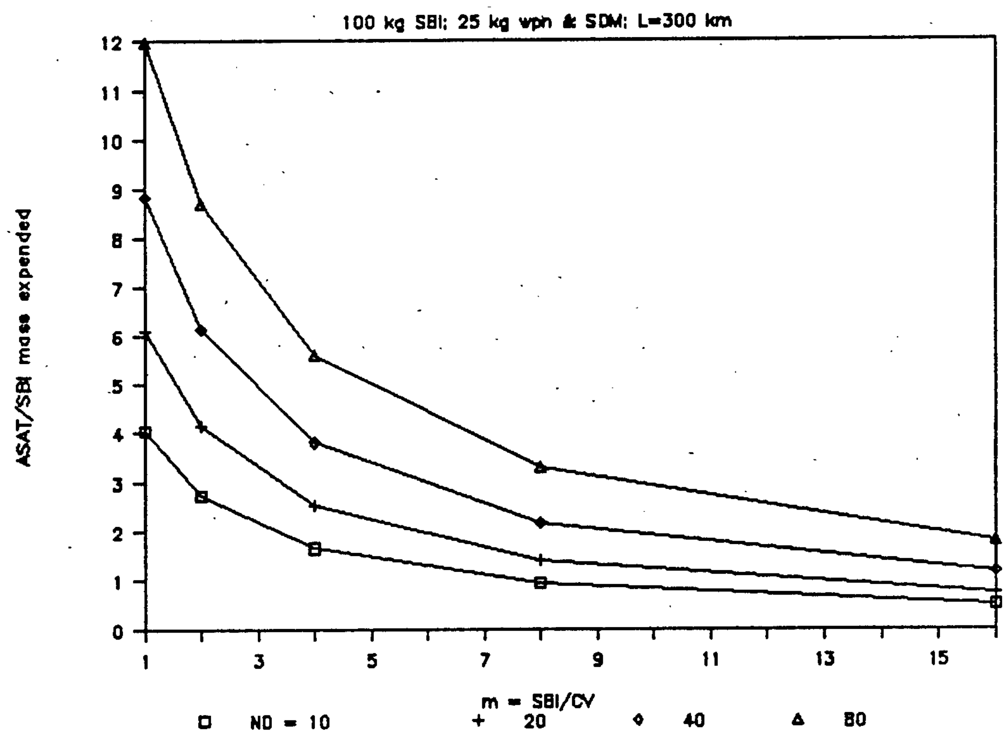

Fig. 2. Decoy and SDM exchange ratios against ideal nuclear ASATS.

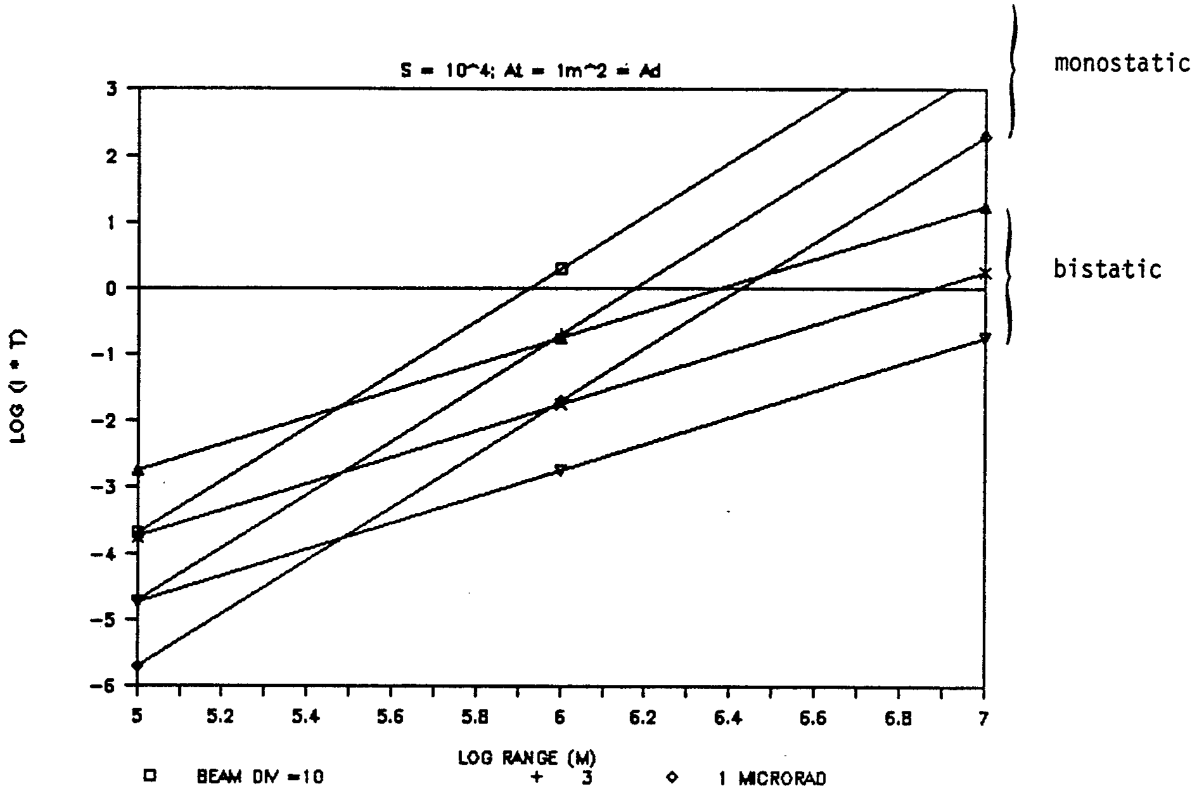

Fig. 3. NPB satellite inspection and protection.

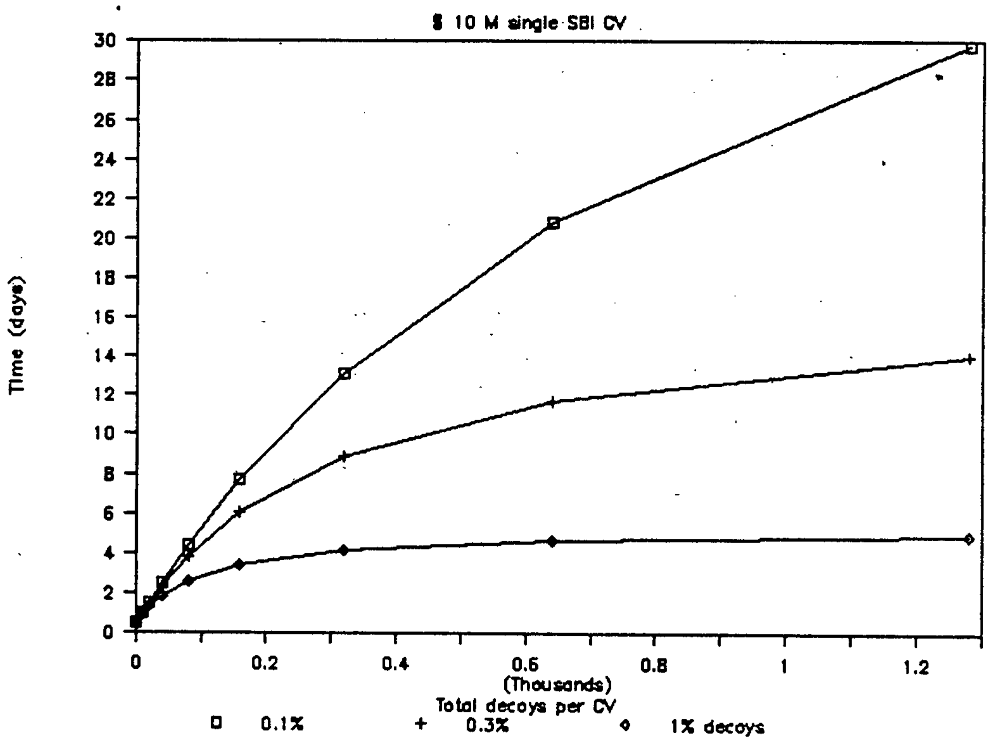

Fig. 4. SBI lifetime for decoy costs equal to SBI costs.

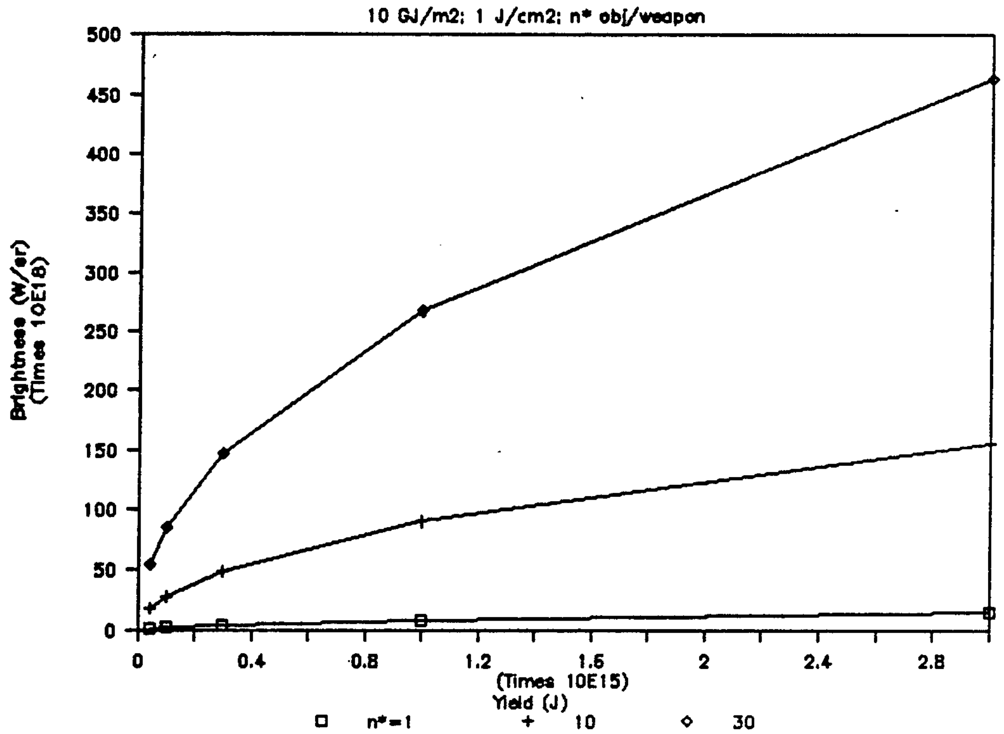

Fig. 5. Brightness required to survive direct nuclear ASATS.

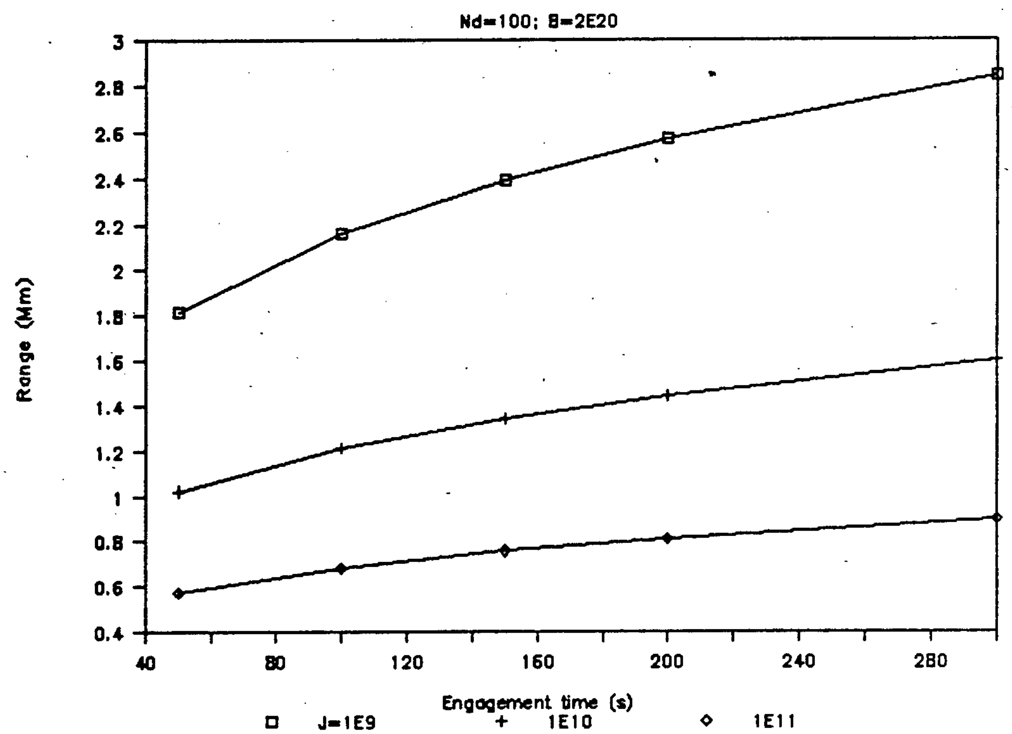

Fig. 6. Space laser ASAT ranges.

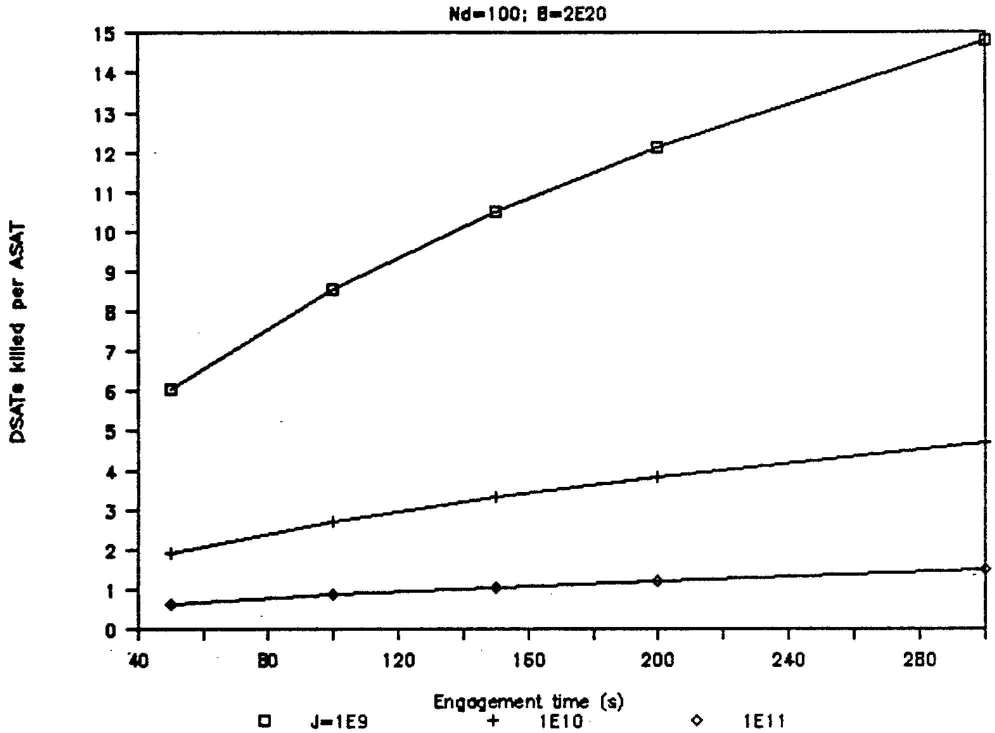

Fig. 7. Space laser ASAT kills.

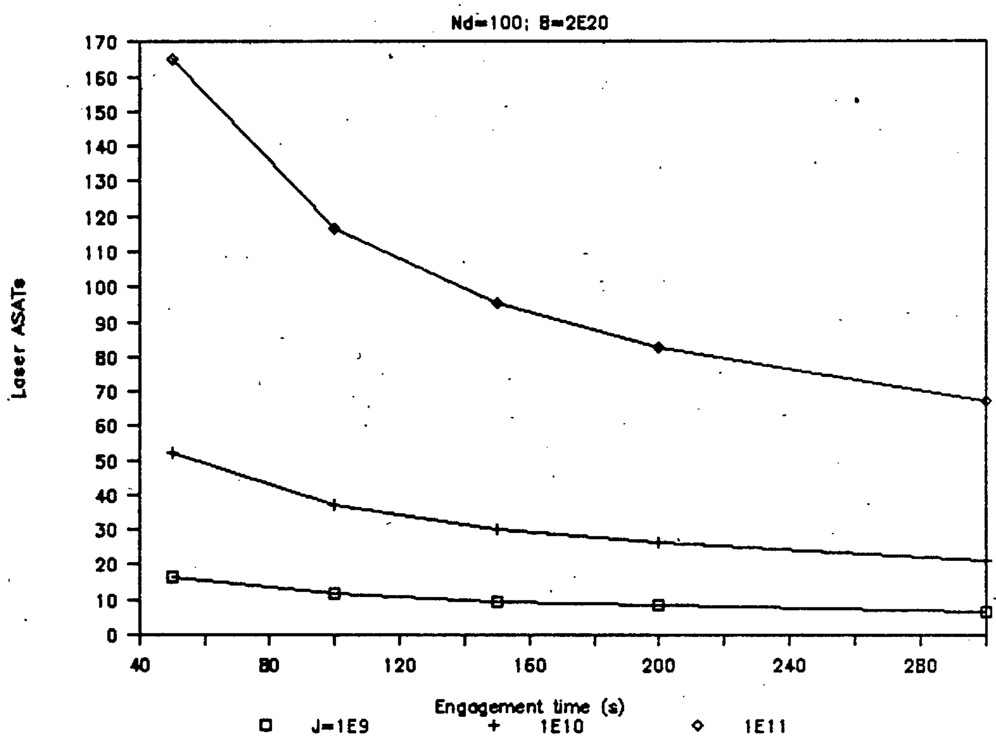

Fig. 8. Space laser ASAT constellation sizes.

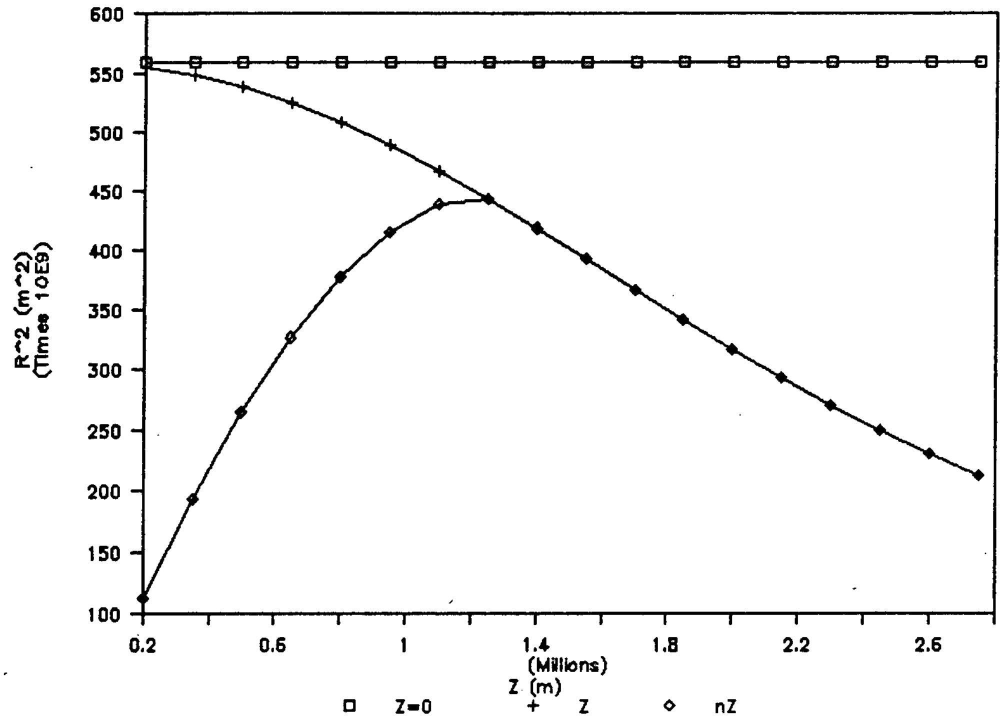

Fig. 9. ASAT sweep area.

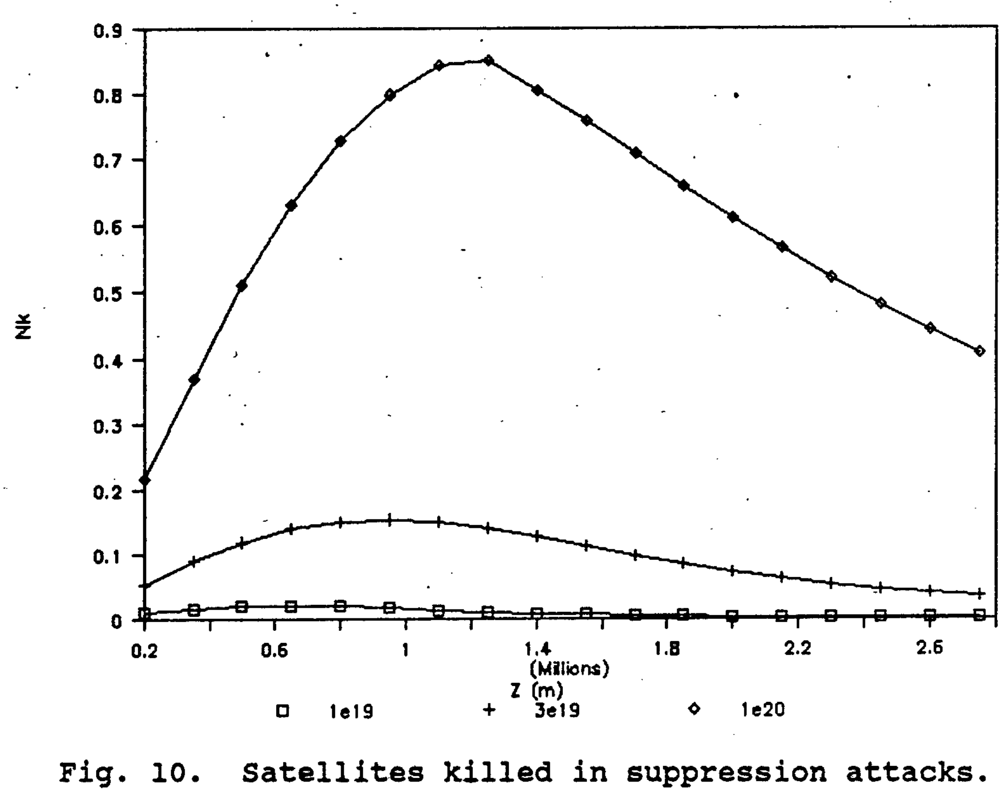

Fig. 10. Satellites killed in suppression attacks.

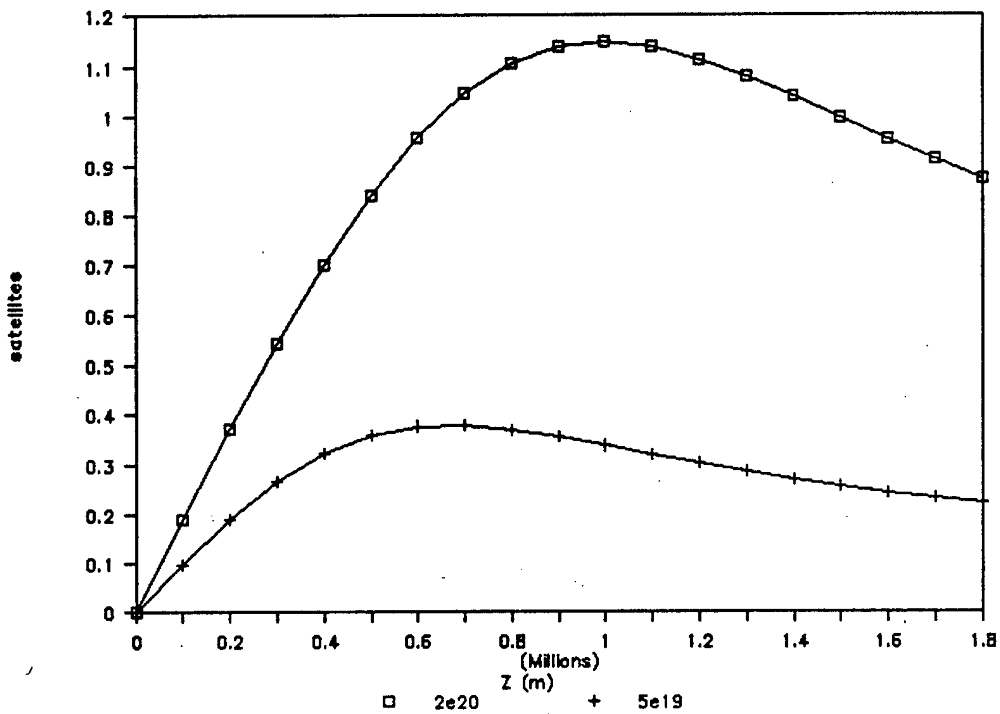

Fig. 11. Satellites within sweep volume.

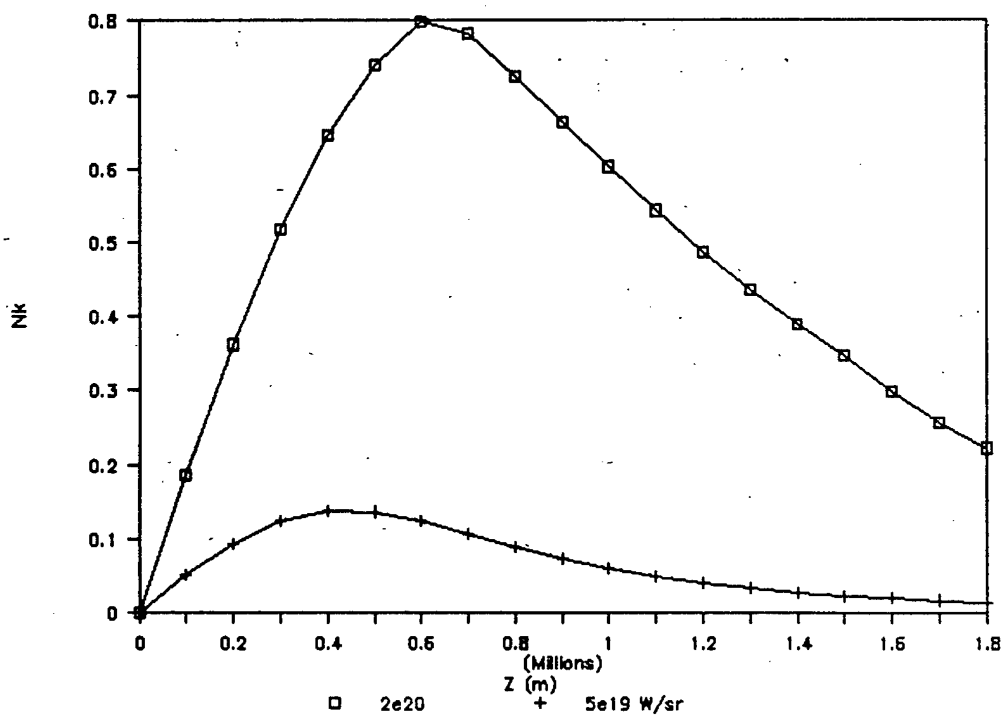

Fig. 12. Satellites killed for thin constellations.

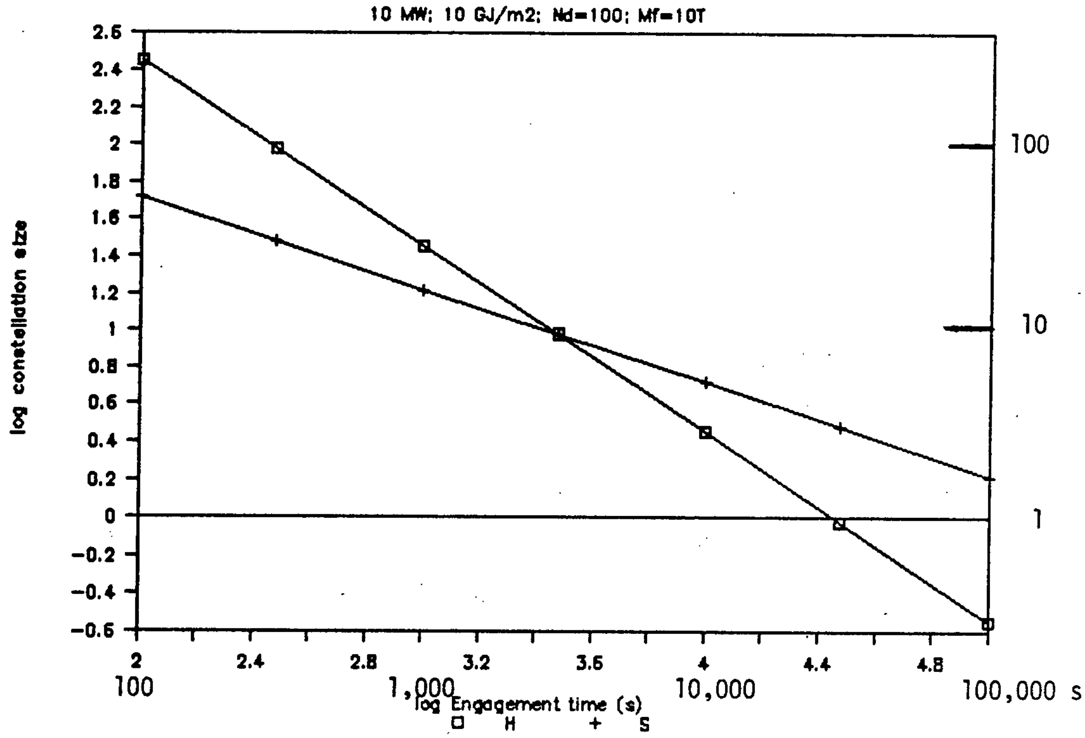

Fig. 13. Hybrid and space constellation sizes.

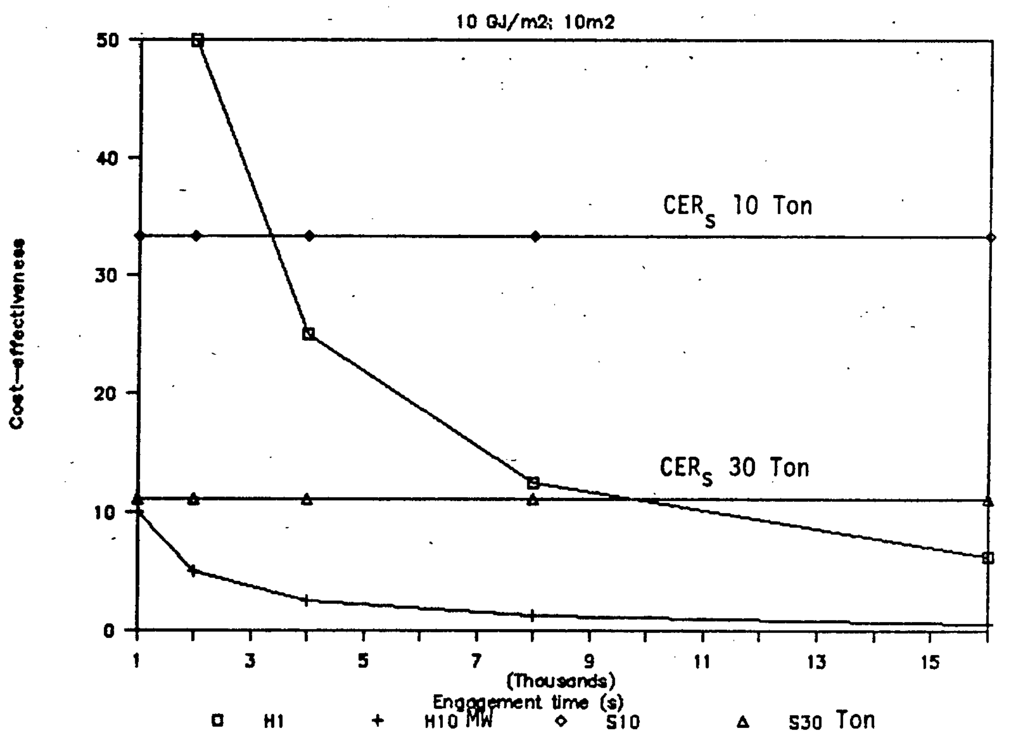

Fig. 14. Hybrid and space ASAT cost effectiveness.

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