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Suppression of Space-Based Interceptors by Neutral Particle Beams

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ABSTRACT

Neutral particle beams (NPBs) popped up before missile launch could irradiate space-based interceptors (SBIs), suppressing those that could effectively attack the missiles. NPB effectiveness could be quite high against unshielded, undecoyed SBIs. The results are sensitive to launch radius, beam brightness, and SBI hardness. Even low-brightness NPBs would be effective in suppressing the threats over compact launch areas.

I. INTRODUCTION

Neutral particle beams (NPBs) that are popped up before missile launch could irradiate space-based interceptors (SBIs) out to ranges of several thousand kilometers from the launch area. Thus, they could impact and possibly suppress essentially all of the SBIs that could participate in the boost-phase defense. NPBs' effectiveness could be quite high against unshielded, undecoyed SBIs.[1] But SBIs would need decoys just to survive antisatellites,[2] and additional shielding against pop-up NPBs need not be prohibitive.[3] Still, if pop-up beams were effective as defenses, they could also be good in defense suppression, although the situations are not completely symmetrical. This report examines their relative effectiveness in the two modes, concluding that the impact of NPBs in defense suppression could be significant.

II. ANALYSIS

Pop-up NPBs can discriminate decoys and kill weapons effectively; doing both could strongly reduce both decoys and weapons.[4] If pop-up NPBs are used for defense suppression, it is straightforward to estimate the number of pebbles killed and show that similar trades can be obtained. For the ≈ 100 decoys needed for a pebble to survive antisatellites, the NPB's discrimination and kill times are about equal. It also holds that if NPBs can strip out their decoys, the bare SBIs would be much easier prey for antisatellites.

SBIs can also be shielded. They are much smaller than reentry vehicles, and their sensitive components could be compacted more. In the absence of NPB suppression, they would use modest shielding in order to minimize their kill package and total masses. NPBs with beam energies of 100-300 MeV could probably be popped up to between 500 and 1,000 km, where they could view and attack all engaged SBIs for the several minutes of launch.

The mass of additional material required to shield against a 100-MeV beam is ≈ 100 kg/m^2; a 200-MeV beam would require about 400 kg/m^2; and a 300-MeV beam ≈ 1 ton/m^2.[5] SBIs have frontal areas of ≈ 0.1 m^2;[6] if 30% of that area was vulnerable, that would give a total area requiring shielding of ≈ 0.03 m^2.[7] Such shielding would require ≈ 100 kg/m^2 x 0.03 m^2 ≈ 3 kg for a 100 MeV beam; and ≈ 12 kg for 200 MeV.

If SBIs could hide behind their shields while they were being irradiated and then discard that shielding mass when they flew out to intercept the offensive missiles, the impact of popping up on the NPBs' cost would be large but tolerable. Shielding would increase a brilliant pebble's orbital mass 10%-100%, but the added mass would largely be bulk material, whose cost would essentially be that of launch. For near-term launch costs of ≈ $6K/kg, the addition to the pebble's cost would be ≈ $20K-80K, which is small compared to that of the pebble. For larger SBIs, the masses, areas, and costs would be proportionally larger, though still small compared to those of their kill packages.

The penalties are more bothersome if the pebbles must remain shielded en route, as would be the case when they faced rapidly retargetable NPBs. Even with high specific impulse fuels, shielded pebble velocities would drop 25%-50% below the ≈ 6 km/s velocities that are optimal for mid- and long-term intercepts in the absence of shielding.[8] That reduction would decrease their availability by a factor of 2-4. Adding more SBIs would restore coverage but would decrease the cost-effectiveness of each by a factor of 2-4, which could be debilitating.[9] Restoring performance would require that the total mass on orbit be increased by a factor of 2-4 (Appendix A).

These penalties would be serious in any case, but they are particularly severe if the SBIs are also penalized by the loss of decoys, which would degrade their survivability. Nuclear antisatellite payload masses are ≈ 400 kg, but their ≈ 20-fold absenteeism reduces their effective masses to ≈ 20 kg.[10] In exchanges with such antisatellites, current ≈ 100 kg SBIs would lose on mass and cost by factors of ≈ 5:1. A 30-kg brilliant pebble would just about break even, which is why they were conceived at a weight that is "too cheap to kill."[11]

With one nuclear intercept for each of the thousands of singlets within range, the SBIs might be hidden well enough to survive.[12] Much lighter "hornets" have been postulated that might be too cheap to kill under these conditions,[13] but SBIs would remain at risk as long as the NPBs could disproportionately increase their shielding penalties by increasing beam energies. The beam energies used for the illustrations above are not limits. A booster can loft ≈ 5 times more payload on a 3 km/s popup trajectory than it can insert into orbit, so essentially any beam energy is available as a popup, and it should be available much earlier in time.

In addition to these gross shielding penalties, NPBs reduce the SBIs survivability during ingress (Appendix B). As the SBIs approach the NPB, they experience a range of fluences. Failure is determined by the integrated dose. The rate and radius at which the SBIs are killed depend on their hardness, number density, and the resulting balance of the rate at which the NPB can kill them and the rate at which the SBIs approach them.

The brightness B needed to keep the SBIs out of a launch corridor of radius W is proportional to $JK(VW)^2T$, or because $V \propto 1/\sqrt{J}$, to KW^2T. Thus, the effectiveness of a given B is increased by compacting the launch in space and time, which is also sought for other reasons. For current launch conditions, a few-hundred-MeV NPB would be required to suppress a full constellation of hardened SBIs. Such an NPB could ideally reduce the SBI kills to 20% of their unsuppressed levels. For superhardened SBIs, a similar number of ≈ 300 MeV platforms would be required.

The number of reentry vehicles successfully deployed by the surviving missiles is sensitive to NPB and SBI parameters. Deployments from the inner rings of the launch area are largely unaffected, but those from the numerous missiles in the outer ring are reduced by factors of 3-10 for typical conditions. Overall, the number of reentry vehicles deployed could be reduced by a factor of ≈ 2, but the remainder is still significantly larger than the number without suppression, which would be about zero. Results are sensitive to the launch area, beam brightness, and SBI hardness. Even modest NPBs could suppress the threats over compact launch areas.

III. CONCLUSIONS

NPBs that are popped up before launch could irradiate SBIs out to several thousand kilometers from the launch area--possibly suppressing the SBIs that would otherwise participate most effectively in boost-phase defense. NPBs should be quite effective against unshielded, undecoyed SBIs; but their ability to efficiently strip decoys and kill the weapons found should make them effective against advanced threats and even heavily shielded SBIs.

Shielding against modest NPBs would significantly increase SBI kill-package masses, which could decrease their velocities, reduce their availability, and degrade their cost-effectiveness by factors of 2-4. The effectiveness of modest brightnesses is increased by compacting the launch in space and time, which is sought for other reasons. The removal of their decoys would also significantly degrade the SBIs' survivability, particularly during ingress, ideally reducing their missile attrition to 20% of unsuppressed levels.

With suppression, the number of reentry vehicles deployed could be reduced by a factor of 2, but that number is to be compared with that for deployment against unsuppressed SBIs, for which the number deployed is essentially zero. Results are sensitive to launch areas, beam brightness, and SBI hardness, but even modest NPBs could suppress the threats over compact launch areas.

ACKNOWLEDGMENT

The author would like to acknowledge useful discussions with Dr. Edward Teller, who brought the subject of defense suppression with popup NPBs to his attention and pursued the matter even after initial results were negative. This report is dedicated to Dr. Teller on his 82nd birthday.

APPENDIX A. SBI SHIELDING

For a small rocket with an effective specific impulse of 250 s, or an effective exhaust velocity of $c \approx 2.5$ km/s, the rocket equation relates rocket mass M to kill package mass m by

$$V/c = \ln[(M+m)/m], \qquad \text{(A-1)}$$

which for $M/m \approx 10$ gives $V = c \cdot \ln(11) \approx 6.0$ km/s for the optimal velocity for mid- to long-term SBIs.[14] Nonidealities such as the rocket's structural fraction and staging are absorbed in c, which is smaller than that of the actual fuels.

The SBI must be shielded enough to cut the penetrating beam down to the lethal fluence J(J/cm^2) of its weakest component. That fluence is roughly the product of the specific energy j(J/g) needed to kill that component and the range L(g/cm^2) particles must penetrate to reach it. Thus, the range increases with beam energy E(MeV) roughly as

$$L \approx k \cdot E^{7/4}, \tag{A-2}$$

where for proton beams, $k \approx 3.3 \cdot 10^{-3}$ g/cm^2-MeV$^{7/4}$. If the SBIs' initial areal density including the vulnerable components is σ,

$$J = j(L + \sigma), \tag{A-3}$$

where j(J/g) ≈ 10-100 J/g is the range of energy depositions required to kill hardened electronics or structural materials.[15]

If the SBI's vulnerable area is $\Phi \approx 0.03$ m^2, the mass of the shielding is $(L+\sigma)\Phi$. For $\sigma = 1$ g/cm^2 and E = 100 MeV, L ≈ 10 g/cm^2, and the shielding mass is ≈ (10+1 g/cm^2)·0.03 m^2 ≈ 3 kg.

If the mass can be discarded before the SBI flies in, the penalty for 100-MeV beams is $\approx L \cdot \Phi \approx$ 3 kg of bulk launch mass. That amounts to roughly 3 kg·$6K/kg ≈ $20K, or 5%-10% of a SBI's cost. If the SBI must carry its shielding with it while it approaches the missiles, the shielding adds directly to the payload mass, whose velocity is degraded to

$$V/c = \ln[(M+m+L\Phi)/(m+L\Phi)]. \tag{A-4}$$

Current SBI designs have kill-package masses of ≈ 10 kg; masses of ≈ 1 kg are suggested[16] for brilliant pebbles.[17] For an interim value of m ≈ 3 kg, the $L\Phi \approx$ 3 kg mass penalty for 100-MeV beams would roughly double the payload. That would decrease V to ≈ c·ln(36/6) ≈ 4.5 km/s, a 25% reduction. That would decrease the fraction of SBIs within range by about a factor of 2 and degrade their cost-effectiveness by a like amount.

Alternatively, the rocket's size could be doubled to maintain V, at a cost of a factor of ≈ 2 in rocket size and, hence, launch mass and mass in orbit. For 200-MeV beams, the mass penalty would be ≈ 12 kg; the velocity would fall to ≈

$2.5 \cdot \ln(45/15) \approx 2.7$ km/s; and the SBI cost-effectiveness would fall by about a factor of 4.

APPENDIX B. SBI EFFECTIVENESS

A NPB of brightness B can kill a weapon at range r that is stripped of its decoys in a time $J/(B/r^2)$; discrimination and switching between targets take similar but smaller times. Thus, the NPB can kill all SBIs out to range R in a time

$$T = \Sigma_0^R \, dr \, 2\pi r \, K''J/(B/r^2)$$
$$= 2\pi \, K''(J/B)R^4/4, \qquad \text{(B-1)}$$

where K" is the density of SBIs in the constellation. If there are K SBIs, $K'' = zK/4\pi R_e^2$, where R_e is the earth's radius and z is the concentration of the constellation possible over land launch areas.[18] If the launch area's radius is W, the SBIs' velocity V, and the missiles are vulnerable for time T during boost and deployment, then $z \approx \surd(W+V\cdot T)$, where W and $V\cdot T$ are measured in thousands of kilometers.[19]

To completely suppress the SBIs, the NPB need only destroy those out to $R = W + V\cdot T$, because those further away could not reach the missiles in any case. Then Eq. (B-1) can be inverted to give

$$B = (zK/8R_e^2)(J/T)(W+VT)^4, \qquad \text{(B-2)}$$

which is analogous to the result obtained for predeployed directed energy platforms interior to the launch area.[20] For typical parameters (K = 5,000, J = 1 Mj/m^2, and T = 300-600 s), the current W = 1,800 km and V = 6 km/s give brightnesses of a few times the $B \approx 10^{18}$ W/sr of a single 100-MeV pop-up NPB.

During the SBIs' ingress, the SBIs experience a range of fluences. Failure is determined by their integrated dose, i.e.,

$$J = \Sigma_0^\theta \, dt \, B/r^2, \qquad \text{(B-3)}$$

where θ is the time when it fails. The rate and radius at which the SBIs are killed depend on their hardness and number density. The radius is determined by the balance of the rate at which the NPB can kill them and the rate at which they flow in. The number that could be killed in time δt at r is $B\cdot\delta t/Jr^2$. The rate of inflow there is $V\cdot K(r,t)$, where K(r,t) is the number of SBIs at radius r at time t. Those SBIs are from a ring of width dr = $V\cdot\delta t$ at radius r + VT at t = 0. Thus, $K = K''2\pi(r+VT)V\delta t$. Equating the two gives

$$B = 2\pi(zK/4\pi R_e^2)(r+VT)VJr^2, \qquad \text{(B-4)}$$

as the brightness needed to keep the SBIs outside of range r. Setting r = W gives the minimum brightness needed to keep the SBIs out of the launch corridor. Although B is bilinear in K and J, the scaling on T and R is weaker than in the static estimate of Eqs. (B-1) and (B-2).

Figure 1 shows B versus r for K = 5000 (i.e., enough SBIs to completely negate the launch in the absence of suppression), J = 1 MJ/m^2 (i.e., SBIs with j = 10 J/g, the 10 g/cm^2 appropriate for a 100-MeV beam), and the corresponding V ≈ 4.5 km/s velocity. The three curves are for 200, 400, and 600 s into the launch. The lowest shows that for 200 s, $B \approx 2.5 \cdot 10^{18}$ (which is about the brightness of one to two 100-MeV pop-ups), would be required to clear the current W ≈ 1,800 km. By the end of current T = 600 s launches, the radius the NPBs could clear would drop to ≈ 1400 km due to the VT scaling of Eq. (B-4).

For an average radius of 1600 km, if the missiles were distributed uniformly over the launch area, the fraction of the missiles killed would be $\approx 2\pi r dr/\pi r^2 = 2dr/r \approx 2 \cdot 200$ km/1800 km ≈ 20%, which would amount to a factor of ≈ 5 reduction in SBI effectiveness.

Figure 2 shows B versus r for J = 10 MJ/m^2 (i.e., the 100 g/cm^2 for a 300-MeV beam) and the corresponding 2.7-km/s velocity. The shapes of the curves are similar to those in Fig. 1, but the values are increased by about a factor of 5, i.e., they increase as the product $J \cdot V$. Clearing 1800 km would still require about 2-4 NPBs, but with 10-fold brighter 300-MeV beams. Just one beam of $5 \cdot 10^{18}$ W/sr could keep a W ≈ 1000 km launch area clear throughout the boost phase.

Figures 1 and 2 show the location of the killing radius, but they do not directly account for the missiles killed. Figures 3-6 show that accounting for 1000 missiles that are vulnerable for 600 s launched from a W = 1800 km radius area, which are essentially current conditions. The calculations are for K = 5000, J = 10 MJ/m^2, and V = 6 km/s, that is, it is assumed that the SBIs are shielded, but their rocket thrust is increased to maintain performance.

Figure 3 shows the SBI kills, which peak at ≈ 60 kills during 100 s at 1200 km when the interior SBIs are being cleared and then ≈ 35 kills per 100 s around r = 1800 km for the rest of the launch as the NPBs kill about 30% of the SBIs crossing the outer radius of the launch area. This radius is about twice that on Fig. 2, but the velocity is about two-fold higher.

Figure 4 shows the distribution of SBIs, which drops rapidly at the kill radius. Figure 5 shows the missile kills there, which increase from ≈ 70 per 100 sec at 100 s to ≈ 140 at 500 s and then drop sharply as the missiles in the outer ring are exhausted.

Figure 6 shows the number of weapons deployed. The upper, straight line is the number that would be deployed in each 100-s interval after the 300-s boost phase in the absence of SBIs. They add up to 10,000 reentry vehicles by 600 s. The next curve is the number deployed between 300 and 400 s by the surviving missiles, given the defense suppression indicated above. The deployments by the inner rings are unaffected, but those from the numerous missiles in the outer ring are down by about a factor of 3. By 500 s, the depression is a factor of 10, and by the end of deployment at 600 s, it is completely shut off.

Overall, for these conditions the number of reentry vehicles successfully deployed is about 5000. That is only about half the no-SBI value, but it is significantly larger than the value without suppression, which is about 0. The results are sensitive to the launch radius, beam brightness, and SBI hardness. The conditions shown here were chosen to illustrate the sharp cutoffs in SBI penetration and missile kills. Less-bright NPBs would be effective in suppressing the threats over compact launch areas.

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Fig.1. Brightness for keepout: hardened SBI

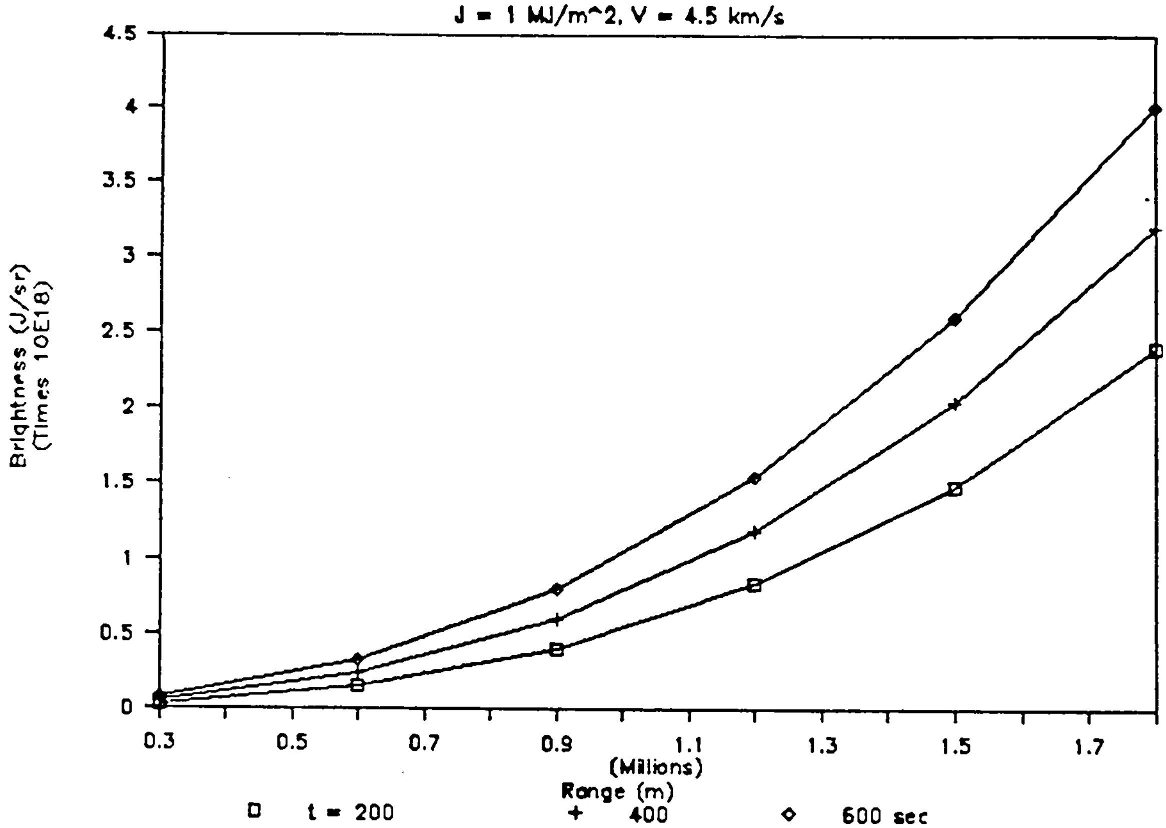


Fig.2. Brightness for keepout: hardened SBI.

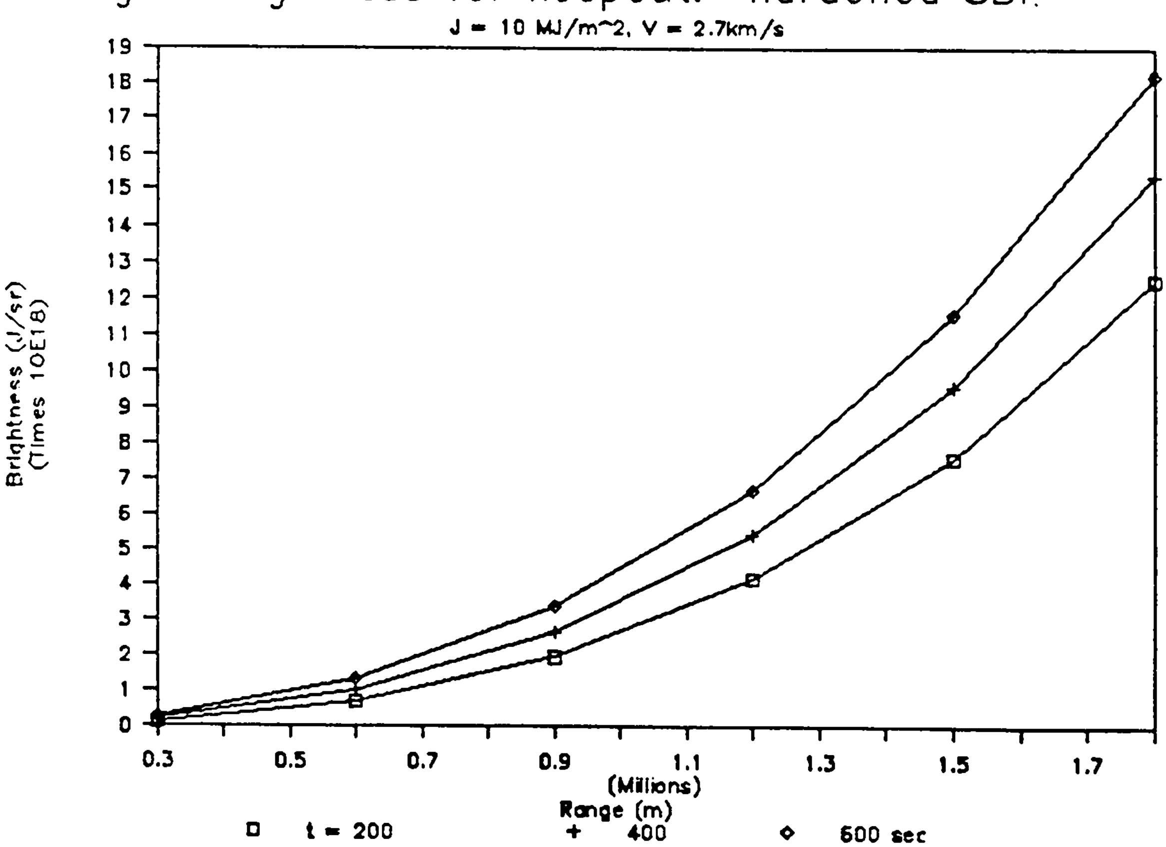


Fig.3. SBI kills.

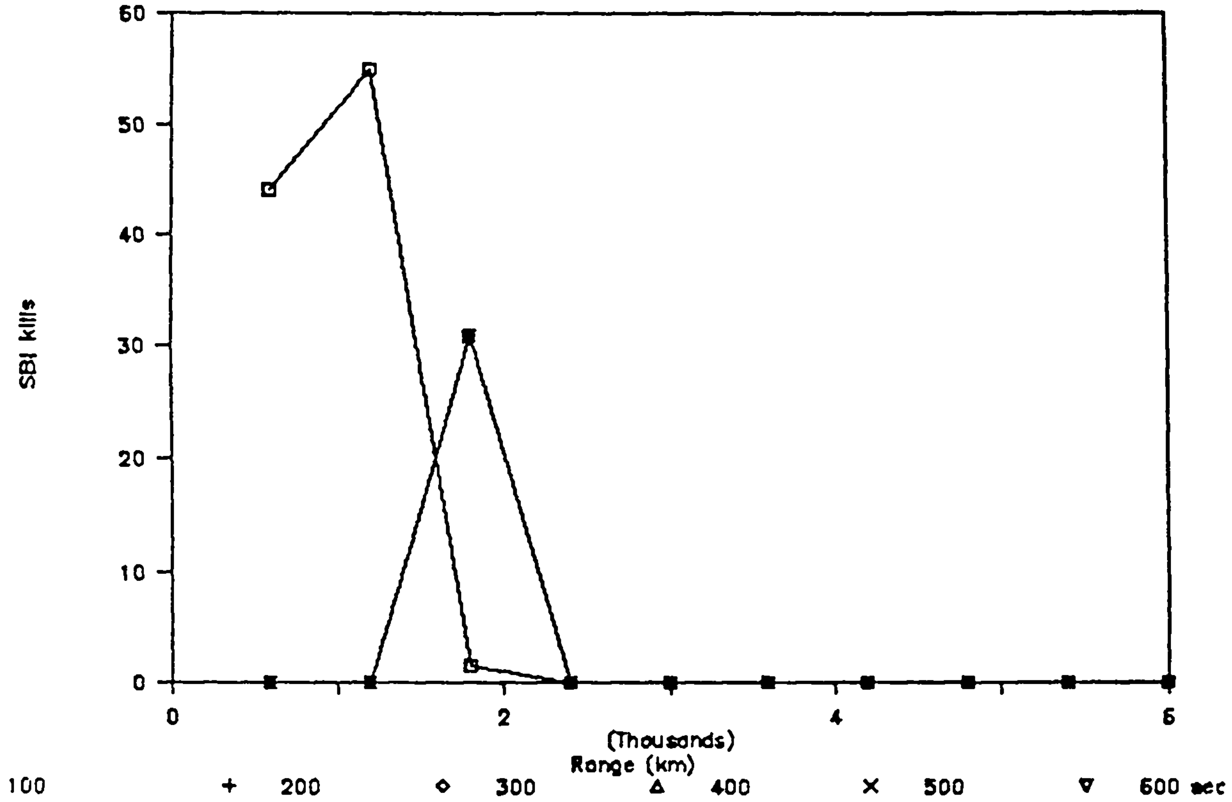


Fig.4. Space-based interceptor distributions.

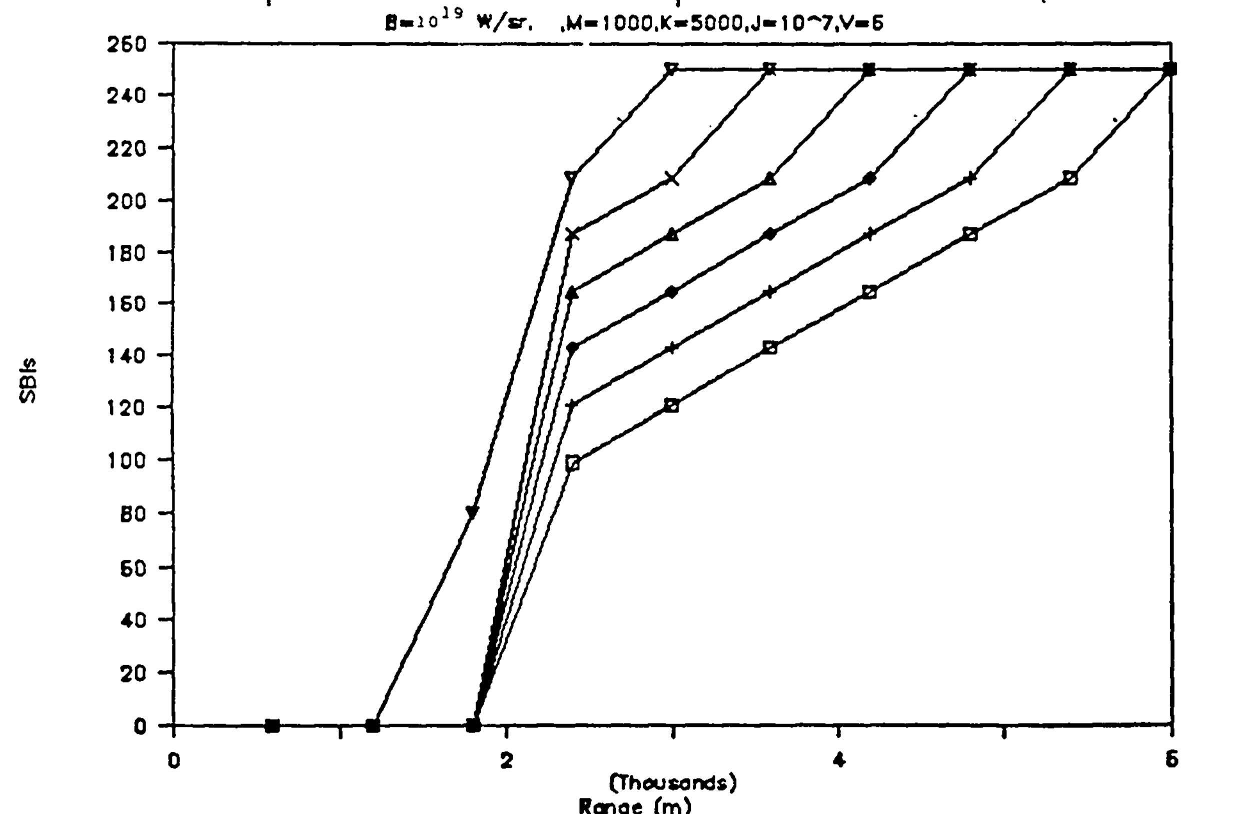


Fig.5. Missile kills

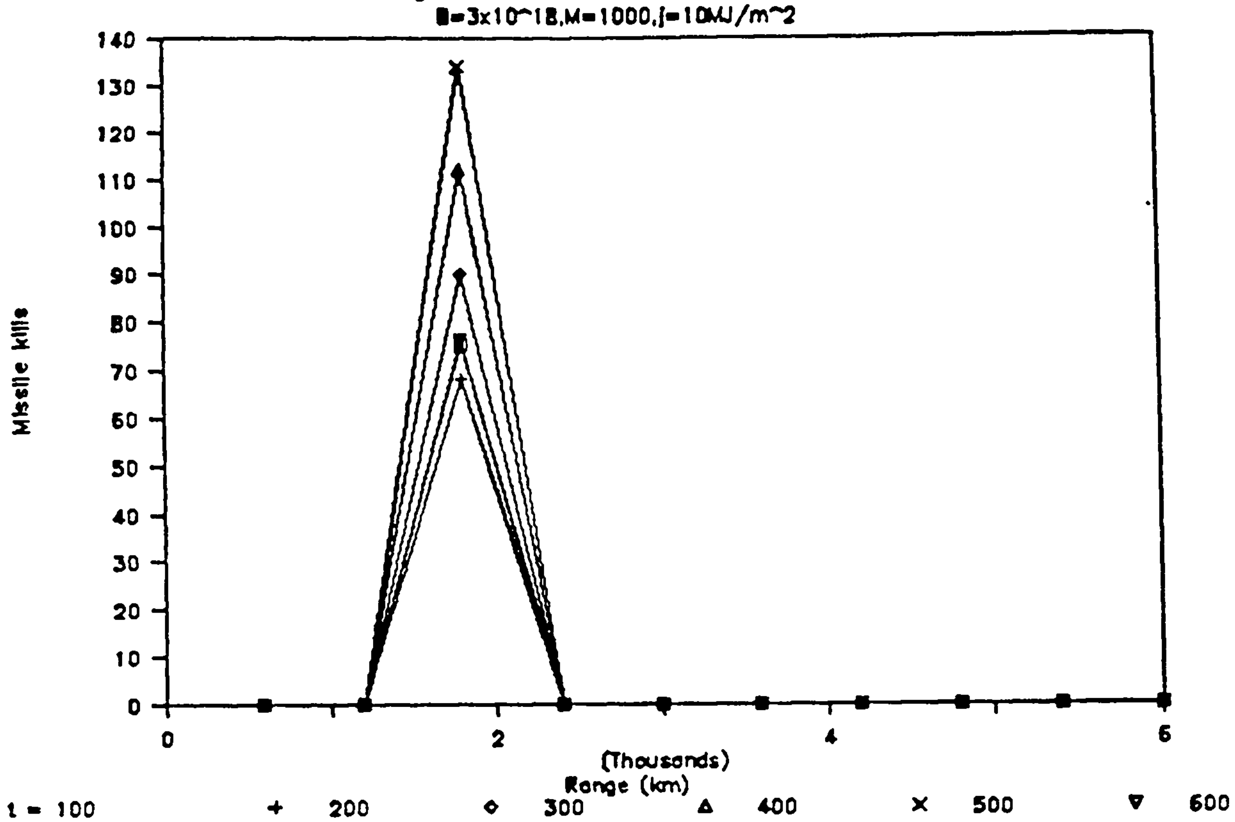
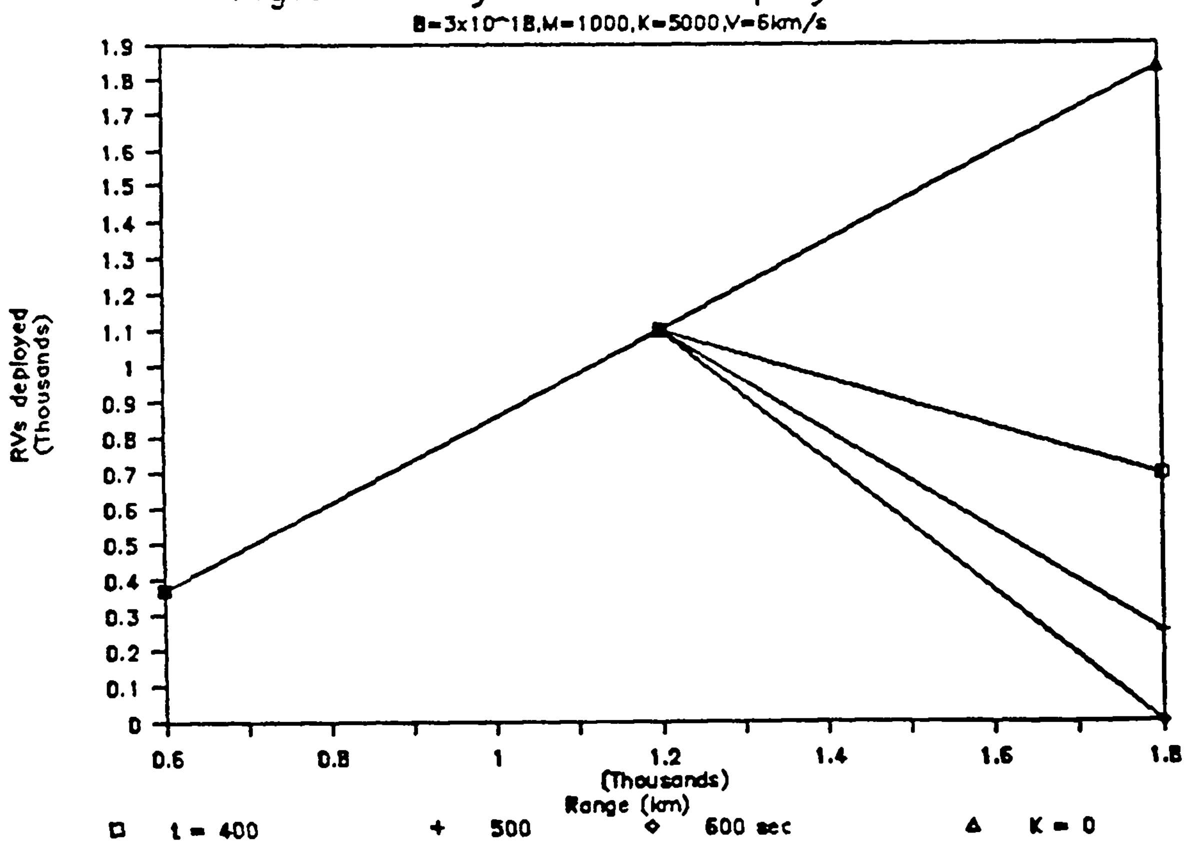


Fig.6. Reenty vehicles deployed



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