

# GAS-BLAST ORBIT MODIFICATION

Guy F. Cooper<sup>1</sup>, Quality Innovative Solutions, Inc., Oxnard, CA

**[Abstract] An Interceptor Missile is described that can gently, or not so gently, change the orbit of an object in space without docking with it. To do this, the shape, mass properties, and vacuum gas-blast “aerodynamics” of the target object must first be determined. As a proposed new Target sensor, the missile’s rocket motor exhaust flow, in combination with a bore-sighted pulse doppler radar, is used; in turn enabling precise aiming and timing of a primary exhaust blast to alter the target’s rotation and/or orbit. The target is characterized by flowing low density exhaust particles over it while the pulse doppler radar observes the spatial pattern of the exhaust particle departure velocity. At a stand-off distance of a few hundred feet, the exhaust particles consist of cold, low density free molecules moving in diverging straight lines, achieved by briefly firing a hybrid rocket motor at minimal thrust setting. The resulting radar image is computer-analyzed to identify and characterize the target. The “aerodynamic” center and “CG” of the target are computed for an aim point to deliver a pure translational impulse, important if the target is unwanted space junk or a dangerous asteroid. Finally, the Interceptor Missile stands-off a proper distance, is aimed, and a full-power rocket motor exhaust gas-blast delivers the desired impulse to the target. Such a target “object” may be a rock pile, or a cloud of debris. Target “porosity” is estimated by computer analysis of the doppler radar image. The “porosity” of man-made objects (antennae, structural members, external electronic boxes, etc) and natural objects are estimated and used for identification. Missions include spin-up, or de-spin of a target for space rescue/recovery where direct docking is impossible with a spinning manned, or high-value satellite or capsule. Target flexibility, due to distributed structures such as antennas, connecting beams, inflated balloon reflectors, etc., can be characterized with a light exhaust blast. Use of a rocket exhaust plume to deliver an impulse to a target object without damage is justified because of the surprisingly rapid radiation cooling of the plume, resulting in a “space chilled” gas-blast. In addition to near isentropic expansion of the gases into space; black body radiation cooling of carbon particles of an assumed size represent the dominant chilling mechanism. After traveling a few hundred feet, the temperature of a carbon particle in the exhaust plume is well below normal room temperature. Thus, no meaningful heating of the target object occurs. Unless there are sizeable particles, almost no sensible exhaust impact should be felt by a space target, other than a gentle push, as felt from a “leaf blower”. A “thrust reverser” is described that captures some exhaust flow to direct it forward, providing a counter-thrust holding the missile in the target’s vicinity longer, for more efficient use of a few missiles. This paper justifies testing, design, and use of a rocket exhaust blast as a space “leaf blower”.**

<sup>1</sup>Senior Engineer, AIAA Senior Member

## Nomenclature

$A_e$	=	Area of rocket exhaust or gas-blast source area
$A_t$	=	Effective cross-section area of rocket exhaust plume at target
$A_{tr}$	=	Total frontal area of Thrust Reverser
$A_{tgtq}$	=	Area of central hole in Thrust Reverser for target impingement flow
$a_r$	=	Acceleration of rocket
$a_t$	=	Acceleration of target
$C_D$	=	Drag coefficient of target
$D_t$	=	Drag force felt by target
$d$	=	Total distance from rocket to target
$d_e$	=	Distance from virtual apex to rocket exhaust plane
$d_r$	=	Distance missile (rocket) moves away from a reference plane
$d_{ro}$	=	Pre-rocket fire stand-off distance to reference plane
$d_t$	=	Distance target moves away from a reference plane
$d_{to}$	=	Pre-rocket fire stand-off target distance
$E_{1,}, E_6$	=	Energy expenditure in various missile maneuvers
$F_D$	=	Drag force on pendulum target
$F_d$	=	Doppler frequency
$h$	=	Convective heat transfer coefficient
$I_t$	=	Impulse delivered to target
$k_d$	=	Exhaust plume spreading factor (area vs. distance)
$k_{ed}$	=	Constant to account for radial distribution of exhaust mass flow rate
$k_{1,}, k_4$	=	Fractional uses of missile's rotation energy budget
$L_h$	=	Length of visible flame in a rocket exhaust plume
$L_{gb}$	=	Length of gas-blast slug in pendulum test
$M_g$	=	Mass of incident gas on pendulum target
$M_{ro}$	=	Initial mass of missile before rocket burn
$M_p$	=	Mass of propellant burned to generate gas-blast in pendulum test
$M_t$	=	Mass of target satellite, etc.
$m_e$	=	Rocket exhaust mass flow per unit time
$m_r$	=	Mass of rocket after given expenditure of propellant
$Q_1$	=	Heat input to Thrust Reverser per unit area & time (radiation + convection)
$Q_2$	=	Heat output from Thrust Reverser per unit area & time (radiation)
$q_e$	=	Dynamic pressure of exhaust gas at rocket exit
$q_t$	=	Dynamic pressure of exhaust gas at target
$r_e$	=	Radius of rocket exhaust plane
$r_t$	=	Effective radius of exhaust plume at target
$S_t$	=	Aerodynamic reference area of target
$T_{comb}$	=	Rocket motor combustion temperature
$T_{etr}$	=	Rocket exhaust temperature chosen to radiate heat to Thrust Reverser
$T_{ex}$	=	Rocket exhaust temperature at nozzle exit
$T_{exr}$	=	Exhaust plume temperature cooled to nearest Thrust Reverser film
$T_r$	=	Recovery temperature of gas impinging on Thrust Reverser
$T_{tr}$	=	Equilibrium temperature of Thrust Reverser foil

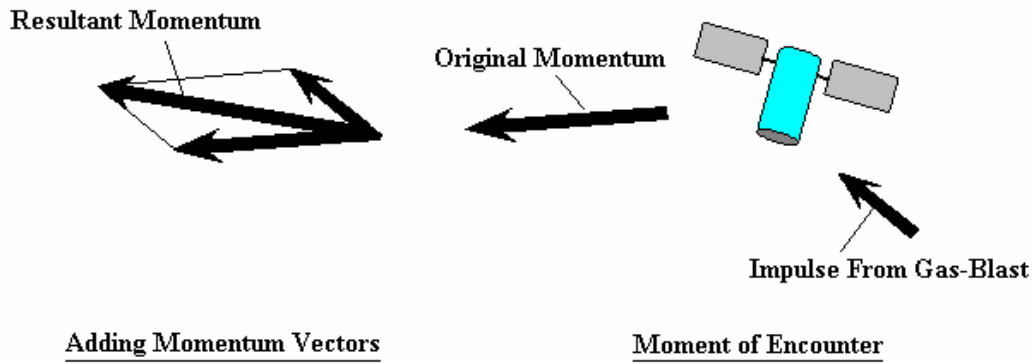
$Th_r$	=	Thrust of rocket
$Th_{tr}$	=	Counter thrust produced by the Thrust Reverser
$t$	=	Time
$\Delta t$	=	Increment of time
$t_b$	=	Duration of rocket burn
$V_e$	=	Velocity of exhaust gas relative to rocket
$Vol_e$	=	Volume of exhaust gas slug generated in unit time
$v_r$	=	Velocity (rel. to reference) radar moves toward target
$v_{rec}$	=	Equivalent velocity of particles equal to recovery temperature energy
$v_t$	=	Velocity (rel. to reference) target's reflecting surface moves toward radar
$v_{tr}$	=	Velocity of particles rebounded forward from the Thrust Reverser
$x_{tr}$	=	Distance from exhaust nozzle to closest Thrust Reverser foil
$\rho_e$	=	Density of exhaust gas at rocket exit
$\rho_t$	=	Density of exhaust gas at target
	=	Stefan-Boltzmann Constant
	=	Emissivity
$\lambda$	=	Wavelength of radar

## I. Introduction

Any number of times it has been wished that one could change the orbit of an object, or objects, in space with out attaching or docking with them due to their geometric configuration or their having a tumbling motion. In many cases the object is a satellite or even a manned vehicle with inoperative thrusters requiring rescue before burning up in the atmosphere. The object in question could also consist of space debris – the ever increasing menace to manned and unmanned space operations. In dire cases, it could be one of the numerous small, but dangerous, asteroids making a close pass to Earth. This paper describes a means of accomplishing this using a specially designed **Interceptor Missile** which can approach close to, but does not mechanically touch, the space object, to be called the **Target**.

Modification of the orbit of the Target object in space can be done by use of a gas-blast to transfer an impulse to the Target object in question. It is proposed that this be done by use of the Interceptor Missile propulsion rocket motor itself – acting as a space “leaf blower”.

The gas-blast delivery of impulse is done at a computer-determined standoff distance and aim point, which depend upon the desired direction for the delivered impulse vector. The delivered impulse may be used to raise the orbit of the Target, or to cause it to re-enter the earth's atmosphere and burn up, or splash-down where and when desired. The gas-blast method of impulse delivery can also be used to rotate, or de-spin a space capsule to change the orientation of solar energy panels or telemetry antennae; or to permit docking for a space rescue, or for emergency maintenance. While the gas-blast can be extremely gentle to avoid damage to a delicate space structure, it can be used in a much more vigorous manner to blow dangerous debris (space junk) out of the orbital corridor occupied by the International Space Station or a planned manned mission. Figure 1 shows how a gas blast can deliver an impulse to a high value satellite whose orbit is to be elevated to prevent premature reentry into the earth's atmosphere; or to move it out of an inadequately low orbit resulting from a partial launch failure; or to alter its orbit for navigational, communication, or earth surveillance purposes.



Toward Earth's Upper Atmosphere



**NOTES:**

- The impulse from the gas blast is the effective impulse acquired by the satellite resulting from drag in the free molecule flow of the gas-blast. Those molecules that do not strike the satellite play no role in transferring momentum.
- The change in satellite momentum vector is shown exaggerated for illustration. In reality, it would be much less to avoid damage to the satellite.
- The example shown here is the rescue of an expensive satellite experiencing orbit decay with the eventual burn-up in the atmosphere.

FIGURE 1 GAS-BLAST TRANSFERS IMPULSE TO A SATELLITE TO INCREMENTALLY BOOST ITS ORBIT

**II. Implementation**

Prior to directing a gas blast at a Targeted space object, it is necessary to image the Target to determine its “aerodynamic” center. Imaging is done in a novel manner by using doppler radar to map departing particles in the exhaust blast that move with it. There may be some special seeding of the exhaust gas if greater radar reflectivity is needed. Where the gases impinge on the Target space object, they “stagnate”, or stop moving rearward. The contour of this particle “stagnation” outlines the profile of the space Target object, enabling determination of its “aerodynamic” center of drag.

A range of encounter trajectories can be designed for closure of the Interceptor Missile with the Target to deliver its impulse gas-blast. In this paper two encounter trajectories are considered. One is a direct ascent trajectory in which the Interceptor Missile is given only enough energy to coast up to the altitude of the Target orbit at which point an impulse is transferred during a brief passing encounter. The Direct ascent

encounter would be used primarily for causing space junk or a dead satellite to de-orbit, or an asteroid could receive a precise “kick” that would eliminate an unwanted collision with Earth years in the future.. This would apply in cases where much is known about the Target and precise guidance and aiming of the Interceptor Missile is possible.

The other encounter is a “Co-orbital” trajectory in which the Interceptor Missile has been given more energy and is placed in an orbit closely paralleling that of the Target. This allows time for an initial gas-blast to image and characterize the “aerodynamics” of the Target, by a technique described below, and would be used in critical missions where precise gas-blast aiming is needed to alter the orbit or change the spin axis of a delicate satellite or manned capsule.

A “Thrust Reverser” concept is described below wherein the outer portions of the Interceptor Missile’s rocket exhaust (that would otherwise go past the Target and be wasted) are captured and directed 180 degrees to provide a counter-thrust, much as a conventional jet aircraft thrust reverser works. This holds the Interceptor Missile in proximity to the Target longer, allowing more impulse transfer to the Target, resulting in more efficient use of the Interceptor Missile, where a number of Interceptor Missiles are required to deliver a major orbit-changing impulse to a large Target.

The gas-blast itself (from whatever source) must contain no shrapnel or particulate matter that could damage the Target. The primary source of gas-blast described here consists of the Interceptor Missile’s main propulsion rocket motor exhaust. Beyond a short distance, a chemical combustion rocket exhaust cools dramatically when flowing into the vacuum of space. While it is *space-chilled*, losing thermal energy through expansion and radiation; the momentum of the gas-blast particles remain the same. The delivery of this gas-blast can be aimed to thrust the Interceptor Missile away from the Target, and, into its own return-to-earth trajectory; thus leaving no “space junk” of its own. A liquid or hybrid fueled rocket can be fired a number of times, each of a controlled duration. The duration of burn at a constant thrust determines the impulse delivered to the Target upon which the exhaust gas impinges.

This paper also describes how the Interceptor Missile’s on-board doppler radar can image and describe the Target object for its relative approach velocity, rotation, and approximate size. A supplemental Target analysis method (available when the missile rocket motor is used), is to direct a very short duration exhaust gas blast at the Target while the Interceptor Missile’s bore-sighted pulse doppler radar measures the Target’s changed rotation to determine its effective aerodynamic drag center as well as its mass properties. This information is then used to determine the magnitude and aiming of the main rocket motor gas-blast in cases where a critical Target impulse vector is involved.

An optional means of the gas-blast delivery is a special warhead (known as the Non-Shrapnel Warhead) involving a nose-cone that splits into captive gore sections, splaying out much as a dandelion stem does, to release a clean, non-shrapnel gas that envelopes the Target and imparts an impulse to it.

#### **A. Use of the Missile Rocket Engine as a Gas Blast Generator**

This is the preferred embodiment and involves an Interceptor Missile with a hybrid or liquid propulsion system that can be turned on and off a number of times and can also be throttled. As shown in Fig. 2, the first use of propellant takes it into the

proper position relative to the Target object. The Interceptor Missile is then rotated 180 deg. until the rocket nozzle is directed at the proper Target intercept point where the exhaust particle cloud will intercept the Target and transfer an impulse to it due to free-molecule gas loads. Selection of the desired intercept point is determined by well-known missile-Target tracking and course-correction laws, which are implemented in both ground control and the Interceptor Missile's own computer. In Fig.2 the missile is shown to fire a second burst to generate a Target "image" used in determination of its gas dynamic center and mass centroid. Aiming correction is made and, as shown in Fig. 2, a third major rocket firing delivers the desired impulse to the Target.

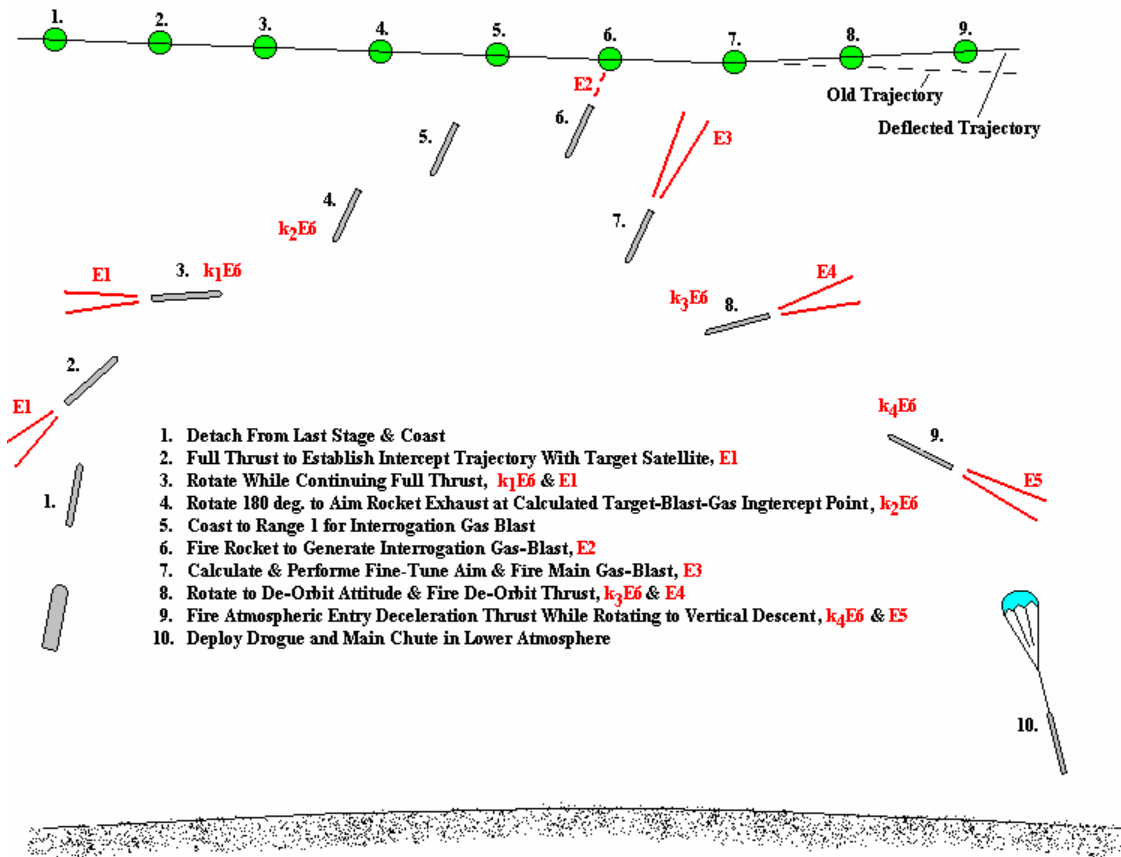


FIGURE 2 INTERCEPTOR MISSILE'S "DIRECT ASCENT" ENCOUNTER TRAJECTORY AIMS ROCKET ENGINE EXHAUST GAS-BLAST AT TARGET

The sequence of energy expenditures, (E1 – E5), in Fig. 2 shown opposite the corresponding Target Interceptor Missile positions represent progressive consumption of missile propellant, or energy budget. The values k1, k2, k3, k4 times E6 are successive fractional uses of the missile rotation energy budget, E6, where small lateral rockets are used, as shown in Fig. 3 below. In a direct ascent encounter the satellite would be moving several orders of magnitude faster than the missile. Thus, very careful pre-calculated aim-points are required for both analysis of the Target's gas-dynamic and mass properties, and for delivery of the primary gas-blast impulse. Because of the brief duration of an encounter, such as shown in Fig. 2, two Interceptor Missiles would be

required; the first to analyze the Target; the second, using telemetered data from the first, would deliver the main orbit-changing gas-blast.

Table I lists the impulse per pound for each of the major rocket firings shown in Fig. 2. Reasonable energy expenditures, as percentages of the total propellant budget, are assumed for a typical Missile-Target encounter scenario. For energy accounting purposes, a small amount of propellant, E6 in Table, I is assumed to be used for missile steering and rotation using lateral rockets.

TABLE I INTERCEPTOR MISSILE IMPULSE BUDGET

Initial Conditions:

Given Propellant Flow Rate =	20 (lb/sec)
Given Specific Impulse, Isp =	200 (sec)
Thrust =	4000 (lb)
Total Burn Time =	160 (sec)
Total Impulse =	64,0000 (lb-sec)

	<u>Propellant Usage:</u> (Firing Sequence)	<u>Propellant</u> (%)	<u>Burn Time</u> (sec)	<u>Impulse</u> (lb-sec)	<u>Missile Vel. Change</u> (fps) (Note A)
Final Intercept Trajectory	E1	13	20.1	83,200	740.3
Analysis Perturbation	E2	3 (Note B)	4.8	19,200	183.9
Main Satellite Perturbation	E3	57	90.3	364,800	5316.6
Missile De-Orbiting	E4	10	15.7	64,000	1714.9
Atmospheric Deceleration	E5	15	23.5	96,000	4090.3 (Note C)
Missile Rotation Budget	E6	2	3.2	12,800	0.0 (Note D)

NOTES:

- A: Accounts For Progressive Loss of Missile Mass.
- B: Only if a Perturbation Blast is Required to Verify Target Gas-Dynamic Center and Mass Properties.
- C: When the Interceptor Missile is to be saved for re-use.
- D: No Missile Translational Velocities Result From Rotation Maneuvers.

From basic rocket engine theory in Reference 1, the following relationships are used to generate the data of Table I:

$$\begin{aligned} \text{Thrust} &= \text{Propellant Flow Rate} \times \text{Specific Impulse} \\ \text{Burn Time} &= \text{Percent Propellant Use} \times \text{Total Burn Time} \\ \text{Impulse} &= \text{Thrust} \times \text{Burn Time} \\ \text{Missile Velocity Change} &= \text{Impulse} / \text{Missile Mass (corrected during burn)} \end{aligned}$$

If determination of the Target gas dynamic center is unimportant, that is, no de-spinning is required or the Target is merely regarded as “space junk” to be de-orbited, then the small test blast against the Target is omitted and its energy used in the main gas blast. This mission is best done in a direct ascent type of encounter.

The issue of the gas blast heating, or, otherwise damaging the Target is addressed by the following empirical formula (Eqn. 5-15 on p. 157 of Reference 1):

$$L_h = \text{square root} (T_r / f) \tag{1}$$

where L is the length of the visible flame in feet, Th is the thrust in pounds, and f is an empirical factor of 10 (when using ft-lb units). The above equation, (1), applies for ordinary propellants at sea level conditions, but it suggests that radiation rapidly cools the exhaust particles. A computer program was written using black body radiation cooling of carbon particles in a typical rocket exhaust stream. Free-molecule flow only is assumed. Results indicate that significant cooling (“space-chilling”) occurs within a short distance of the nozzle exit. Tables IIA and IIB for carbon particles of 1.0 and 0.1 micron radius respectively list these results. Figure 3 plots the results for carbon particles of radius 1.0, 0.5, 0.1, 0.05 and 0.02 micron radius

Using equation (1), the 4000 lb thrust rocket motor (used in Tables IIA and IIB) will have a visible exhaust plume out to 20 ft. From the model used to create the tables, at 20 ft, the carbon particle temperatures range from approximately 1900 deg R for the 1.0 micron radius to 600 deg R for the 0.02 micron radius size.

Potential gas-blast damage to the Target object was estimated using the kinetic energy of the assumed carbon particle and assuming the structural strength of the weakest material to be found on a satellite. A typical fiberglass component having a 3000-psi compressive failure strength was selected. Carbon particle impact cratering was sized by converting the kinetic energy of the carbon particle into cratering work: pressure x depth of crater x material failure strength. The resulting crater depth was about .01 mm. Blackbody radiation was assumed to carry away most combustion-caused residual heat of the particle. Reheating due to impact was determined by converting 30 percent of the carbon particle’s kinetic energy into heat of the carbon particle itself. Results indicated about 720 deg R temperature rise due to impact of a two micron diameter carbon particle. This was assuming the rest of the particle’s kinetic energy went into digging the crater or into elastic rebound of some of the carbon particles.

TABLE II-A EXHAUST PARTICLE TEMPERATURE-DISTANCE HISTORY

----- INITIAL CONDITIONS -----

A 2 micron Carbon Particle in Exhaust Flow Has the Following Properties:

Volume = 1.5E-16 (cu-ft), Area = 1.4E-10 (sq-ft), Mass = 6.2E-16 (slugs).

For an Initial Temperature of 3000 (o R), the Initial Heat = 1.8E-11 (Btu)

Particle Moves 6.1 mm in 3.4 micro-sec at exhaust velocity of 6000 fps = .02 (ft);

Particle Emissivity Assumed = 1

<b>Time</b> (sec)	<b>Distance From Exit</b> (ft)	<b>Particle Temp. TC</b> (o R)
-----	-----	-----
0	0	2999
.00001	.061	2990
.000021	.123	2981
.000031	.186	2972
.000041	.249	2963
.000077	.463	2934
.000148	.888	2879
.000307	1.84	2768
.000691	4.14	2558
.001179	7.07	2364
.001757	10	2194
.002925	20	1959
.010517	63	1379
.012852	77	1297
.013436	80	1280
.015188	90	1232
.016356	98	1204
.018703	112	1154
.024005	144	1067
.03	180	986
.04	240	911
.05	300	842
.06	380	778
.08	490	718
.1	620	664
.13	790	613
.17	1020	567

TABLE II-B EXHAUST PARTICLE TEMPERATURE-DISTANCE HISTORY

----- INITIAL CONDITIONS -----

An 0.2 micron Carbon Particle in Exhaust Flow Has the Following Properties:

Volume = 1.48E-19, (cu-ft), Area = 1.35E-12 (sq-ft), Mass = 6.2E-16 (slugs).

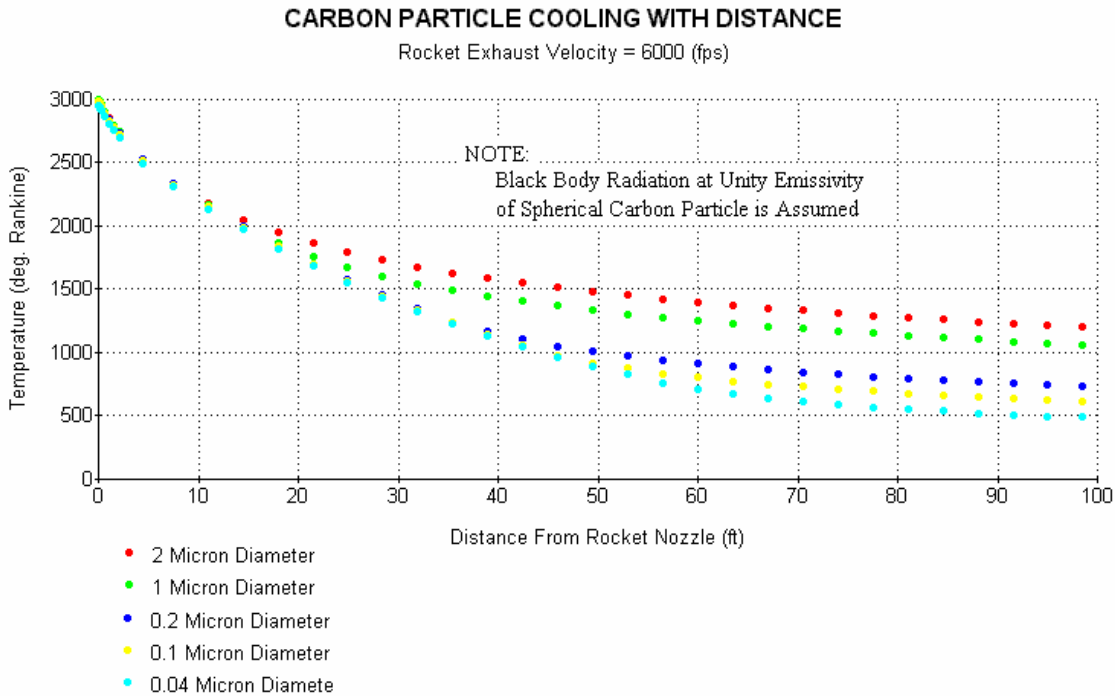
For an Initial Temperature of 3000 (o R), the Initial Heat = 1.80E-14 (Btu)

Particle Moves 6.1 mm in 3.4 micro-sec at exhaust velocity of 6000 (fps)

Particle Emissivity Assumed = 1

<b>Time</b>	<b>Distance Particle</b>	<b>Temp.</b>
<b>(sec)</b>	<b>From Exit</b>	<b>(o R)</b>
-----	-----	-----
0	0	2991
.000001	.006	2982
.000002	.01	2976
.000003	.017	2967
.000003	.019	2964
.000003	.021	2961
.000005	.027	2953
.000008	.047	2926
.000015	.09	2871
.000031	.186	2761
.00007	.418	2551
.000119	.713	2357
.000181	1.086	2178
.00026	1.56	2013
.00036	2.16	1860
.006232	40	783
.007261	43	745
.008975	50	695
.00966	57	678
.010003	60	671
.011717	70	637
.012403	74	625
.013088	78	614
.014116	84	599
.014802	90	589
.016173	97	572
.019034	114	542
.024151	142	501

Figure 3 below shows the radiation cooling of various sized carbon particles with distance. The range of particles shown is typical of the soot found in rocket exhausts. Figure 3 is developed using the same computer program used with Tables II A and II B above.



**FIGURE 3 COOLING OF VARIOUS SIZED CARBON EXHAUST PARTICLES WITH DISTANCE FOR A 6000 FT/SEC EXHAUST VELOCITY**

Using equation (1) for a 4000 lb. thrust rocket motor & a value of constant  $f = 10$ , the visible plume length is 20 ft. For a larger 20,000 lb. thrust rocket motor, the visible plume length would be 44.7 ft. It is seen that based purely upon black body radiation cooling of carbon particles, very modest temperatures are achieved a short distance from the rocket exhaust nozzle.

All of these variables (plume cooling distance, Target heating and/or impact damage) can be tested at sub-scale in a space chamber, as described below in Sub-Scale Testing.

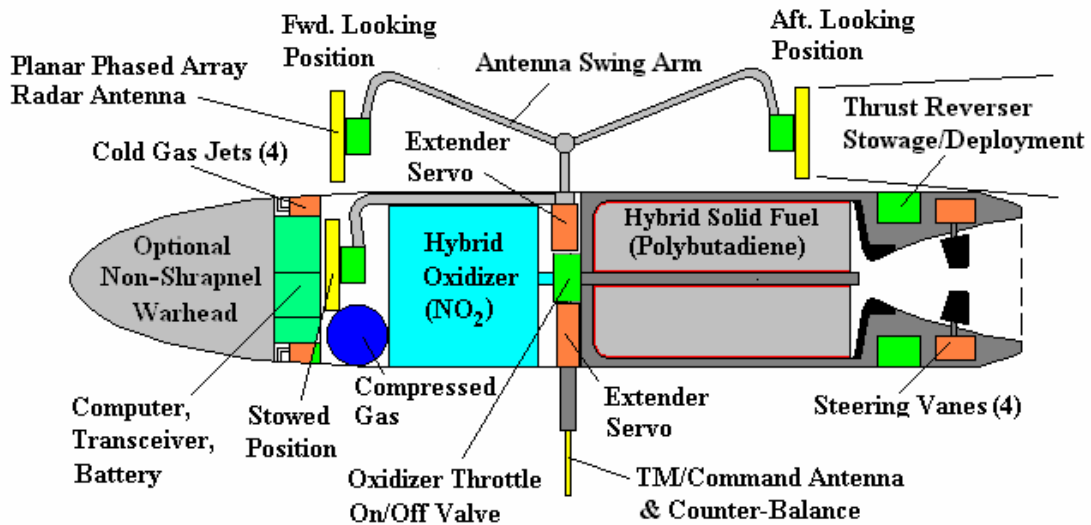
### **B. Interceptor Missile Design**

The design of the Interceptor Missile for use as a direct rocket motor exhaust blast trajectory deflection device is shown in Fig. 4. The high frequency Ka band radar allows for small antennas and microwave hardware. It is estimated that 10 watts of radar power is adequate because the intercept distances are relatively short, once the boost phase has placed the missile in an intercept box to encounter the selected Target satellite.

Figure 4 is a generalized design that can accommodate either the Non-Shrapnel Warhead or the rocket exhaust means of delivering the gas-blast. In the case of the rocket-generated gas-blast, the radar array first un-stowed and looks forward for location of the Target and for guiding the initial phase of approach. It then swings aft. to allow close-up identification of the Target and determination of its silhouette “image” for purposes of selecting the gas dynamic aim point center. The radar also tracks departing exhaust gas particles impinging on the Target to refine the free-molecule “image” of the Target.

The cold gas jets rotate the missile end-for-end, when the rocket motor is to deliver the gas-blast, and for fine aiming prior to the main gas-blast delivery.

The extended antenna for telemetry and command reception is designed to provide enough mass to counterbalance the extended radar antenna on the opposite side. This keeps the CG on the thrust centerline to eliminate unwanted moments during rocket thrusting, or during the optional Non-Shrapnel Warhead discharge.



**TYPICAL SPECIFICATIONS:**

Weight:	4000 lb.
Thrust:	4000 lb.
Specific Impulse, Isp:	200 to 250 sec.
Mass Ratio (fuel wgt/total wgt):	0.8
Radar (ranging & target analysis):	10 W Pulse Doppler

**NOTES:**

- Counter-Balance maintains CG on thrust center-line regardless of antenna location.
- Compressed Gas (dry nitrogen) powers the Cold Gas Jets for vernier steering/rotation. Cold Gas Jets may also be located at the rear near Steering Vanes for faster rotation.
- Antenna Array looks forward to locate & guide on target satellite; looks rearward to identify target silhouette for blast-gas aiming purposes.
- Hybrid Fuel (polybutadiene) lateral surfaces are inhibited to allow end-burning only so that thrust remains constant for all burns.

FIGURE 4. INTERCEPTOR MISSILE DESIGN TO USE AIMED, SPACE-CHILLED ROCKET EXHAUST AS THE GAS-BLAST GENERATOR

**C. Radar Determination of Target Shape and Motion**

During a “Co-orbital” trajectory, determination of the Target shape for computer-determination of aim-point for the gas blast is done by using the doppler radar to observe the departure velocity pattern of reflecting particles seeded into the rocket exhaust. These

particles are best seeded into the exhaust gases by having mixed them into the solid fuel grain of the hybrid rocket during manufacture. Particles with a high dielectric constant will be evenly distributed in the butadiene fuel at a very low density (less than a fraction of a percent of the weight of the fuel grain). The size and density of the particles will be selected to provide maximum scattering in the Ka microwave band to provide a detectable velocity signature for the pulse doppler receiver. Particles with a high dielectric constant provide more scattering. It is possible that normal hybrid rocket exhaust particles have sufficient dielectric constant to provide an adequate backscatter to the Ka band microwaves. If not, then some metal, such as aluminum, could be dispersed in powder form in the fuel grain during manufacture. During combustion, aluminum oxide would result, having a high dielectric constant.

Figure 5 shows the seeded rocket exhaust impinging on a satellite Target and also the pulse doppler radar receiver beam (defined by half power contour), with resolution cells, centered on the satellite profile. Figure 5 shows the relation between the resolution cell size and the satellite Target size and the final doppler scatter map used for computer identification of gas-dynamic aiming points. These are similar to the silhouette images on page 517 of reference 2, although reference 2 merely discusses resolution for the purpose of radar surveillance mapping, as opposed to the purpose of this proposal.

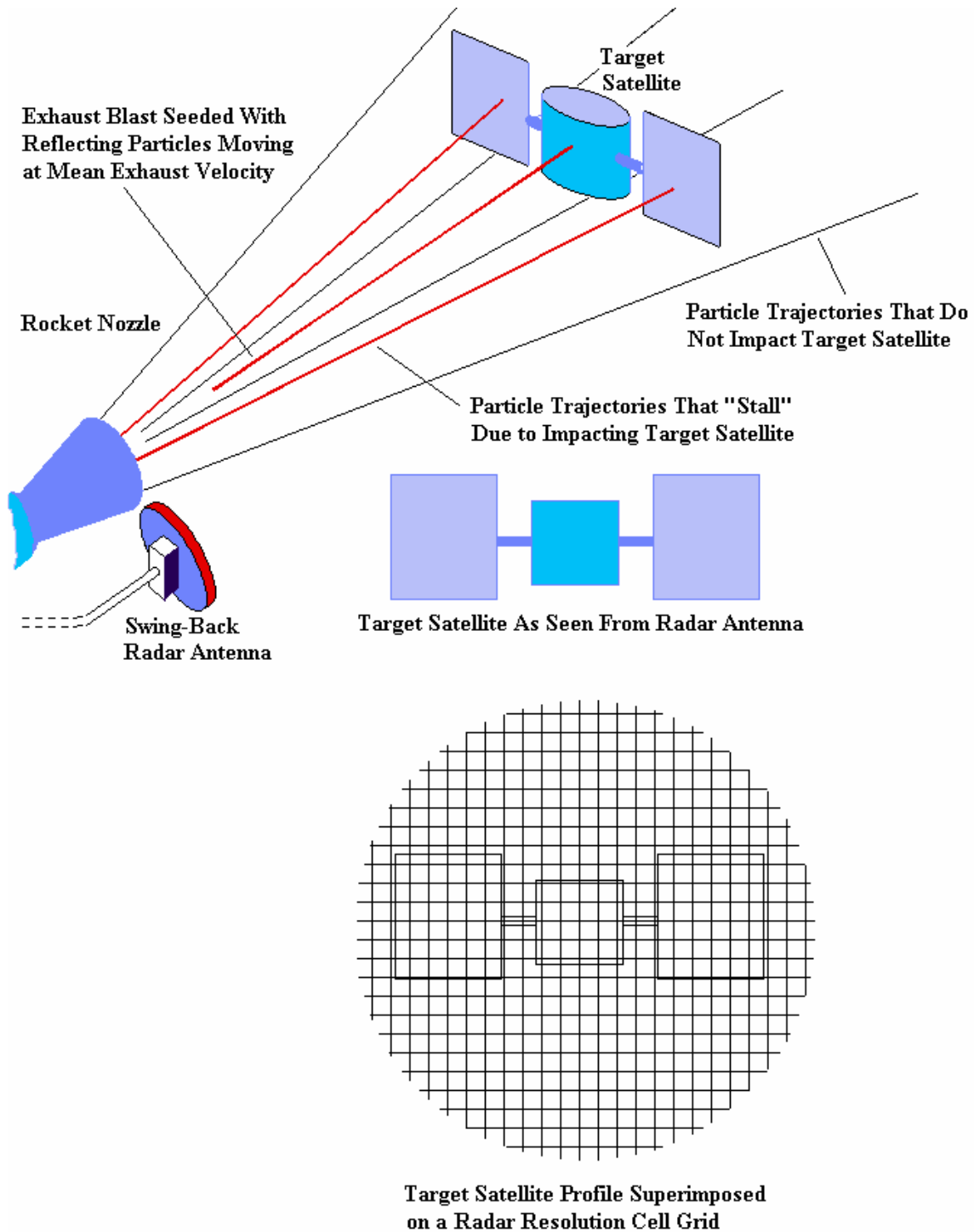
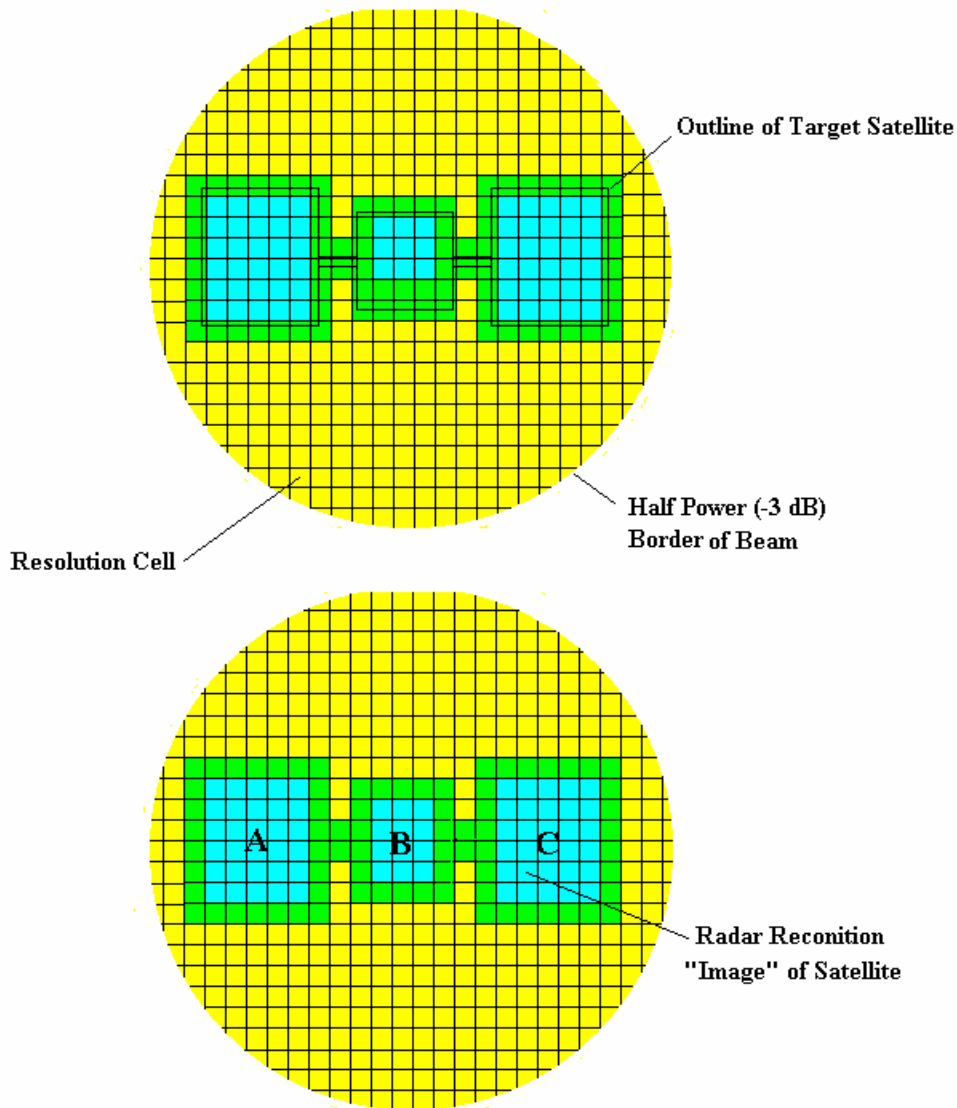


FIGURE 5 TARGET SATELLITE SILHOUETTE IMAGED USING IMPINGEMENT OF RADAR-SCATTERING PARTICLES IN ROCKET EXHAUST



**NOTES:**

- Cell fully filled with full-departure velocity doppler shift shown in yellow. ■
  - Cell partially filled with full-departure velocity doppler shift shown in green. ■
  - Cell fully filled with stopped particles (little or no doppler shift) due to impact with target satellite are shown in blue. ■
- Gas Dynamic Centers, Depending Upon Impulse Transfer Mission: **A, B, C**

**FIGURE 6 RESOLUTION OF SATELLITE "IMAGE" BY DOPPLER RADAR TRACKING REFLECTING EXHAUST PARTICLES**

By the use of doppler radar and comparing reflections from different portions of the Target, it is possible to establish its rotation: the rate and the axis of rotation. Figure 7 below shows an idealized Target satellite with its axis of rotation in the plane of the paper and normal to the line of sight from the Interceptor Missile to the satellite Target.

### Reflecting Surface of Rotating Satellite

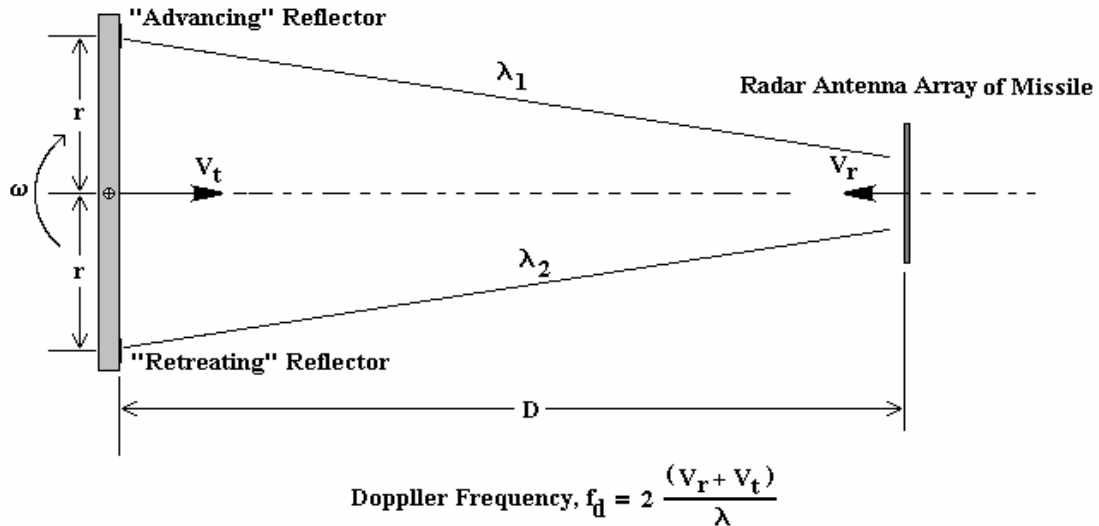


FIGURE 7 DOPPLER RADAR DETERMINS TARGET APPROACH & ROTATION

The equation for doppler frequency of radar reflecting from a Target, when the Target and the radar platform (missile) are moving toward each other, is:

$$f_d = 2 (V_r + V_t) / \lambda \quad (2)$$

Where:

- $f_d$  = Doppler Frequency (Hz)
- $V_r$  = Velocity of Reflecting Surface Toward Radar (m/sec)
- $V_t$  = Velocity of Radar Toward Reflecting Surface (m/sec)
- $\lambda$  = Wavelength of Radar (m)

As an example, using eqn (2), if 0.8 mm radar (upper Ka band) is employed (the short wavelength, as well as low powers, allow smaller and lighter equipment), then for Target rotation of 1 rad/sec (9.55 revolutions per minute), and reflective surfaces 4 meters apart from a mid-point axis of rotation, then the differences in reflected doppler frequencies from the two surfaces are about 159.54 Hz). Since a satellite in circular low earth orbit (LEO) is moving at 7.9 km/sec; and assuming the Interceptor Missile is an essentially stationary position at the top of its vertical trajectory ( direct ascent intercept), then the doppler frequency of the reflected radar at the radar of the missile is 3114.5 KHz. Both of these frequencies are easily detectable with today's equipment. Table III lists the results of computing both approach and rotation doppler frequencies for various basic radar frequencies. A head-on relative speed, as shown in Fig. 7, is assumed. It is assumed that the Interceptor Missile is lofted (in a direct ascent intercept) to the altitude of the satellite Target, but has essentially zero velocity parallel to the orbit of the satellite.

TABLE III RADAR DOPPLER FREQUENCIES

Given Target Conditions:

LEO Satellite Velocity = 7.90 (km/sec); Missile Velocity = 0 (km/sec)

Translation Doppler Frequency = 5.871515 (KHz)

Major Reflecting Surfaces of Satellite are 1 and 2 m from Rotation Axis

Rotation at 1 radian per second

Frequency (GHz)	Reflector Radius (m)	Translation Doppler Frequency (KHz)	Rotation Doppler Frequency (Hz)
12	1	632.4	160.0
18	1	948.6	240.0
24	1	1264.9	320.0
30	1	1581.1	400.0
36	1	1897.3	480.0
12	2	632.4	320.0
18	2	948.6	480.0
24	2	1264.9	640.0
30	2	1581.1	800.0
36	2	1897.3	960.0

Infrared imaging can supplement the radar imaging of the Target satellite.

Figure 8 shows the Interceptor Missile flying in close proximity to a Target during a “Co-orbital” interception. Its rocket exhaust blast is seen imparting an impulse to the Target to change its orbit.

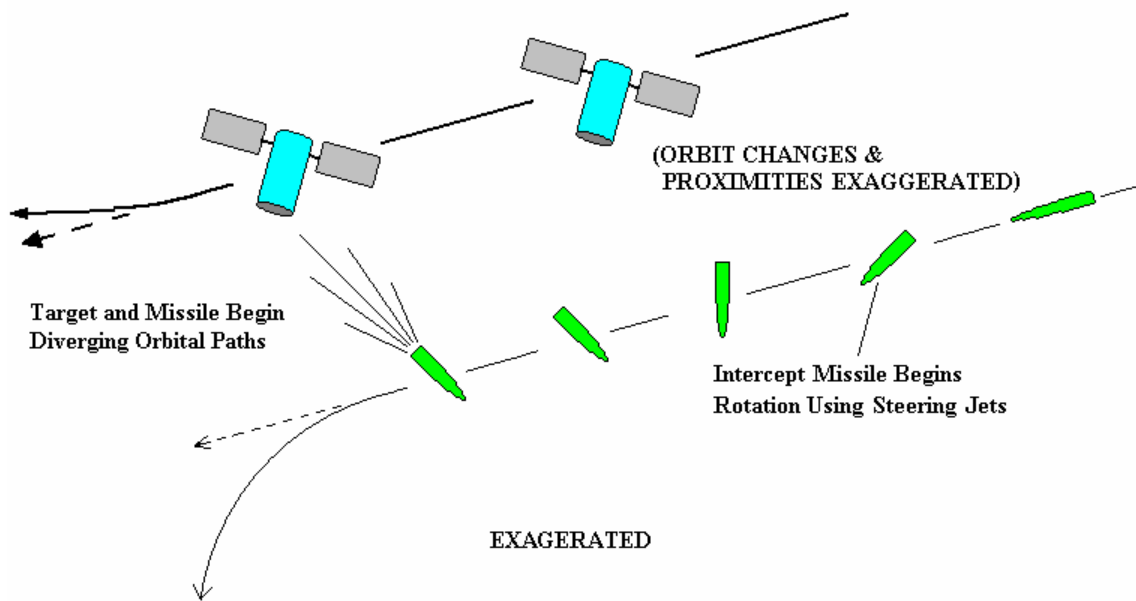
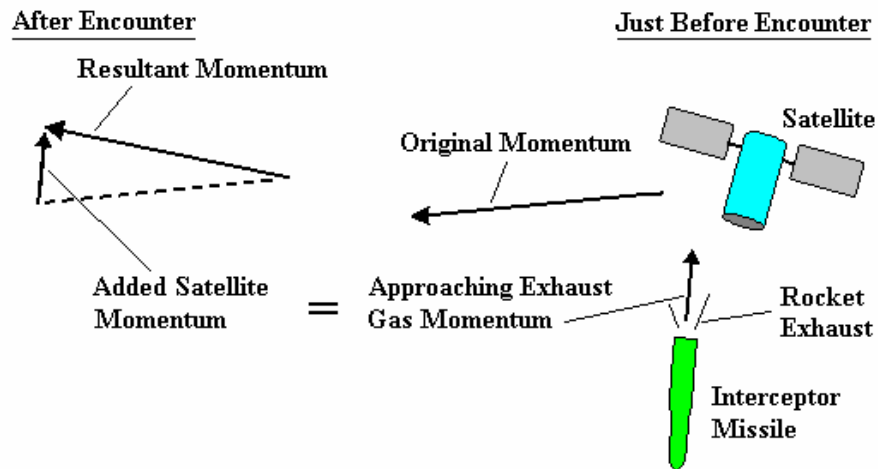


FIGURE 8 INTERCEPTOR MISSILE ENCOUNTERS A SATELLITE DURING A  
 "CO-ORBITAL" TRAJECTORY

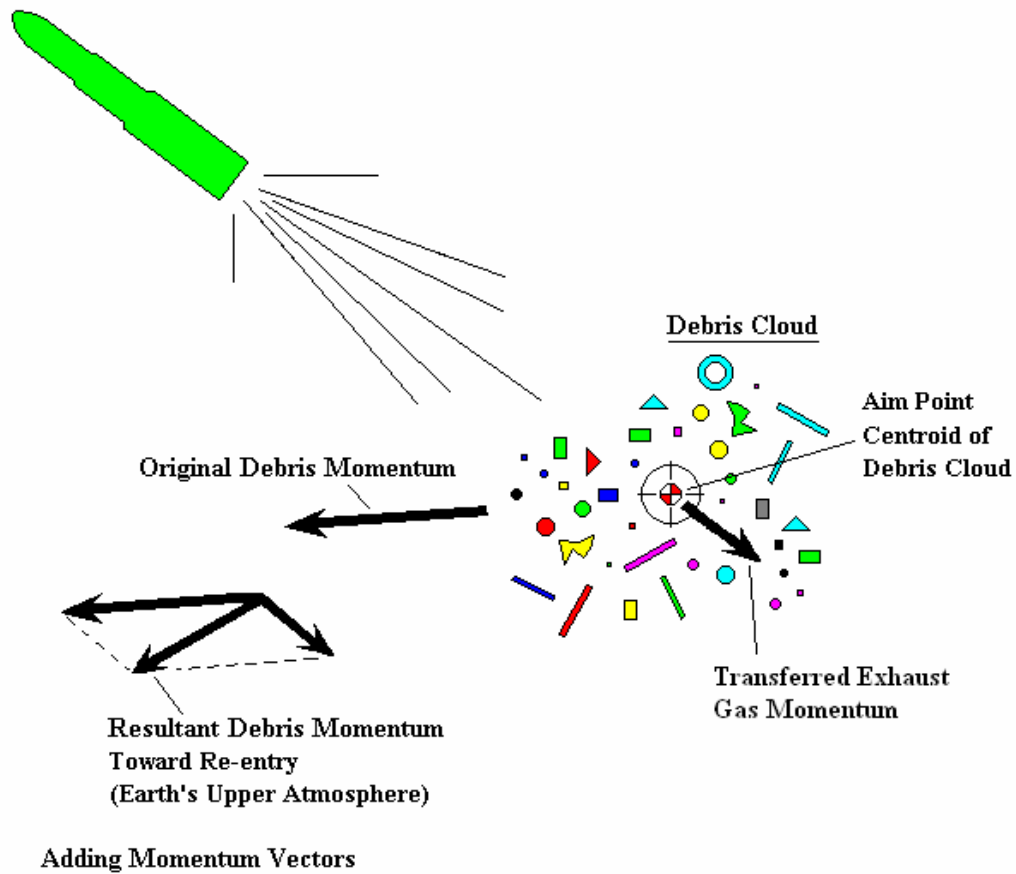
The moving blast-gas cloud transfers momentum to any Target it intercepts, as shown in Fig.'s 9 and 10. The same transfer of momentum applies to the rocket exhaust version of this proposal.



**NOTES:**

- The example shown here is the rescue of an expensive satellite experiencing orbit decay with eventual burn-up in the atmosphere.
- The momentum of the rocket exhaust gas is the impulse acquired by the satellite due to drag in the free molecule flow of the exhaust. Those molecules not striking the satellite play no role in transferring momentum.
- The change in satellite momentum vector is shown exaggerated for illustration. In reality, it would be much less, to avoid damage to the satellite. A number of encounters may be required to gently alter the orbit of the satellite.
- Proof-of-concept testing in space would involve an instrumented satellite (accelerometers, strain gages on deformable structures, and GPS for orbit determination). Various rocket exhaust values and stand-off distances would be evaluated.

**FIGURE 9 INTERCEPTOR MISSILE DELIVERS ORBIT-CHANGING IMPULSE TO A SATELITE TO LIFT ITS LEO ORBIT**



**NOTES:**

- Rocket exhaust gas-blast would occur at a greater distance from the debris cloud, with a greater fan-out, to envelope as many debris objects as possible.
- No attempt would be made to avoid "damage" to the debris, as in rescuing a satellite.
- The intercept would be made at a time, location, and direction of impulse to cause the debris to re-enter at a safe location on Earth.

FIGURE 10 INTERCEPTOR MISSILE BLOWS DEBRIS OUT OF ORBIT

**D. Effectiveness of Gas-Blast Orbit Modification**

To determine the effectiveness of the Gas-Blast orbit modification technique, an idealized relation between an interceptor missile and a Target if parallel (“Co-orbital”) orbits is assumed. As the Interceptor rocket motor fires, its exhaust plume impinges on the Target, imparting an impulse by virtue of free-molecule “drag”. The result is that both the Interceptor Missile and the Target are forced in opposite directions from a reference plane between them. While the rocket thrust is constant, the dynamic pressure sensed by the Target diminishes as the rocket recedes, resulting in diminished thrust on the Target. In the section below it is shown how a Thrust Reverser can slow the departure of the Interceptor Missile, thus increasing the impulse delivered to the Target.

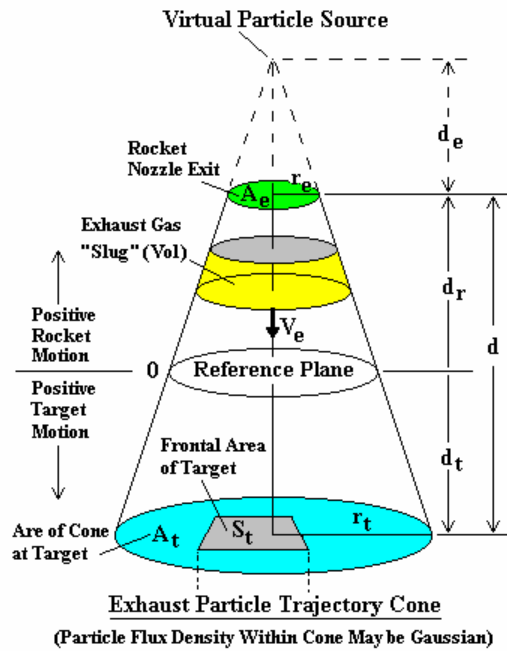
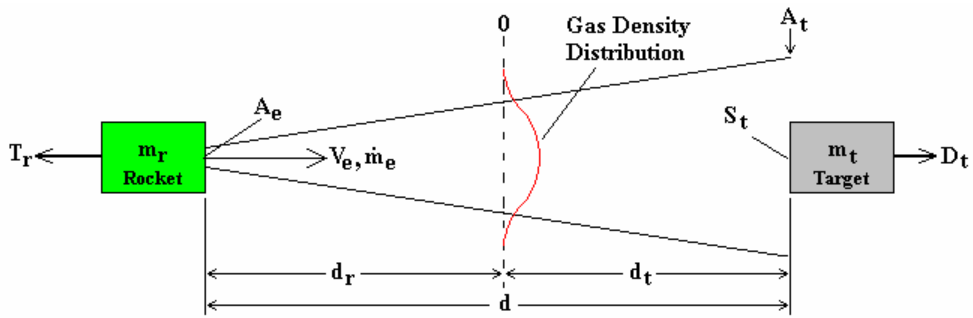


FIGURE 11A IDEALIZED GEOMETRY RELATING INTERCEPTOR MISSILE EXHAUST PLUME AND TARGET

From the Exhaust Particle Trajectory Cone:

$$\frac{A_t}{A_e} = \left(\frac{r_t}{r_e}\right)^2 = \left(\frac{d + d_e}{d_e}\right)^2, \quad d = d_r + d_t, \quad \therefore \frac{A_t}{A_e} = \left(\frac{d_r + d_t + d_e}{d_e}\right)^2 = k_d$$

$k_d$  = a particle spreading factor

Effective Dynamic Pressure at Rocket Exhaust:

$$q_e = \frac{1}{2} \rho_e V_e^2, \quad \text{Vol}_e = A_e V_e \Delta t$$

$$\rho_e = \frac{\dot{m}_e \Delta t}{\text{Vol}_e} = \frac{\dot{m}_e \Delta t}{A_e V_e \Delta t}, \quad q_e = \frac{1}{2} \frac{\dot{m}_e \Delta t}{A_e V_e \Delta t} V_e^2$$

$$\therefore q_e = \frac{1}{2} \frac{\dot{m}_e}{A_e} V_e$$

Effective Dynamic Pressure at Target:

$$q_t = \frac{1}{2} \rho_t V_e^2, \quad \text{Vol}_t = A_t V_e \Delta t$$

$$\rho_t = \frac{\dot{m}_e \Delta t}{\text{Vol}_t} = \frac{\dot{m}_e \Delta t}{A_t V_e \Delta t}, \quad q_t = \frac{1}{2} \frac{\dot{m}_e \Delta t}{A_t V_e \Delta t} V_e^2$$

$$q_t = \frac{1}{2} \frac{\dot{m}_e}{A_t} V_e, \quad A_t = k_d A_e$$

$$\therefore q_t = \frac{1}{2} \frac{\dot{m}_e}{k_d A_e} V_e^*$$

\* Exhaust Velocity Sensed by Target Decreases Slightly as Rocket & Target Accelerate Apart:  $V_e^* = V_e - V_t - V_r$

Motion of Target:

$$D_t = q_t S_t C_D = \frac{1}{2} \frac{\dot{m}_e}{k_d A_e} V_e S_t C_D = \frac{\dot{m}_e V_e S_t C_D}{2 A_e} \frac{1}{k_d} = \frac{\dot{m}_e V_e S_t C_D}{2 A_e} \left(\frac{d_e}{d_r + d_t + d_e}\right)^2$$

$$a_t = \frac{D_t}{M_t}, \quad v_t = \int a_t dt = \int \frac{D_t}{M_t} dt = \frac{\dot{m}_e V_e S_t C_D d_e^2}{2 A_e M_t} \int \left(\frac{1}{d_r + d_t + d_e}\right)^2 dt$$

$$\therefore v_t = \frac{\dot{m}_e V_e S_t C_D d_e^2}{2 A_e M_t} \int \left(\frac{1}{d_r + d_t + d_e}\right)^2 dt \quad d_t = d_{t_0} + \frac{\dot{m}_e V_e S_t C_D d_e^2}{2 A_e M_t} \int \left(\frac{1}{d_r + d_t + d_e}\right)^2 dt$$

Motion of Rocket:

$$\therefore v_r = V_e \ln \left(\frac{M_{r_0}}{M_{r_0} - \dot{m}_e t_b}\right) \quad d_r = d_{r_0} + V_e t_b \left[1 + \frac{M_{r_0} - \dot{m}_e t_b}{\dot{m}_e t_b} \ln \left(1 - \frac{\dot{m}_e t_b}{M_{r_0}}\right)\right]$$

Relative Motion of Target & Rocket:

$$\text{Separation Velocity, } v_{\text{sep}} = v_t + v_r$$

(No Relative Velocity is Assumed Prior to Rocket Firing)

$$\text{Separation Distance, } d_{\text{sep}} = d_t + d_{t_0} + d_r + d_{r_0} \quad (d_{t_0} \text{ and } d_{r_0} \text{ are Assumed Pre-Firing Stand-Off Distances})$$

FIGURE 11B IDEALIZED EQUATIONS RELATING INTERCEPTOR MISSILE EXHAUST PLUME AND TARGET

Figures 11A and B show the idealized geometry and equations involved in expressing the response of the Target to impingement of the Interceptor Missile rocket exhaust gases. Both are assumed to be in a co-orbital stationary relationship at the start of the rocket burn. As a result of the molecular “drag” load on the Target and the rocket thrust on the Interceptor Missile, both separate from a reference mid-plane. The thrust on the rocket is constant and it obeys the basic rocket equations as it loses propellant mass.

The “drag” load on the Target diminishes with the total distance from the rocket nozzle. However, the Target mass and “aerodynamic” properties remain constant, unless, of course, it is a “rubble pile” of micro-asteroids or space junk which would be blown apart.

A computer program incorporating the equations in Fig. 11B is used to integrate Interceptor Missile and Target load accelerations to velocities and displacements in Table IV and Fig.12 below. The gas dynamic “drag” force acting on the Target, its resulting velocity, and the Interceptor Missile propellant used. Table IV covers only one condition of no separation between the Interceptor Missile and the Target and only a 50% effective thrust reverser (described below). Figure 12 shows the resultant “drag” loads on a target located at various distances from the nozzle of a rocket and for two different exhaust plume diverging cones. It will be noticed that the “drag” force is constant out a further distance for a narrow focused exhaust plume and, over a given time, delivers a greater total impulse to the target. This is because the narrower exhaust plume is smaller than the target area out a further distance. See Fig. 11A for the assumed geometry.

A full study of the resultant Interceptor Missile and Target separation velocities would involve simulating a range of the following independent variables and initial conditions:

- 1) Rocket exhaust velocity and mass flow rate.
- 2) Initial separation distance between Interceptor Missile and Target.
- 3) Rocket exhaust plume spreading geometry and cross-section flux density profile.
- 4) Thrust Reverser effectiveness in capturing and re-directing outer plume layers.
- 5) The effective drag area-to-mass of the Target.
- 6) The duration of rocket burn while aimed at the Target.

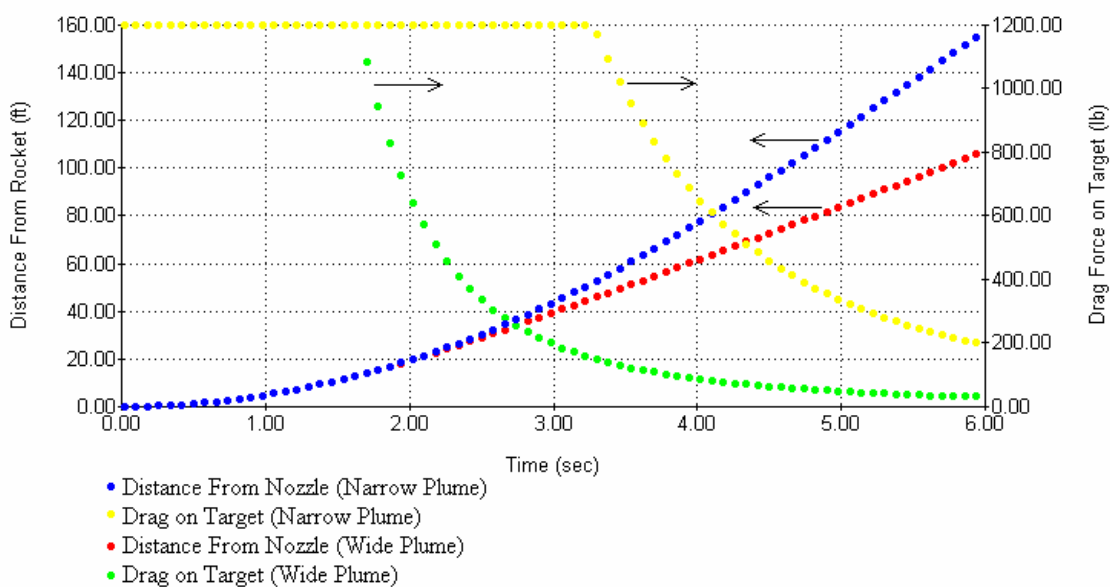
The greater the effectiveness of the Thrust Reverser (described below), the larger the longer the Interceptor Missile remains near the Target, and the greater the impulse transferred to the Target.

TABLE IV ROCKET AND TARGET DISPLACEMENT DUE TO VARIOUS LEVELS ROCKET THRUST

Initial Wgt of Rocket = 4000 (lb) of Target = 4000 (lb)					
Propellant Flow Rate = 21.44933 (lb/sec) at Veo = 6000 (fps)					
Initial Mass Ratio of Rocket (Propellant Wgt./Total Wgt.) = .8					
Exhaust Velocity = 6000 (ft/sec)					
STAND-OFF DIST. (Dro) = 0 (ft) Plume Focus, (De) = 20 (ft)					
NET MISSILE THRST = 4000 (lb)					
Time	Total Sep'n	Drag on	Acceler'n	Target	Propellant
	Distance	Target	of Target	Velocity	Used
(sec)	(ft)	(lb)	(ft/s/s)	(fps)	(lb)
0.02	-0.06	1200.00	9.65	0.19	0.43
0.10	0.23	1200.00	9.65	0.97	2.14
0.18	0.84	1200.00	9.65	1.74	3.86
0.26	1.63	1200.00	9.65	2.51	5.58
0.34	2.90	1200.00	9.65	3.28	7.29
0.42	4.43	1200.00	9.65	4.05	9.01
0.50	6.25	1200.00	9.65	4.83	10.72
0.58	8.38	1200.00	9.65	5.60	12.44
0.66	10.89	1200.00	9.65	6.37	14.16
0.74	13.73	1200.00	9.65	7.14	15.87
0.82	16.85	1200.00	9.65	7.91	17.59
0.90	20.28	1200.00	9.65	8.69	19.30
0.98	24.09	1200.00	9.65	9.46	21.02
1.14	32.55	1200.00	9.65	11.00	24.45
1.38	47.66	1200.00	9.65	13.32	29.60
1.54	59.41	976.38	7.85	14.75	33.03
1.70	72.33	721.87	5.81	15.81	36.46
1.86	86.45	542.72	4.37	16.60	39.90
2.10	109.82	364.59	2.93	17.45	45.04
2.34	135.69	253.29	2.04	18.03	50.19
2.58	164.04	181.16	1.46	18.44	55.34
2.82	194.82	132.89	1.07	18.73	60.49
3.30	263.56	76.21	0.61	19.12	70.78
4.02	384.74	37.38	0.30	19.43	86.23

## TARGET RESPONSE TO PLUME STRUCTURE

Narrow & Wide Exhaust Plume Focus



Assumed Initial Conditions:

Exhaust Velocity = 6000 fps

Propellant Flow Rate = 21.45 lb/sec

Apex of Exhaust Particle Divergence Cone From Exhaust (See Fig. 11):

20 ft. Narrow Plume    5 ft. Wide Plume

Weight of Target = 4000 lb

Reference Area of Target = 40 ft<sup>2</sup>

Target "Drag" Coefficient = 0.6

Area of Rocket Exhaust = 3.1416 ft<sup>2</sup>

FIGURE 12 DRAG LOADS ON A TARGET AT VARIOUS DISTANCES FROM A ROCKET NOZZLE WITH TWO DIFFERENT EXHAUST PLUMES

### E. Thrust Reverser

By capturing a portion the rocket exhaust blast and deflecting it 180 deg. from its normal direction, a reverse thrust can be imparted to the interceptor rocket to partially cancel its thrust and thus delay its departure from the area of the Target object. Thus, more impulse can be transferred to the Target. Figure 13 below shows the "thrust reverser" reflector to accomplish this. It acts as a "mask" to allow only the beam of exhaust particles needed through the center hole to envelope the Target. The exhaust particles outside the hole in the "mask" are then deflected backwards by one or two rebounds from the "thrust reverser" surface. Their momentum is saved and used to slow the departure of the interceptor rocket.

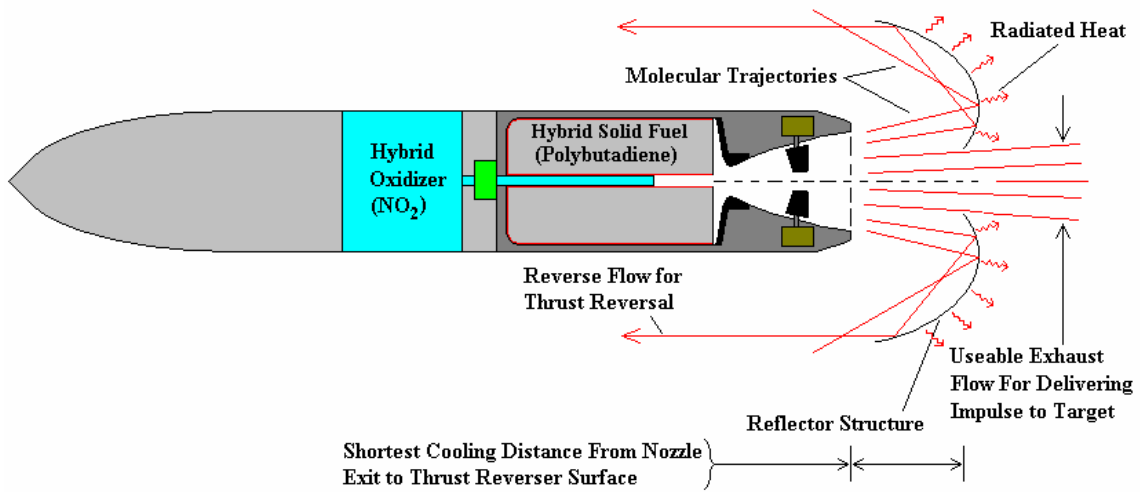
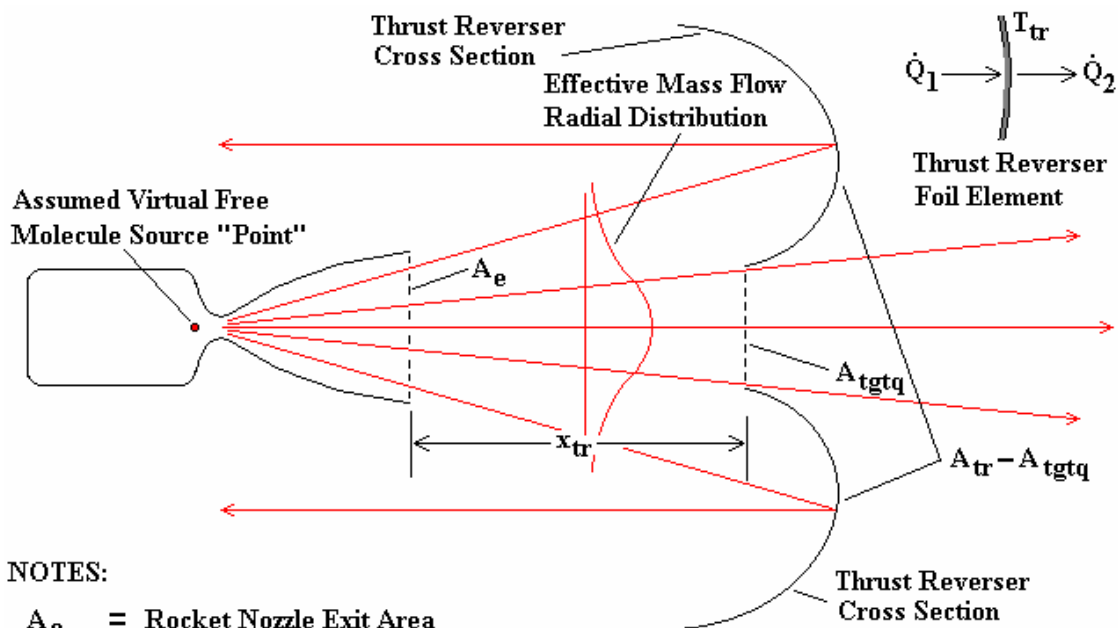


FIGURE 13 THE “THRUST REVERSER”

For single molecule “reflection” parabolic zone mirrors are positioned relative to a “focal point” of assumed exhaust gas emanation. The result is redirection of the exhaust gas molecules back parallel to the missile, as shown below in Fig. 14. Depending upon the transition from exhaust continuum flow to free-molecule flow in the plume, different “focal points” may be necessary for different conical zones of exhaust flow as seen by the Thrust Reverser. The inner zone of the Thrust Reverser reflector foil may direct first reflections to a second reflection from an outer zone.



**NOTES:**

- $A_e$  = Rocket Nozzle Exit Area
- $A_{tr}$  = Total Frontal Area of Thrust Reverser
- $A_{tgtq}$  = Area of Hole in Thrust Reverser For Target Impingement Flow
- $\dot{Q}_1$  = Heat Input Rate to Thrust Reverser Foil (Radiation & Convection)
- $\dot{Q}_2$  = Heat Output Rate From Thrust Reverser Foil (Radiation)
- $T_{tr}$  = Equilibrium Thrust Reverser Foil Temperature
- $x_{tr}$  = Distance From Exhaust Nozzle to Closest Thrust Reverser Foil

The thrust reverser will be made of steel foil in parabolic zones whose foci will be assumed as molecule source "points". It will be deployed & held in shape and position by steel shroud lines.

FIGURE 14. DESIGN FACTORS OF THE THRUST REVERSER

The Thrust Reverser reflector itself is made of thin flexible steel foil to retain strength at elevated temperatures. The steel foil reflector is deployed as a drogue chute, positioned at the proper distance, & stabilized with fine steel cables. Its back side is coated with amorphous carbon powder to maximize heat radiation, so that it behaves much the same as "boiling water in a paper cup". The distance of the thrust reverser foil, as shown in Fig. 14, is selected so that its equilibrium temperature is reached well below its plastic temperature. The closer its location, the smaller the "Thrust Reverser".

A number of trade-offs are involved in the design of the "Thrust Reverser":

a) The weight and material of the "thrust reverser" reflector, is a function of its size and distance from the rocket exhaust ( $x_{tr}$ , shown in Fig. 14); and its expected heat load from the rocket exhaust. This latter is a function of: cooling distance of exhaust particles; heat radiation from the back side ( $Q_2$  shown in Fig. 14); heat pickup by radiation from the rocket exhaust; heat imparted to the reflector from imperfect molecular rebound. Additional design factors include the mechanism for stowing in flight, and then unfolding/deploying the Thrust Reverser when in the Target encounter zone.

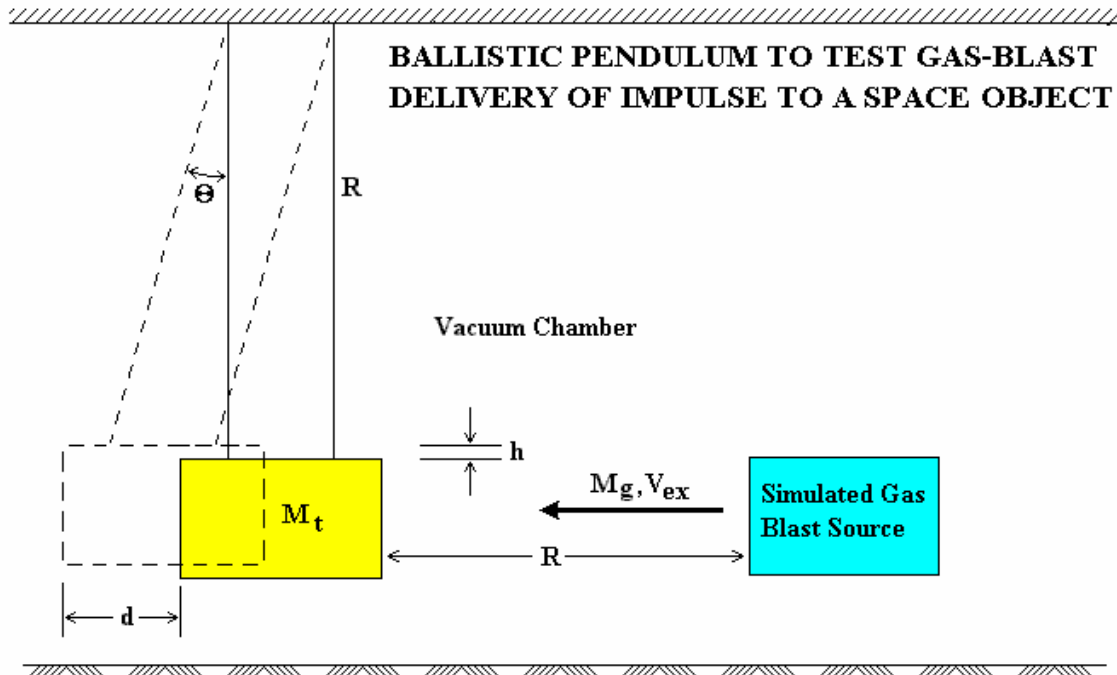
b) The size of the center hole and the outer diameter, as well as the shape,

of the Thrust Reverser” reflector will be a function of: the exhaust “molecular beam” size (half-angle) expected to envelope the Target; the desired acceleration of the Interceptor Missile away from the vicinity of the Target. This translates into the reverse-thrust load it is expected to generate. The reflector shape will depend upon whether there is one, two, or multiple rebounds (reflections) involved in the trajectory of a molecule.

c) The exhaust molecular gas dynamics going on in the reflector will be very complex and will involve the following issues: the build-up of gas molecules at the reflector surface may cause the flow to revert from free-molecule to semi-continuum flow; the resultant boundary layer and shock waves will control the thermal convection into, or out of, the reflector surface. This may in turn alter the re-direction angle imparted to the exhaust gases, and thus the net reverse thrust. Since the reflector will be made of steel foil, its shape will both affect, and be a result of, the molecular gas dynamics. As described in pp 376-378 of Ref.3, the inelastic recoil of molecules from a boundary are described with such terms as “accommodation coefficient” and “slipping”. This will cause a deviation from the perfect reflection assumed to describe the parabolic zones of the Thrust Reverser reflector. A sub-discipline should be recognized involving the study of thermal and dynamic interactions of free molecular beams and various reflector and Target geometries.

## **F. Sub-Scale Testing**

Many features of the gas-blast missile’s functions can be tested sub-scale in a large vacuum chamber employing a ballistic pendulum. Figure 15 shows the principle variables involved with sub-scale examination of using a gas-blast to deliver an impulse to a space object.



$$\text{Drag Force, } F_D = C_D q_{gb} S_t = \frac{1}{2} C_D \rho_{gb} V_{ex}^2 S_t$$

$$q_{gb} = \frac{1}{2} \rho_{gb} V_{ex}^2$$

$$I_t = F_D T_{gb} = M_t \sqrt{2 g h}$$

$$\frac{1}{2} C_D \rho_{gb} V_{ex}^2 S_t T_{gb} = M_t \sqrt{2 g h}$$

$$\rho_{gb} = \frac{M_p k_d}{L_{gb} A_e}$$

$$L_{gb} = V_{ex} T_{gb}$$

$$\rho_{gb} = \frac{M_p k_d}{V_{ex} T_{gb} A_e}$$

$$\frac{1}{2} C_D \frac{M_p k_d}{A_e} V_{ex} S_t = M_t \sqrt{2 g h}$$

$M_t$  = Mass of Target (Pendulum)

$M_g$  = Mass of Incident Gas

$S_t$  = Ref. Area of Target

$I_t$  = Impulse Delivered to Target

$t_{gb}$  = Duration of Gas Flow

$A_e$  = Gas Blast Source Exhaust Area

$L_{gb}$  = Length of Gas Blast "Slug"

$k_d$  = Correction For Diverging Gas Flow (0.4 to 1.0)

$M_p$  = Mass of Propellant Expelled During Burn to Generate the Gas-Blast

$C_D$  = Effective Drag Coefficient of Target

FIGURE 15 A VACUUM CHAMBER BALLISTIC PENDULUM TO EVALUATE DESIGNS FOR GAS-BLAST IMPULSE TRANSFER TO A TARGET

The equation developed in Fig. 15 is repeated below:

$$\frac{1}{2} C_D (M_p k_{gb} / A_{ex}) V_{ex} S_t = M_t (2 g h)^{1/2} = I_t \quad (3)$$

where:

$A_{ex}$  = Exit Area of Rocket Nozzle

$C_D$  = Drag Coefficient of Space Target

$I_t$  = Delivered Gas-Blast Impulse = Acquired Momentum of Target

$k_{gb}$  = Constant to Account for Divergence of Blast-Gas "Slug"

$M_p$  = Propellant Mass Used to Generate Gas-Blast  
 $M_t$  = Mass of Target to Receive Impulse

Equation (3) relates the principle variables involved and can be used to scale-down the full sized space encounter for sub-scale testing in a space chamber, where  $h$  is determined from the swing of the Target pendulum in response to an incident gas-blast. It is interesting to note that the duration of rocket motor burn, or, duration of blast-gas generation, does not appear in the above equation. Thus, short, high density blast-gas slugs can be used to transfer momentum during the short time a space Target and the Interceptor Missile are in proximity. This can be done up to the limit of the structural loading that the Target, such as a satellite's solar panels, can take. It is also interesting to note several dimensionless ratios in Eqn. (3): one is the ratio of missile propellant mass to Target mass,  $M_p / M_t$  ; the other is the ratio of the Target aerodynamic reference area to missile rocket nozzle exit area,  $S_t / A_{ex}$ .

Thermocouple and microphone instrumentation of the Target pendulum can verify effects of blast-gas impingement on a Target model.

Figure 16 illustrates one form of a gas-blast generator. It would be more suitable for simulating a short duration pulse-type gas-blast delivery, rather than a sustained gas flow, as represented by a rocket motor exhaust.

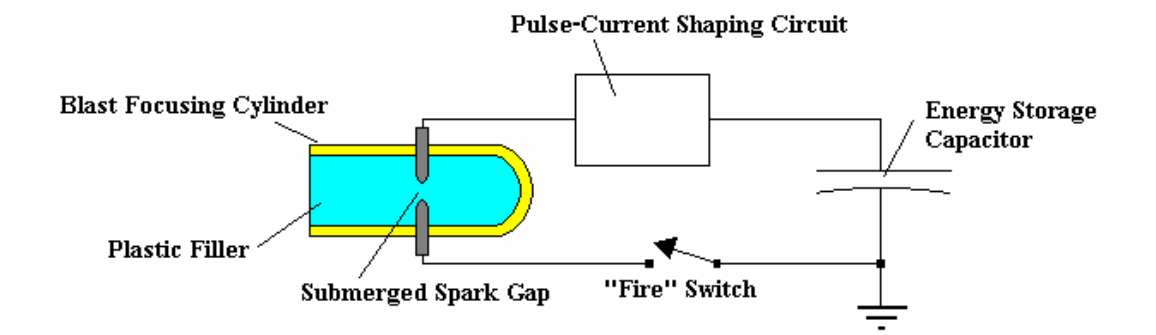


FIGURE 16 SIMULATING A GAS-BLAST SOURCE USING A CAPACITOR-DRIVEN SUBMERGED SPARK GAP

The stored energy in the capacitor should equal a scaled fraction of the energy of the propellant, plus additional energy for circuit losses. The plastic filler should be frangible into minute particles and should scale to the modeled mass of propellant.

### G. Non-Shrapnel Warhead Option

An alternate design for delivering a gas-blast is known as the Non-Shrapnel Warhead. Figure 17 shows a design for the Non-Shrapnel Warhead.

The Non-Shrapnel Warhead consists of lightly fused tapered gore sections designed to tear open along pre-formed lines of weakness during the explosion so that a dandy lion-like peeled-back stem results. Both the stand-off detonation distance and the warhead's chemical explosive formulation are selected so that the greatest impulse is imparted to the Target without exceeding the structural strength of the Target's weakest part (solar arrays, antennae, optical sensors, etc.). The warhead chemistry is designed to

control the rate of gas generation and the formation of any micro-particles. After detonation, the remaining missile structure will be a single unit that adds no additional debris to space. The post-detonation trajectory of the Interceptor Missile with a Non-Shrapnel Warhead is selected to make it de-orbit. Prior to detonation, the low drag aerodynamic nose cone containing the explosive is in the shape of an ogive to minimize air drag during ascent through the earth's atmosphere. Such a missile can be surface, air, or space launched and is guided to a computer-controlled standoff intercept, most likely a direct ascent type of intercept.

Figure 17 shows the variables and assumed warhead geometry for a study of the Non-Shrapnel Warhead explosion and blast-gas release. Variables shown are being used in a computer simulation of the gore shape change, using finite element analysis, as described below.

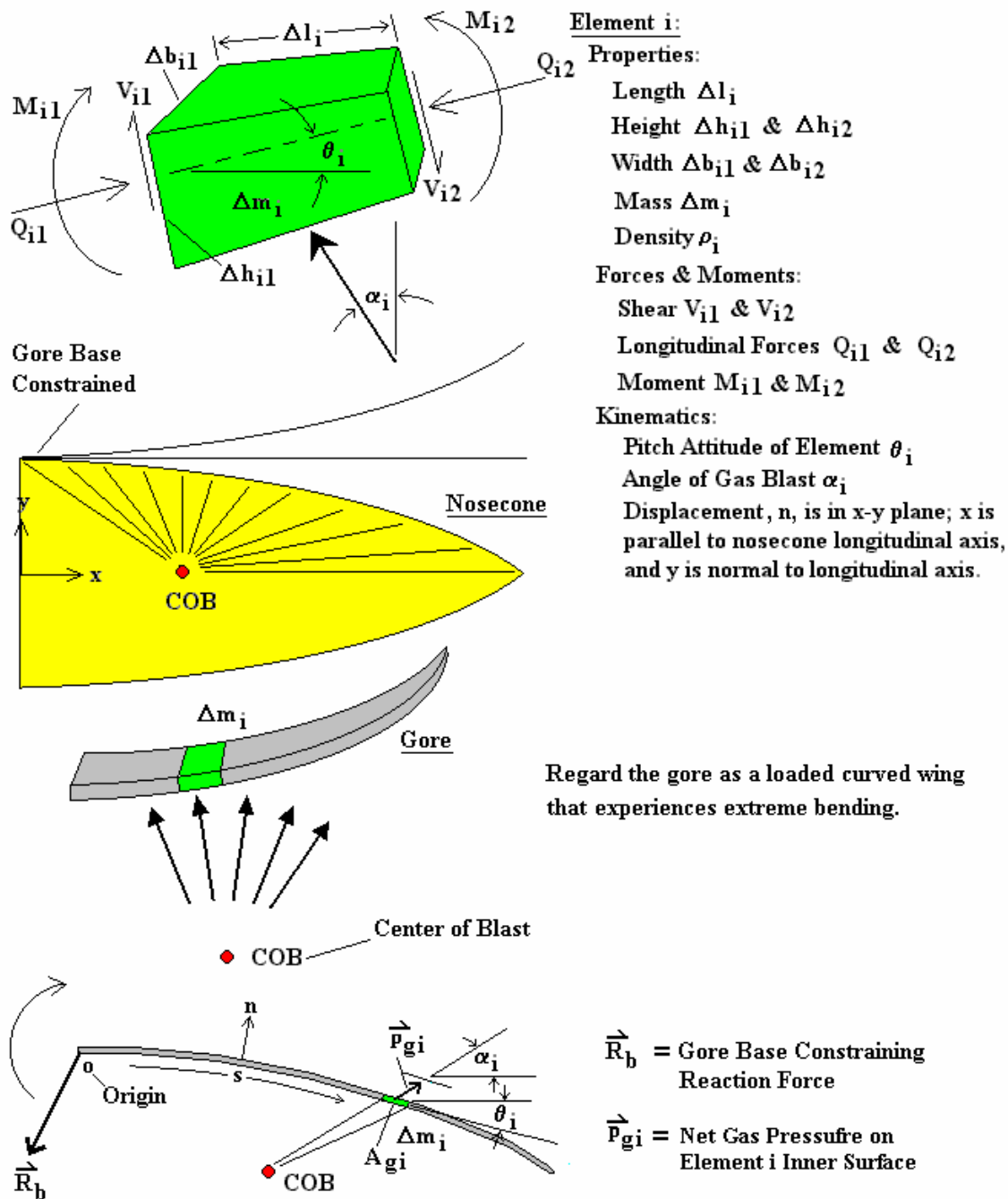


FIGURE 17 FINITE ELEMENT ANALYSIS OF NOSE CONE GORES

Before warhead detonation, the low drag aerodynamic nose cone includes lightly fused gore sections that envelop the explosive in the shape of an ogive to minimize aerodynamic drag during ascent through the earth's atmosphere. Such a missile can be surface, air, or space launched and is guided to a computer-controlled standoff intercept during a direct ascent or co-orbital trajectory. The nosecone, shown in Fig. 17, tears open

along pre-formed lines of weakness so that tapered gore sections are formed during the explosion. Both the stand-off detonation distance and the warhead's chemical explosive formulation are selected so that the greatest impulse is imparted to the Target object, without exceeding the structural strength of the weakest part of a valuable Target (solar arrays, antennae, optical sensors, etc.). The warhead chemistry controls the rate of gas generation and the characteristics of gas and micro-particles. The remaining missile structure after detonation is a single mass adding no additional debris to space since it can use its remaining propellant budget to rotate and re-enter the earth's atmosphere.

### III. Conclusions

The following points are important features of the concept, systems, and designs described in this paper:

1) It is demonstrated theoretically that an Interceptor Missile can generate a gas-blast to transfer an impulse to a Target object in space to alter its rotation and/orbit. The effectiveness of this technique depends upon the design and operational use of the Interceptor Missile.

2) The exhaust of a rocket engine can both propel a missile, and, when directed to intercept an approaching satellite Target, can impart an impulse vector without thermally damaging it by virtue of the space-chilled exhaust gas which becomes a free-molecule wind. The impulse vector can be delivered in an extremely attenuated form so that no damage occurs to the most delicate of space structures; or, it can be delivered with extreme intensity where damage, and heating, of the Target is of no consequence.

3) The determination of a Target satellite (or other space vehicle) silhouette, for purposes of gas-blast aim point, is done by using a pulse doppler radar to observe the pattern of departing microwave-scattering particles seeded into the rocket exhaust blast. The return doppler pattern in the radar resolution cells provides data to a computer for identification of the Target silhouette; analogous to weather radar mapping of rain cells.

4) The aiming of the missile to achieve a precise intercept of its exhaust gas "slug" with the Target is achieved by determining the Target's relative trajectory and rotation using low power, high frequency pulse doppler radar. Due to the very short ranges involved, miniature, low power radar electronics can be used.

5) A Thrust Reverser, similar to a solar sail, is proposed for decreasing the net thrust on the Interceptor Missile, by capturing some of the unused exhaust flow and re-directing it 180 deg. as a reverse thrust to reduce the Interceptor Missile's net acceleration, slowing its departure from the Target vicinity. Thus, more impulse is transferred to the Target, increasing the Interceptor Missile's mission effectiveness. A central hole in the Thrust Reverser canopy permits the central portion of the rocket exhaust through to impinge on the Target object (satellite or space junk) to transfer an orbit-changing impulse.

6) The Thrust Reverser is fashioned of steel foil to survive the exhaust blast temperatures. The steel foil is coated to radiate heat fast enough to keep the it sufficiently below its melting temperature. The steel foil canopy of the Thrust Reverser is held in place with steel cable "risers", much like a deployed parachute.

7) The Interceptor Missile may have an optional nosecone designed to split into longitudinal tapered gores that bend, but do not break, under an explosive gas blast, and are retained at the base of the nosecone. The selected gore shape and material, in combination with the explosive formulation, helps concentrate and focus the blast gases

by virtue of the inertial confinement provided by the gore strips. At the same time it releases no shrapnel that would otherwise add to space junk or damage a valuable Target.

8) The operational use of the gas-blast impulse technique involves a co-orbital intercept trajectory that closes with the Target object, or objects, at a selected angle to deliver the desired impulse vector for achieving the desired final Target momentum vector. The post-encounter departure trajectory of the Interceptor Missile is designed to de-orbit it for recovery, or to take it away from the final orbit of the Target.

9) Operational use of the gas blast non-shrapnel warhead also involves end-point aiming to deliver the gas-blast accurately at the Target centroid for maximum impulse transfer. The actual gas slug-Target intercept may involve a computed lead angle to account for range, relative closure velocities, and gas-blast flight speed.

10) Finally, operational use of the optional non-shrapnel warhead involves the distance from the Target object at which detonation occurs (fusing); thus affecting lateral spread of the blast gases and the free-molecule dynamic pressure applied to the Target mass.

11) Selecting the proper intercept trajectory (whether direct ascent, or co-orbital) to position the Interceptor Missile and the aim of a gas-blast at a space Target should be easier than docking an un-manned cargo rocket, such as the Russian Progress which is frequently docked with the International Space Station. (The Progress did, however, suffer a docking collision.)

12) Inexpensive sub-scale testing of the gas-blast impulse transfer concept in a vacuum chamber with a ballistic pendulum is recommended for determining a number of critical variables for design of the Interceptor Missile and its encounter trajectories.

## References

<sup>1</sup>Rocket Propulsion Elements, by George P. Sutton, John Wiley & Sons, 2<sup>nd</sup>. Edition, 1956

<sup>2</sup>Introduction to Airborne Radar, by George W. Stimson, Hughes Aircraft, Co., El Segundo, CA, 1983

<sup>3</sup>Elements of Gas Dynamics, by H. W. Liepmann, & A. Roshko, John Wiley & Sons, 1957

<sup>4</sup>GAS BLAST ORBIT MODIFICATION, Provisional Patent; PRO-114805; Guy F. Cooper, Ian B. Owens, 16 March 2006

<sup>5</sup>Use of a Gas-Blast Warhead to Perturb a DEFT Body Orbit by Guy F. Cooper, AIAA Planetary Defense Conference, February, 2004, AIAA Paper No. 2004-1440.

<sup>6</sup>A GAS-BLAST WARHEAD TO MODIFY A SPACE OBJECT'S ORBIT, by Guy F. Cooper, & Paul W. Fournier, U.S. Patent Office Disclosure DDP Docket #: 539800; Oct. 14, 2003

<sup>7</sup>Rocket Exhaust Plume Phenomenology, Frederick S. Simmons, Aerospace Corporation, El Segundo, CA, 2000