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Scaling of Nonnuclear Kinetic-Energy Antisatellites

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by

Gregory H. Canavan

ABSTRACT

Nonnuclear antisatellites could release particles in the paths of satellites. The antisatellite would have about a twofold mass advantage in attrition and about a tenfold advantage in suppression over the defensive satellite. Antisatellites would weigh 5-10 tons; satellite shields could weigh a factor of 2-4 less. Exchange ratios scale strongly on antisatellite mass, maneuver, and range. Such antisatellites would be less effective against directed-energy satellites, which could clear their paths or destroy the antisatellites before deployment.

I. INTRODUCTION

A nonnuclear kinetic-energy antisatellite could pop up into the path of a large defensive satellites, explode, and release a cloud of particles into the satellite's path, which would be destroyed by running into the particles. Such antisatellites would represent the simplest and earliest level of technology available to an attacker. They should also be relatively insensitive to countermeasures.

II. ANALYSIS

This section discusses antisatellite trajectories, required particle numbers and mass densities, requirements for satellite shielding, optimal deflection, minimum maneuver and shielding penalties for survival, and corresponding exchange ratios (ERs).

A. Trajectories

The antisatellite is assumed to pop up into the path of the satellite, whose trajectory has been determined. Popping up gives the antisatellite a significant mass advantage in attrition attacks, and ground basing gives the anti-satellite a large mass advantage in suppression attacks for which only the fraction of the satellites within range of the launch must be addressed.

1. Antisatellite Trajectories

To pop the antisatellite up to a maximum altitude of h = 1,000 km, the nominal orbit of the large defensive satellite would require a burnout velocity of about $(2gh)^{1/2} \approx 4.5$ km/s, which is lower by 8 km/s - 4.5 km/s ≈ 3.5 km/s than that of the satellite's orbital velocity. Thus, a booster with a specific impulse of approximately 250 s would give the anti-satellite an advantage of a factor of $e^{3.5/2.5} \approx 4$. If the antisatellite was popped out to an angle of 45^{o} from the vertical to give it a cross range of 2,000 km, the booster's burnout velo-city would be increased to $\surd 2 \cdot 4.5$ km/s or about 6.4 km/s, and the antisatellite's advantage would be reduced to about $e^{1.6/2.5} \approx 2$.

2. Satellite Trajectories

The antisatellite has a greater advantage for use in suppression attacks in which satellites are destroyed within range of the launch. At any given time, most satellites would be elsewhere in their orbits, so that in simultaneous launches, only about 10% of them could contribute to the defense. However, the defender would have to pay for building and launching all of them (Appendix), which increases the effective cost of the defender's payloads by about a factor of 10 relative to those of the antisatellite. For suppression attacks, the antisatellite's advantage is the product of the trajectory and absentee ratios, which is about a factor of $X_S = 20$ (Appendix).

Because the antisatellite's particles and the satellite's shielding and fuel for maneuver are bulk materials, their costs per unit mass should be comparable. If the satellite's defense is successful,[1] the mass and cost of the satellite's interior mission-related components do not enter, and the defense's ER is essentially the ratio of the mass of the antisatellite's particles to the mass of the satellite's shield and fuel for maneuver.

The antisatellite could be put into place when the satellite was at about 1,000 km or at about 150 s away. To minimize the mass for its particles, the antisatellite should wait for the satellite to detect it and make its evasive maneuver before ejecting its particles. This action concentrates the particles in space and maximizes the satellite's penalty for maneuvering around them. Maneuver ranges are typically 5-10 km and drift times are approximately 100 s, so the particles would need a velocity of about 5-10 km ÷ 100 s or about 0.05-0.1 km/s to cover the area accessible to the satellite. Accelerating the particles to those low velocities would not add much mass or complication to the antisatellite.

B. Particles

A particle of density μ and diameter d would have a mass m of about $\mu d^3/2$; when d = 1 mm, m is approximately 10^{-5} kg. Thus, the number of μ = 20 g/cc particles that could be deployed from an $M_A \approx 1,000$ kg antisatellite would be $N \approx M_A/m = 1,000\ kg/10^{-5}\ kg \approx 10^8$ particles. If the satellite could deflect a transverse distance r from its initial trajectory and the antisatellite did not have directional sensors active, the antisatellite would have to cover the whole πr^2 area with particles. If the satellite's exposed area was A, the number of particles required to produce, on the average, at least one hit on the satellite is $\pi r^2/N = A$.

Thus, the number of particles required is $N = \pi r^2/A$, and the attacker's total particle mass is

$$M_A = N \cdot m \approx \pi r^2 \mu d^3/2A. \quad (1)$$

Although the scaling on r is obvious, that on d is significantly modified by the satellite's shielding tradeoffs discussed below.

C. Shielding

Although the particles would drift outward relatively slowly, the satellite would run into them with hypersonic velocity. In such collisions, the satellite would need a shield of areal density roughly equal to that of the particles, μd, to survive.[2] Thus, the total mass of the satellite's shield is

$$M_S \approx \mu dA. \quad (2)$$

For a given shield mass, the areal density provided to the satellite is $\mu d = M_S/A$, which is a detriment to satellites with large areas.

D. Maneuver

For the small deflections of interest here (e.g., 5-10 km ÷ 1,000 km ≈ 5-10 mrad < 0.1°), the mass for maneuver is

$$M_M \approx MV\langle x\rangle/cL, \quad (3)$$

where M is the satellite's total mass, $V \approx 8$ km/s is its orbital velocity, $\langle x\rangle$ is its average transverse displacement, $c \approx 3$ km/s is the specific impulse of its fuel, and L is the range over which the satellite must generate that deflection.[3] To force the antisatellite to disperse particles to all radii and angles, the satellite must be capable of penetrating the cloud at all points. If x is the radial coordinate of deflection, the average deflection is

$$\langle x\rangle = \Sigma\, dx \cdot 2\pi x \cdot x \div \Sigma\, dx \cdot 2\pi x = 2r/3, \quad (4)$$

so that the mass to maneuver is

$$M_M \approx M \cdot 8 \text{ km/s } (2r/3) \div 3 \text{ km/s} \cdot L \approx 2Mr/L. \quad (5)$$

The mass for maneuver scales as M, which again penalizes large satellites, as 1/L, which favors long-range detection of the antisatellite and initiation of maneuver by the satellite, and also as r; although by Eq. (1), the attacker's mass for maneuver scales as r^2.

E. Optimal Deflection

The satellite's total mass penalty for defense is the sum of the penalties for shielding and maneuver, which is

$$M_D = M_S + M_M \approx \mu dA + 2Mr/L, \qquad (6)$$

so the satellite's mass ER is the ratio of M_A to M_D,

$$ER = M_A/M_D = M_A/(M_S + M_M). \qquad (7)$$

It is useful to solve Eq.(1) for

$$\mu d = (2\mu^2 A M_A/\pi r^2)^{1/3}, \qquad (8)$$

in terms of which the satellite's shield mass is

$$M_S = \mu dA = (2\mu^2 A^4 M_A/\pi r^2)^{1/3}. \qquad (9)$$

Maneuver forces the antisatellite to spread particles over a larger area. A fixed M_S causes the areal density of the antisatellite's particles to decrease as $r^{-2/3}$; this reduces the thickness and mass of the satellite's shield and makes penetration easier. Substituting this result into Eq. (6) gives

$$M_D = (2\mu^2 A^4 M_A/\pi r^2)^{1/3} + 2Mr/L. \qquad (10)$$

The first term on the right-hand side varies as $1/r^{2/3}$, the second, as r. Thus, their sum has a minimum, and the ER has a maximum, at

$$r_m = 0.47(\mu^2 A^4 M_A L^3/M^3)^{1/5}. \qquad (11)$$

The strongest scaling of the optimal deflection r_m is on $A^{4/5}$ and $(L/M)^{3/5}$; its scaling on the antisatellite's mass is only ${M_A}^{1/5}$. The optimal deflection for survival, r_m/L, scales as $L^{-2/5}$, which is much weaker than the r/L of Eq. (6).

F. Mass Penalty for Survival

Substituting Eq. (11) into Eq. (10) gives the optimized, or minimized, defensive mass penalty,

$$M_{Dmin} = 2.4(\mu^2 A^4 M_A M^2/L^2)^{1/5}, \qquad (12)$$

to which the contributions from shielding and maneuver are in a ratio of approximately 60:40, respectively. The strongest scaling is proportional to $A^{4/5}$. The optimized ER is

$$ER_O = 0.4({M_A}^4 L^2/\mu^2 A^4 M^2)^{1/5}, \qquad (13)$$

which scales as $M_A^{4/5}$, which is the satellite's main advantage against large antisatellites. It can, however, be disadvantageous against small ones.

If the satellite's dimensions scale proportionally (i.e., $A \alpha M^{2/3}$), then $A^4M^2 \alpha M^{14/3}$, and

$$ER_O \alpha 1/M^{14/15} \approx 1/M, \tag{14}$$

which means that increasing a satellite's mass tenfold would reduce its survivability about tenfold.

The ERs above are based on payload masses. As discussed in Subsection II.A, antisatellites have an advantage of a factor of $X_A \approx 2$ in attrition attacks because of their trajectories, and an additional advantage of a factor of $X_S \approx 10$ in suppression attacks because of absenteeism. The antisatellite's overall advantage is $X = X_A X_S \approx 2 \cdot 10 = 20$. Corrected for those advantages, the ER for attrition attacks ER_A is

$$ER_A = 0.4(M_A{}^4L^2/\mu^2A^4M^2)^{1/5}/X_A = 0.2(M_A{}^4L^2/\mu^2A^4M^2)^{1/5}, \tag{15}$$

and that for suppression attacks ER_S is

$$ER_S = 0.4(M_A{}^4L^2/\mu^2A^4M^2)^{1/5}/X = 0.02(M_A{}^4L^2/\mu^2A^4M^2)^{1/5}. \tag{16}$$

Because the two simply differ by a factor of 10, both can be shown on the figures that follow.

III. RESULTS

Figure 1 shows the optimized mass ERs from Eq.(15) and (16). The abscissa is M_A, the left ordinate is ER_A, and the right ordinate is ER_S. The top curve is for L = 1,000 km, the middle is for 300 km, and the bottom is for 100 km. For the first, ER_A ranges from about 0.4 at M_A = 500 kg to about 4.2 at M_A = 10 tons with the $M_A^{4/5}$ scaling of Eq. (15). The curves for smaller L scale down by $L^{2/5}$, as expected from Eq.(15).

The ERs are marginal at small M_A, but approach the desired ER = 3-10 at large M_A. For M_A = 10 tons and L = 300-1,000 km, $ER_A \approx$ 3-4.2, which is acceptably above the break-even point. For M_A = 10 tons and L = 100 km, ER_A drops to 1.5, which is not large enough for robust survivability. For L = 1,000 km, ER_A drops to unity at $M_A \approx$ 1,500 kg; for L = 100 km, ER_A drops to unity at about 6 tons. For small L, $ER_A \approx 0.15$-0.4, which is not acceptable.

For suppression attacks, the ER is reduced by another factor of $X_S \approx 10$. The right-hand side of the figure shows that none of the nominal satellite parameters discussed above would lead to useful levels of survivability.

Figure 1 is constructed for M = 30 tons. For 10-ton satellites, the ERs would increase by about $3^{2/5} \approx 1.6$, which for M_A = 10 tons gives $ER_A \approx 6.5$--a significant improve-ment. Scaling down to the M = 100 kg of current space-based interceptors would increase ER_A by about $300^{2/5} \approx 9.8$ to about 40 and ER_S to about 4, which would be useful even against suppres-sion attacks. Thus, the kinetic-energy antisatellites discussed here are not appropriate against very small satellites.

Figure 2 shows r_m, as a function of M_A and L. For M_A = 10 tons and L = 1,000 km, $r_m \approx 8$ km. For a smaller M_A, r_m falls as $M_A{}^{1/5}$ to about 4.5 km by M_A = 500 kg. For that attacker mass and L = 100 km, r_m falls as $L^{3/5}$ to about 1 km. Such deflections would not be difficult for the antisatellite to generate, although the fuel required for the satellite to maneuver that far is significant.

IV. SENSITIVITIES

There are a number of other variables that could be used by the attacker to decrease the exchange ratio or by the defender to increase it.

A. Attacker Options

The sensitivities the attacker can exploit are more numerous and generally stronger than those available to the defender, but they do have countermeasures.

1. Attacker Mass

The strongest sensitivity that the attacker can exploit is that the ER is proportional to $M_A{}^{4/5}$, which drives antisatellites toward a smaller M_A. That decreases $r_m \alpha M_A^{1/5}$; hence, the cloud area decreases as $r_m^2 \alpha M_A^{2/5}$. By M_A = 500 kg, the area would drop to about 2,000 km^2. That would, however, still allow significant error in positioning the antisatellite. The timing accuracy required would be about $r_m/V \approx 4$ km ÷ 4 km/s ≈ 1 s. Because ER α $1/\mu^{2/5}$, the antisatellite could also increase μ, but the figures are already constructed for μ = 20 g/cc, which is the maximum density possible.

The attacker cannot determine M_A unilaterally because the particle and shield's areal densities must be about equal. By Eq. (1),

$$M_A \ \alpha \ (\mu d)^3 \ \alpha \ M_S^3, \tag{17}$$

so by increasing M_S, the satellite could force M_A to increase to any desired level. The ER would then increase as approximately $M_A/M_S \ \alpha \ M_A^{2/3}$. [The small discrepancy between $M_A^{2/3}$ and the $M_A^{4/5}$ of Eq. (12) results when the variation of $r \ \alpha \ M_A^{1/5}$ in Eq. (17) is ignored]. Thus, the satellite can force M_A to levels at which the ER is more favorable to it.

Figure 1 shows that for L = 1,000 km and M_A = 10 tons, the ER against attrition attacks would be about 4:1, so that the satellite's shield would weigh about 10 tons ÷ 4 ≈ 2.5 tons, or about 10% as much as the satellite. For L = 100 km and M_A = 2 tons, the ER would be about 0.4:1, and the shield would weigh about 2 tons ÷ 0.4 ≈ 5 tons, or about 17% of the satellite. Effective shields are neither small nor light.

Equation (1) assumed one particle per area A. If a larger number k ≈ 10 of particles were used (e.g., for greater lethality), N would increase as k, M_S would decrease as $1/k^{1/5}$, and ER would increase as $k^{1/5}$. For k = 4-10, the increase in ER would be a factor of about 1.3-1.6, which would not qualitatively change the discussion above.

The calculations above ignored the masses for the antisatellite's communications, sensors, controls, etc. Those should, however, be small because the sensors and communications are intended to be rudimentary; most could even be executed from the ground. For comparable functions other antisatellites might have payload overheads of 50-100 kg, which would be a negligible fraction of the 1- to 10-ton antisatellite payloads discussed above. The mass required to accelerate one ton of projectiles to about 0.05 km/s should be less than a kilogram of explosives.

2. Decoys

The previous section discussed sensitivity to the antisatellite's real mass. That mass can be multiplied by the use of decoys. If the booster deployed the antisatellite somewhere in an array of D decoys, which the satellite could not discriminate with onboard sensors in the short period of approach, the satellite would have to treat all of the attacking objects as real antisatellites. The net effect would be to multiply M_A in Eq. (1) by a factor of $D \approx 100$, which would increase r_m and M_D by a factor of $D^{1/5} \approx 2.5$, which would subsequently decrease ER by a factor of $D^{-1/5} \approx 0.4$. This procedure would reduce even the largest of the attrition ERs in Fig. 1 to about unity, and the suppression ERs would fall to about 0.1%.

3. Maneuver Range

Antisatellites could also decrease L by jamming the satellite's sensors because ER α $L^{2/5}$. In the limit of $L \approx 0$, maneuver would lose its effectiveness, and $M_D \approx M_S = (2\mu^2 A^4 M_A/\pi r^2)^{1/3} \; \alpha \; r^{-2/3}$, which is unbounded as $r \approx 0$. Decreasing L would be catastrophic to the satellite, but again there are countermeasures to it.

4. Directionality

Ejecting the particles primarily in the direction in which the satellite had made its evasive maneuver would have the effect of increasing the effective antisatellite mass by the reciprocal of the angle into which they were ejected. Such a strategy would not greatly complicate the antisatellite's release of its particles, but it would require that the antisatellite have sensors capable of tracking the satellite for longer periods of time. Such sensors would of necessity be more susceptible to jamming than ones that only timed the release of the particles.

Such directionality has competition from ground-based interceptors (GBIs), which would use precision sensors and thrusters to put a unitary kill package or a few kilograms of projectiles within about 1 m of the satellite. That could reduce the total payload mass by a factor of about 100, but it requires imaging sensors that would be susceptible to even more jamming modes than postdivert trackers, let alone mechanical timers. The main advantage of nondirectional particle antisatellites is their simplicity and modest information requirements and, hence, their insensitivity to jamming and interference. Directional or pursuit approaches would be lighter, although not necessarily cheaper, but they would face further jamming and countermeasures that are difficult to bound. Thus, the figures simply show the results parametrically in a form that makes it possible to study the results of these tradeoffs.

5. Particle Distribution

The calculations of Subsection II.B were generated under the assumption that all particles have exactly the same diameter d. By introducing a spread of particle diameters, the antisatellite can extract an additional penalty from the satellite because the satellite would then have to add extra shielding to account for the possibility of a random encounter with a particle with d much greater than the average <d>. The thicker the shield, the greater the satellite's probability of survival; however, the shield's launch cost would also increase. The thinner the shield, the lower its cost; however, a thinner shield increases the probability that a large particle could penetrate it and destroy the expensive components inside the satellite.

If the particle diameters had an exponential probability density function, for current satellite fabrication-to-launch cost ratios of about 10:1, the shields would optimize at a thickness of about 2<d>. The additional cost to the satellite would then be a factor of about 1.4, which would decrease the ERs in Fig. 1 by a factor of about 0.7. The satellite's probability of surviving an encounter would then be about 86%. Such a survivability rate is significant. However, although the satellite could survive particles of one diameter, an effective economic trade can only be possible for an antisatellite with a distribution of particular diameters.

6. Accompanying Attack

The preceding sections described a geometry in which the antisatellite intercepted the satellite as it passed over its own country in peace or wartime. Antisatellites could also be used to accompany the attack and negate the sensors or defenders popped up on warning in the midcourse. It would be necessary to determine their trajectories to within 5-10 km, but the approximate milliradian accuracies required could be accomplished by small, nonsurvivable satellites.

Nonnuclear antisatellites would be less effective in this geometry because in it their trajectories would be about the inverse of the missiles, and there would be no absenteeism. They would not be effective in suppressing small GBIs, whose approximately 100-kg payloads would give ERs of approximately 100. Large satellites' ERs might remain at 1-4, depending on how much shielding could be afforded in a pop-up mode.

But an even exchange would remove all of the defenders. Because each could have been expected to have removed about 1,000 reentry vehicles, the impact on the defense would be quite serious. This function could also be provided by nuclear antisatellites, but their lethal radii would be no greater and their information requirements would be the same. They would also produce more fratricide in the attacking forces.

B. Defender Variations

It is clear from the ER α $(L/A^2M)^{2/5}$ scaling of Eq. (13), that it is important for satellites to reduce their mass and area and maintain their range to maneuver. The masses of large sensor and directed-energy weapon satellites are, however, closely tied to their missions. Thus, M cannot be decreased significantly without reducing performance. Much the same applies to A. Maintaining L requires countermeasures to antisatellite jammers and sensors, as discussed above.

1. Decoys

Small space-based defenders can use decoys with hardening and maneuver to achieve ERs of 6-12 against nuclear antisatellites. Those ERs, however, fall roughly as 1/M for a larger M, which means they would not be acceptable for satellites that were about 100 times heavier than approximately the 100-kg defenders, even during attrition attacks.[4] Moreover, the decoys for 10- to 30-ton satellites would be large, heavy, and difficult to deploy. Decoys appear to give antisatellites a unilateral advantage, whenever they can be used.

Directed-energy weapon satellites should be able to negate antisatellite decoys, which would be a major defensive gain for these satellites against what could otherwise represent a factor of 2-3 advantage to the antisatellite.

2. Sweeping Particles

Satellites with high-power beams might be capable of clearing the particles out of the area through which they would pass. The requirements are, however, demanding. A 1-cm particle with μ = 20 g/cc would have μd = 20 g/cm^2, so that for an ablation energy of 10 kJ/g, the energy to ablate each particle would be 200 kJ/cm^2. If a laser of power P began to irradiate the area A from a distance $L \approx 1{,}000$ km and continued to do so for a time $L/V \approx 100$ s, it would deposit a fluence PL/VA. Thus, to burn through 1-cm particles, the laser would need

$$P \approx 200\ \text{kJ/cm}^2 \cdot (VA/L) \approx 200\ \text{MW}, \qquad (18)$$

which is about an order of magnitude larger than the lasers under development for their primary defensive missions. Clearing the whole area at once is apparently not a viable way of eliminating particles.

Alternatively, the laser could scan from particle to particle--assuming it could detect something that small--which would take advantage of the laser's ability to focus its beam to a spot much smaller than A. At range L, a laser of power $P \approx 20$ MW, wavelength $w \approx 3$ μm, and mirror diameter $D_L \approx 10$ m would produce a spot diameter of about $Lw/D_L \approx 10^6 m \cdot 3 \cdot 10^{-6} m \div 10 m \approx 0.3$ m and hence a flux of $P/(Lw/D_L)^2 \approx 200$ MW/m^2. It would take about 200 kJ/cm^2 ÷ 200 MW/m^2 ≈ 10 s to clear one particle. Ten particles would saturate it, although particles could be cleared faster in time as the laser approached the cloud.[5]

Thus, clearing some number of particles individually appears feasible, although it is not free. A 20-MW laser running for 100 s would produce 2 GJ of output energy. At an efficiency of about 500 J/g such an output of energy would require 4,000 kg of fuel, which is about as large as the mass for fuel to maneuver around the cloud. Thus, clearing particles is an option, but such an option cannot significantly increase the ER.

The best time to destroy the particles is before they have been dispersed. A 20-MW, 10-m laser could destroy a payload canister in about 200 kJ/cm^2 ÷ 200 MW/m^2 ≈ 10 s for 400 kg of fuel. Such a laser not only would eliminate the possible dispersion of multiple particles in the path through the cloud but also would eliminate the need to maneuver altogether, which could give the laser an ER of about 10:1. The comments above are stated in terms of lasers, but the powers are about the same for particle beams, although the masses are somewhat lower because of the higher efficiencies of particle beams.

Obviously this option is not available to sensor satellites that do not have high-power beams. Interestingly, it is not available to small defensive missiles either. They could neither reach the antisatellite before dispersal nor afford to do so. A 100-kg interceptor attempting to suppress a 1,000-kg antisatellite would have an adverse ER of (1,000 kg ÷ 20) ÷ 100 kg ≈ 0.5.

C. Summary

Not all of the options discussed above have large or equal impacts. For the attacker, reducing M_A potentially has great impact because of the $M_A^{4/5}$ scaling of ER, but the satellite can block reductions of M_A through the interaction described in Eq. (17). The particles should, however, be quite effective against current satellites, which are essentially unshielded. Similarly, the number and distribution of particles have little impact--if their shift is properly anticipated. Thus, M_A is a transient effect. The range to maneuver is also a significant variable, but subject to countermeasures. The range of Ls studied above seems appropriate.

Particle antisatellites apparently are equally effective over their own territory or in accompanying offensive attacks.

Antisatellite decoys have great potential impact. They could reduce passive sensor satellites' ERs to approximately unity. They should not, however, have much impact on directed-energy satellites equipped to detect and discriminate them. Directed-energy satellites could also clear particles from their path--somewhat inefficiently. Better, they could prevent their dispersal by attacking the antisatellite earlier, which could negate the whole concept of particle antisatellites.

Overall, the most effective scenario would be to destroy the anti-satellite before its particles are dispersed, but even this scenario has countermeasures. The dense particles could be deployed early and at an altitude of about 20-50 km where particle beams could not reach them and lasers might not be able to see them at ranges where deployment was shielded by curved-earth effects. In that case, other satellites in the constellation should be in range, although even they would be susceptible to additional countermeasures such as antisatellite booster hardening and decoys, which would be more effective for them than for intercontinental missiles.

V. CONCLUSIONS

This note examines the effectiveness of nonnuclear kinetic energy antisatellites that pop up, explode, and release clouds of particles that drift into the path of satellites, which are subsequently destroyed by running into the particles. Particle antisatellites are the simplest and earliest antisatellites available to an attacker; they are also relatively insensitive to counter-measures. Their pop-up trajectories would give them a mass advantage over the satellite of a factor of about 2; their use in suppression would give them an additional advantage of a factor of 10. They are apparently equally effective over their own territory or accompanying offensive attacks on the other's territory.

Particle sizes and satellite shield masses are coupled, producing antisatellites weighing 5-10 tons. Optimal satellite shielding, maneuver, and deflection lead to shield masses of a few tons and deflections of 5-10 km. The ER scales most strongly on antisatellite mass, range to maneuver, and satellite size. Antisatellite decoys would appear to be very effective against passive sensors, but hey could be offset by directed-energy satellites. Directed-energy satellites could clear the paths of satellites, which would be useful; they could also destroy antisatellites before deployment, which could eliminate the leverage of antisatellites all together.

Overall, satellites can apparently achieve ERs of approximately 4:1 in attrition, which is marginal, and 0.4:1 against suppression, which is unacceptable. The only defensive option that can significantly improve those ratios is to use directed-energy satellites to destroy the antisatellites before they are deployed. However, this option requires detection at long range, very fast reaction, and cooperation between satellites in the constellation. Destroying antisatellites before they are destroyed is also susceptible to additional countermeasures such as antisatellite booster hardening and decoys.

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APPENDIX

SATELLITE AVAILABILITY

If the missile launch area is A_L, so that its effective radius is $W = (A_L/\pi)^{1/2}$, the missile's acceleration plus deployment time, T, and the defender's velocity, V, the defender can reach a missile if it is within range $R = W + V \cdot T$ of the center of the launch area. Near-term values--W = 1,800 km, T = 600 s, and V = 6 km/s--give $R \approx 5{,}400$ km, which would contain a fraction,

$$f \approx zf_u = z\pi R^2/4\pi R_e^{\,2} \approx z[(W+V\cdot T)/2R_e]^2, \qquad \text{(A-1)}$$

of the satellites in the constellation. The earth's radius is $R_e = 6{,}400$ km, f_u is the fraction of the satellites that could reach the launch from a uniform constellation, and $z \approx 2.5/\sqrt{R(\text{Mm})}$ is the factor by which it is possible to increase the concentration of the satellites over the launch area by optimizing their inclinations.[6]

For the near-term parameters above, $f = zf_u \approx 1.08 \cdot 0.18 \approx 0.2$. If in the midterm the attacker decreased W and T by a factor of 2 each, f_u would drop by a factor of about 4 to about 4.5%, but z would increase by $\sqrt{2}$ to about 1.5, and $f \approx 0.07$. Thus, the calculations in the text use an average <z> = 0.1. These geometric estimates agree with near-exact, quasi-analytic solutions to within 10-20%.[7]

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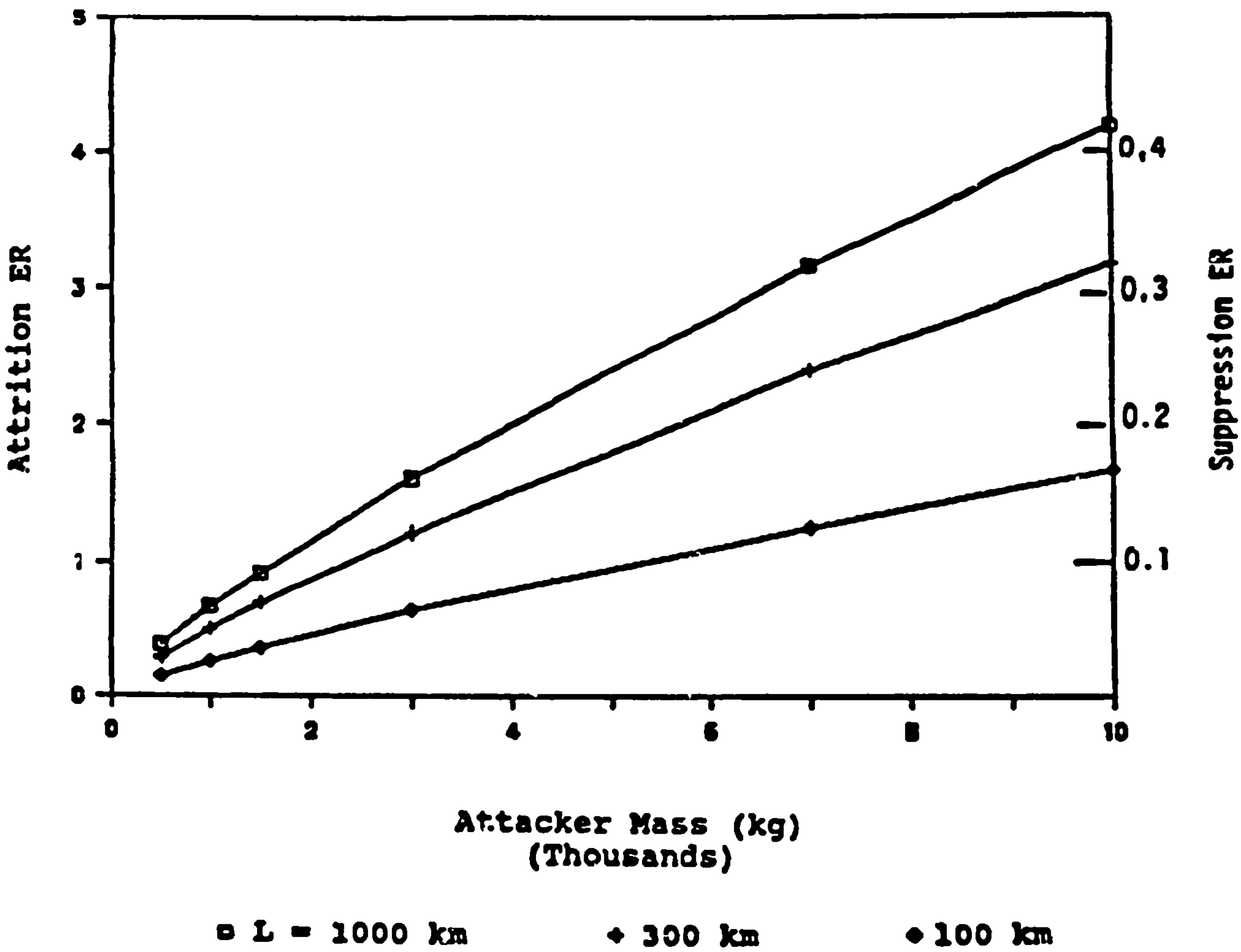

Fig. 1. Defensive Mass Ratio

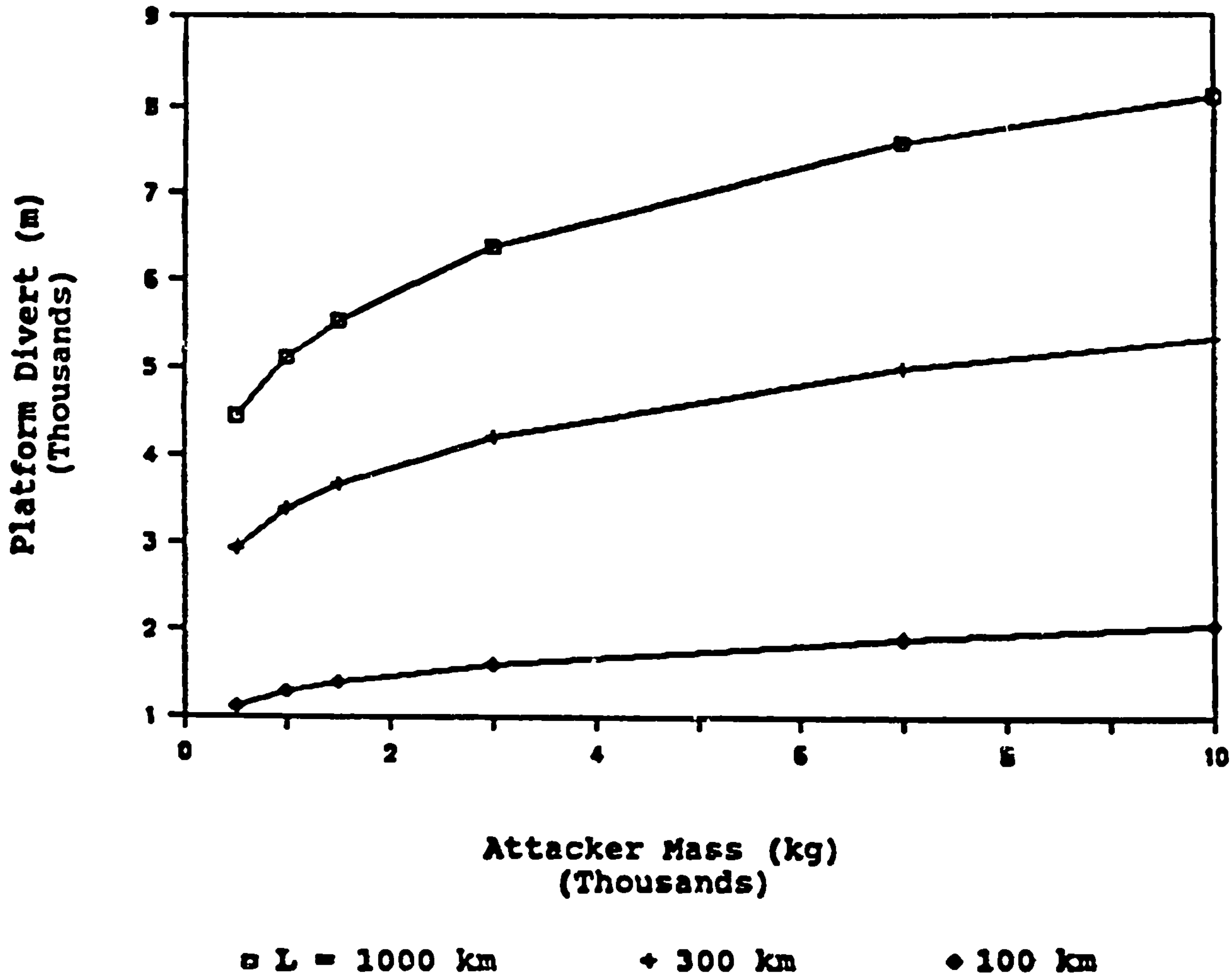

Fig. 2. Defensive Platform Divert

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