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An Entry-Level Conventional Radar-Driven Rocket Anti-Satellite

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AN ENTRY-LEVEL CONVENTIONAL RADAR-DRIVEN ROCKET ANTI-SATELLITE

by

Gregory H. Canavan

ABSTRACT

Simple anti-satellites (ASATs) can be based on current, conventional technology available to most countries today. ASATs based on radar-guidance could release pellets in front of a satellite to destroy it or consume its maneuver fuel. The relationship between satellite mass and area is fixed, as is that with altitude. Sensor satellites should be large and high; non-sensor satellites should be small. The optimized radar powers and areas and ASAT masses are in the range of components now in commerce, which suggests that they could be developed and used soon.

I. INTRODUCTION

Anti-satellite (ASAT) systems based on current hit-to-kill technology will probably be widely available within a decade.[1] This note discusses even simpler ASATs based on current, conventional technology that is available to most today.

II. ENTRY-LEVEL ASAT

The ASAT discussed here is based on the radar-guided release of pellets in front of a satellite to destroy it or consume its maneuver fuel so that it will be vulnerable on subsequent passes.

The ASAT rocket is assumed to be guided by radar to a point at which it releases N_P pellets, each of mass m_P. Their total mass is $M_P = N_P \cdot m_P$.

A satellite of mass M_S and average density μ has dimension $\approx (M_S/\mu)^{1/3}$ and area $A_S \approx (M_S/\mu)^{2/3}$. To destroy it the pellets must have areal density $\approx 1/A_S$, which means the pellets can cover an area

$$A_P \approx A_S \cdot N_P \approx (M_S/\mu)^{2/3} \cdot M_P/m_P. \qquad (1)$$

For M_S = 10 ton and $\mu \approx 300$ kg/m^3, $A_S \approx 10.5$ m^2. For M_P = 1 ton and m_P = 0.1 kg, $M_P/m_P \approx 10^4$ particles. For these parameters, $A_P \approx 0.1$ km^2, a significant area.

III. RADAR

To hit the satellite, the pellets must be placed in front of it. This section explores the requirements that places on the ASAT radar.

A. Beam Division

To arrive in front of the satellite, the rocket must be aimed to an angular precision of

$$\phi \approx \sqrt{A_P}/R, \qquad (2)$$

where R is the range to the intercept. For R = 500 km, $\phi \approx 1$ mrad. A radar of aperture area A has a diffractive beam spread $\theta_D \approx w/\sqrt{A}$, where w is the radar wavelength. For X-band and A ≈ 3 m, $\theta_D \approx 0.03$ m/3 m ≈ 10 mrad, which is about 10 times ϕ. It should, however, be possible to take advantage of high signal to noise, i.e., large power and aperture, to divide the beam to about this extent. For signal-to-noise ratio S/N, the beamwidth is[2]

$$\theta \approx w/2\sqrt{(A \cdot S/N)}. \qquad (3)$$

For S/N ≈ 25, $\theta \approx \phi$. Equation (3) can be set equal to ϕ and inverted to find the S/N required for adequate beam division

$$S/N \approx (Rw)^2/(4A_P \cdot A), \quad (4)$$

which scales strongly on R^2, but also inversely on A and M_P.

B. Radar Scaling

The radar equation is[3]

$$P = 4\pi\Omega R^4 kT_R L(S/N)/TA\sigma, \quad (5)$$

where Ω is the solid angle searched, $T_R \approx 100^oK$ is the noise temperature of the radar front end, k is Boltzmann's constant, L $\approx$ 10 is a system loss, T is the time for search or track, and σ is the target cross section. For track, $\Omega \approx \theta_D{}^2$, and

$$S/N \approx PTA\sigma/4\pi\theta_D{}^2 R^4 kT_R L. \quad (6)$$

IV. ANALYSIS

This section determines the parameters needed for successful beam division. It also optimizes the ASAT and satellite for attack and survival, respectively.

A. Closure

The radar power and aperture needed for successful division can be determined by equating Eq. (6) to Eq. (4) to find

$$PA^3 \approx 4\pi R^6 kT_R Lw^4/4A_P T\sigma$$

$$PA^3 M_P \approx 4\pi R^6 kT_R Lw^4 m_P(\mu/M_S)^{2/3}/4T\sigma. \quad (7)$$

In this equation the attacker controls P, A, M_P, and w. The defender controls m_P by hardening, M_S by reducing the size of the satellite, σ by reducing observables, R by increasing deployment altitude, and T by maneuvering throughout the ASAT's approach.

B. Optimization of ASAT

The ASAT's main parameters appear in the combination

$$J \equiv PA^3 M_P, \quad (8)$$

P, A, and M_P can be costed on a common basis. Radar power costs p $\approx$ \$100/watt; radar aperture costs a $\approx$ \$10M/m^2; and ASAT payload mass on sounding trajectories costs m $\approx$ \$5K/kg. Their costs are additive, so the total attack cost is

$$C \approx pP + aA + mM_P, \quad (9)$$

which is minimized by the choice

$$P = mM_P/p = aA/3p. \quad (10)$$

For the optimum ASAT, J reduces to

$$J = PA^3M_P = P(3pP/a)^3(pP/m) = (27p^4/a^3m)P^5, \quad (11)$$

for which Eq. (7) becomes

$$P_{opt} \approx [4\pi a^3 mR^6 kT_R Lw^4 m_P(\mu/M_S)^{2/3}/108p^4 T\sigma]^{1/5}, \quad (12)$$

from which optimal A and M_P can be derived.

C. Optimization of Defender

The defender ostensibly controls m_P by hardening, but in practice it is set by the size of pebble that is convenient for the ASAT to deploy. Below it is assumed that that is $m_P \approx 100$ g.

Observables can only be reduced so much for low-altitude satellites, which are continually observed from many angles with many phenomenologies.[4] Thus, σ scales as $\sigma \propto (M_S/\mu)^{2/3} \propto M_S{}^{2/3}$.

R is not completely independent either. For a sensor satellite, the diameter of the sensor's entrance, and that of the satellite, increases with altitude and R. The sensor--and satellite--mass increases as roughly the cube of the sensor's aperture, so the satellite's mass scales as $M_S \propto R^3$. In Eq. (7) these parameters occur in the combination

$$R^6/\sigma M_S{}^{2/3} \propto R^6/M_S{}^{4/3} \propto M_S{}^2/M_S{}^{4/3} \propto M_S{}^{2/3}. \quad (13)$$

Thus, a sensor satellite's survivability against this type of ASAT is best served by making the satellite large and keeping it at a correspondingly high altitude.

Note, however, that for non-sensor satellites, M_S is essentially independent of R,[5] so the survivability parameter of Eq. (13) is proportional to $R^6/M_S{}^{4/3}$, which is maximized by minimizing M_S for whatever R produces the required effectiveness.

The defender can also control T by maneuvering throughout the ASAT's approach, which makes the intercept much more difficult. The satellite could move out of the way of the cloud of pellets by generating a transverse acceleration a_T such that

$$a_T T^2/2 > \sqrt{A_P}, \quad (14)$$

but that would require an acceleration of

$$a_T \approx 2\sqrt{A_P}/T^2. \quad (15)$$

If the ASAT could respond on a time scale of $T = 1$ s, for $A_p \approx 0.1$ km^2, that would take an acceleration of $2 \cdot \surd 0.1$ km^2/1s$^2 \approx 65$ g's. That might be tolerable for small, specially constructed satellites, but would probably be beyond the capabilities of large ones. However, from Eq. (12), $P_{opt} \propto 1/T^{1/5}$, so $T \approx 1$ s is carried as a parameter below.

V. RESULTS

Figure 1 shows P_{opt} as a function of satellite mass M_S for the parameters used in illustrations above. The power is about 30 KW for 500 kg satellites. By Eq. (12) it scales only as $(1/M_S{}^{4/3})^{1/5} = 1/M_S{}^{4/15}$, which is not strong. For a 50 kg "brilliant pebble," the power would increase to $10^{4/15} \cdot 32$ KW ≈ 60 KW, which is appreciable. For a 50 ton satellite the power would decrease to $0.01^{4/15} \cdot 32$ KW ≈ 10 KW, which is within the capabilities of commercial units.

Figure 2 shows the ASAT radar area as a function of M_S. For $M_S = 500$ kg it is about 1 m^2; for 5 tons it drops to about 0.6 m^2. Figure 3 shows ASAT mass, which drops from about 600 kg to about 400 kg, because the larger satellites are assumed to be easier to locate.

The strongest scaling in Eq. (12) is $P_{opt} \propto R^{6/5}$, as shown in Fig. 4 for a $M_S = 1$ ton satellite. P_{opt} increases from about 10 KW at 200 km to about 130 KW at 1,800 km. Figure 5 shows ASAT area A, which increases from 0.3 to 3.7 m^2, which are typical of radars in commerce. Figure 6 shows ASAT payload mass M_P, which increases from 200 to 2,600 kg, which can be lifted by simple rockets.

The attacker can also impact range. For a given satellite altitude, h, the intercept range is a combination of altitude and cross-range r: $R = \surd(r^2 + h^2)$. The satellite can choose h, but the attacker can minimize R by minimizing r, which he does by using a number of ASATs and distributing them over his territory. That also produces redundancy, which improves the survivability of the whole ASAT system. For a satellite altitude of 500 km and a cross range of 200 km, $R \approx 540$ km, so in practice the intercept range need not be much greater than the satellite altitude over countries of 500-1,000 km dimensions.

VI. SUMMARY AND CONCLUSIONS

This note discusses simple ASATs based on current, conventional technology that is available to most today. The ASAT is based on the radar-guided release of pellets in front of a satellite to destroy it or consume its maneuver fuel. The ASAT is assumed to be guided by radar to a point at which it releases its pellets. The satellite mass and density determine the area that must be covered. That determines the ASATs precision and mass. The required beam division could be accomplished with commercial radars.

The ASAT can optimize power, aperture, and ASAT mass. The relationship between satellite mass and area are essentially fixed. So is that with altitude, for sensor satellites, which should be large and high. Non-sensor satellites should be small. Track time is largely set by the ASAT bandwidth.

The resulting optimized powers are in the tens of kilowatts. Radar areas are a few square meters. ASAT masses are a few hundred kilograms. All are in the range of components now in commerce. That suggests that such ASATs could be developed and used soon, ending the utility of large, low-altitude satellites.

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4. G. Canavan and E. Teller, "Strategic defence for the 1990s," Nature, Vol 344, pp. 699-704, 19 April 1990.

5. G. Canavan and E. Teller, "Strategic defence for the 1990s," op. cit.

Fig. 1 ASAT power versus satellite mass

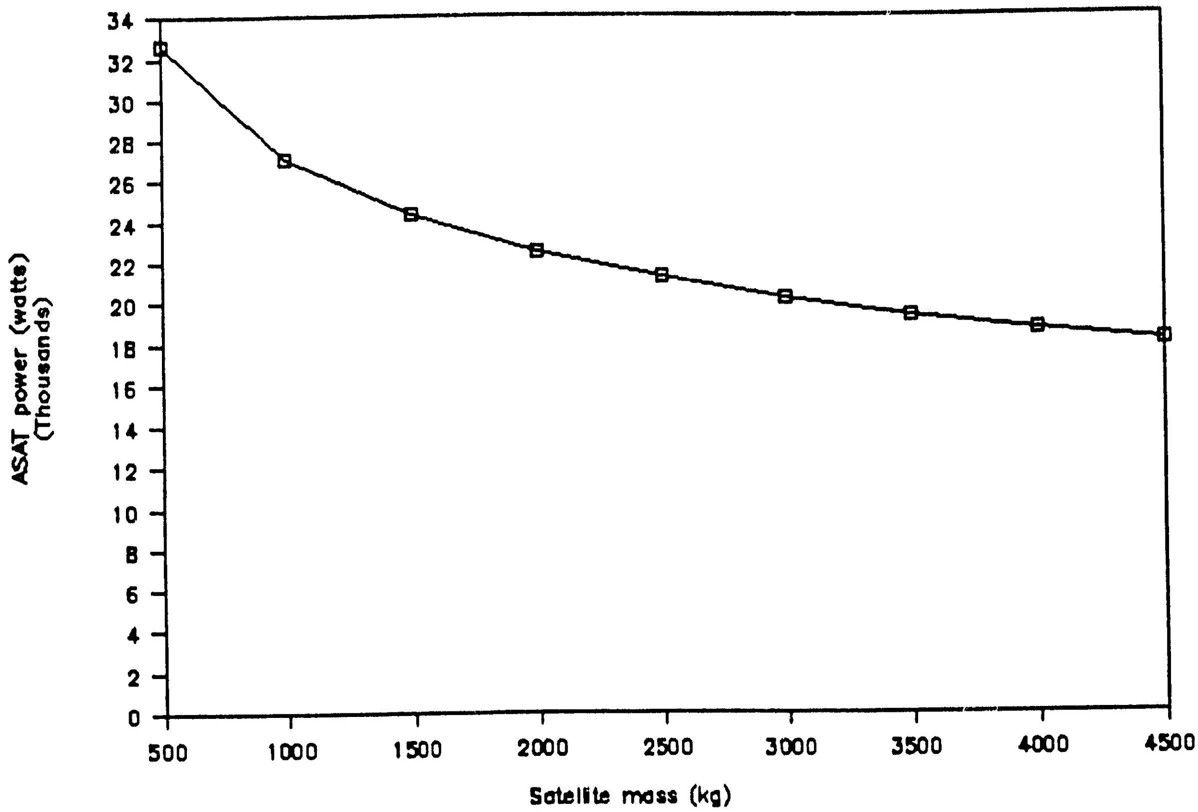

Fig. 2 ASAT radar area versus sat. mass

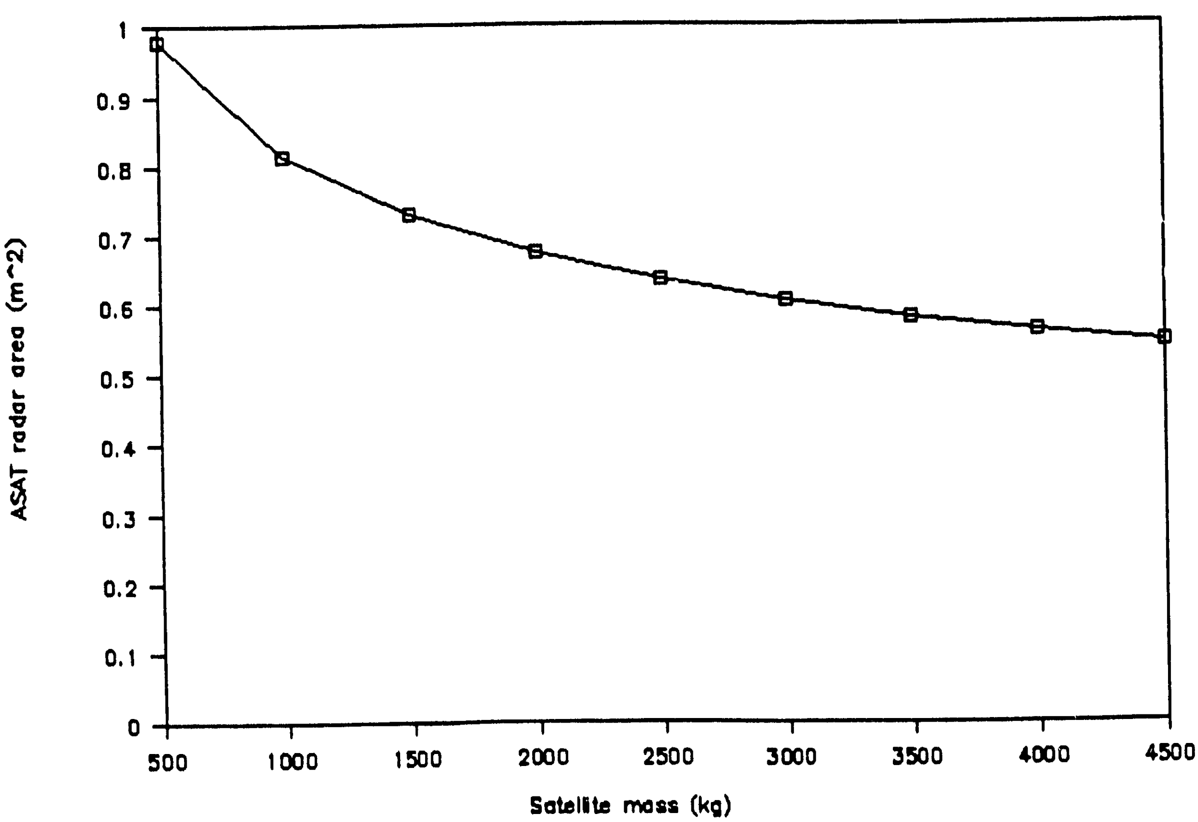

Fig. 3 ASAT mass versus satellite mass

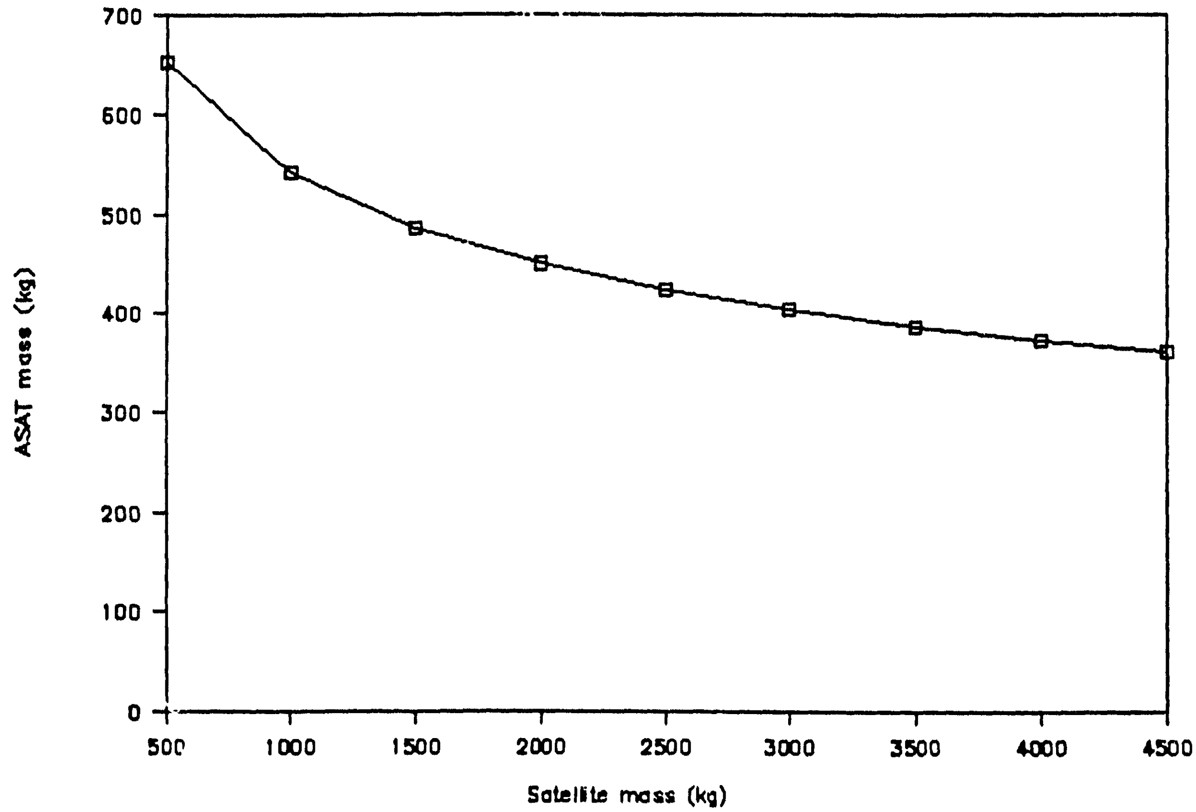

Fig. 4 ASAT power versus altitude

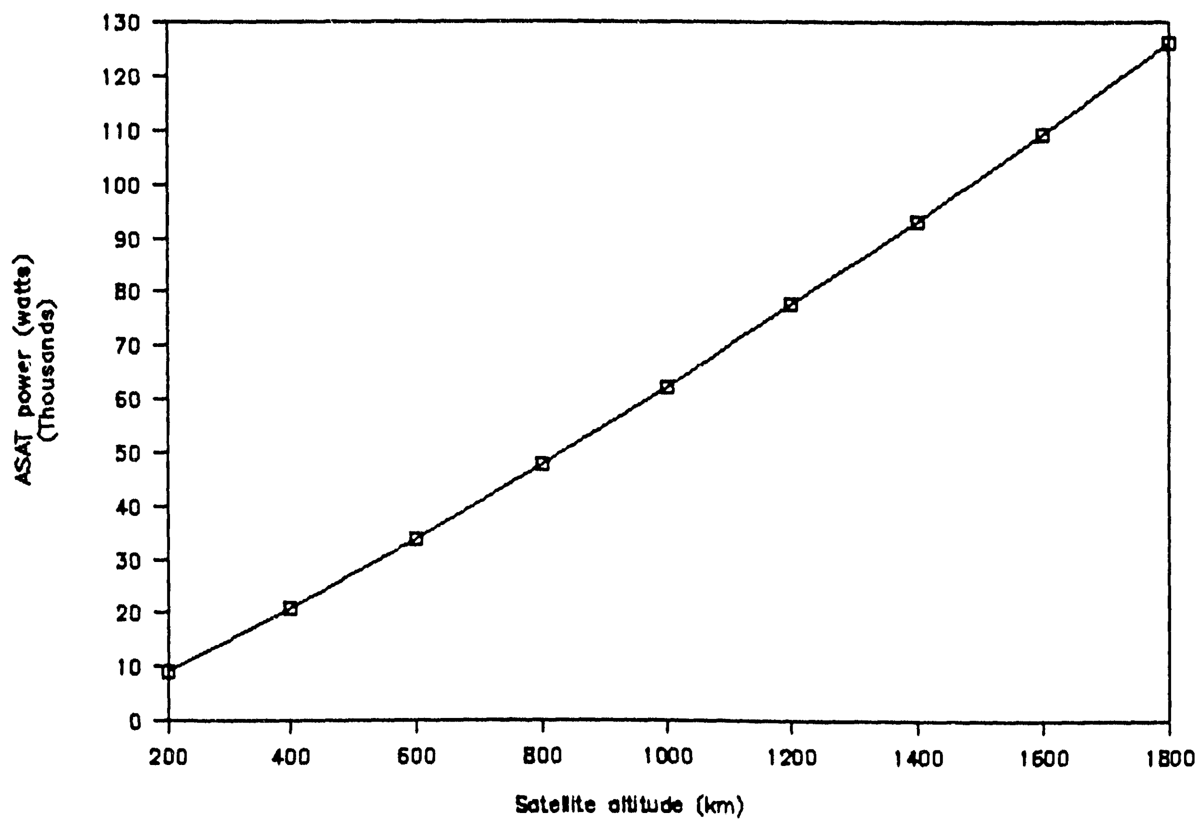

Fig. 5 ASAT area versus range

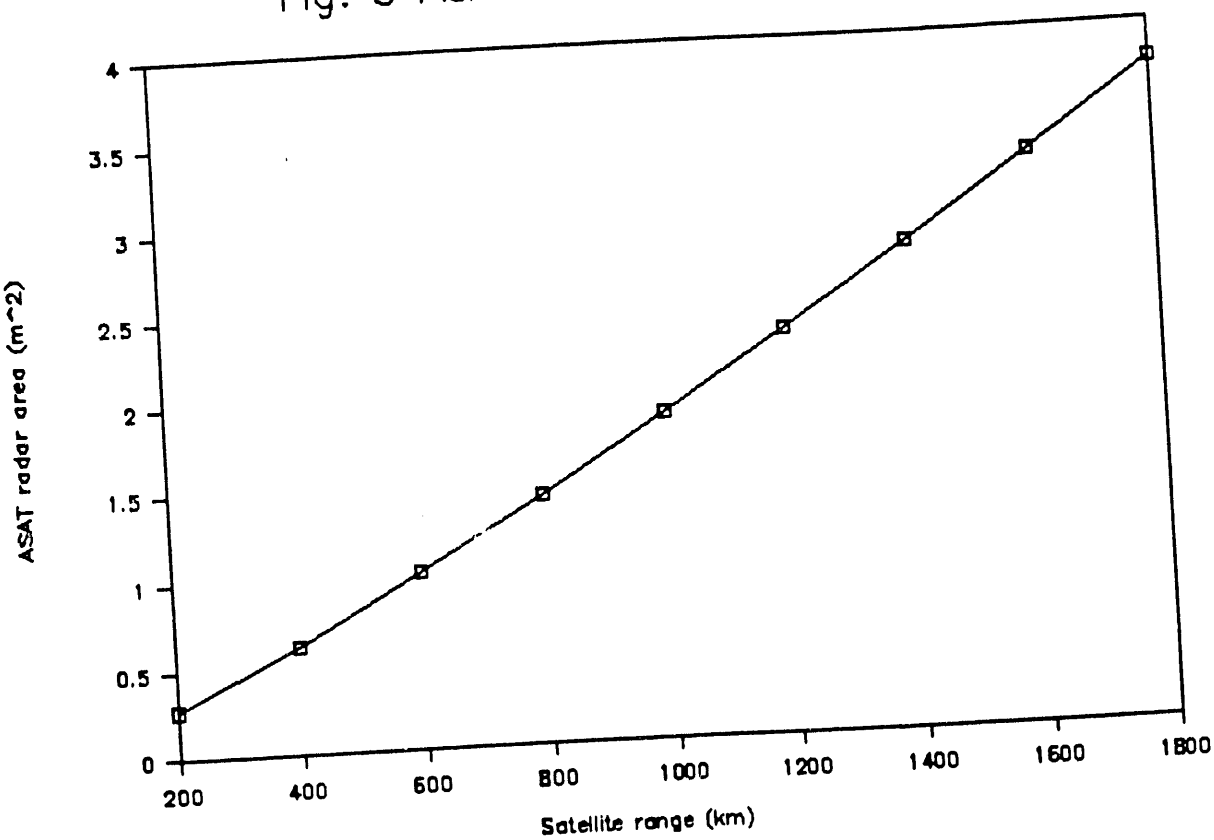

Fig. 6 ASAT mass versus range