APPENDIX E

Orbital Debris Effects from Space-Based Ballistic Missile Interception

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Abstract: Effects of natural (meteoroid), manufactured, and missile interception orbital debris (OD) on satellite assets are quantitatively assessed. Enhanced levels of OD generated from either ground- or space-based interceptors are not likely to significantly affect space based (satellite) assets if the OD generated from ballistic missile warhead interception is limited in mass and transit time and is essentially sub-orbital debris. The primary, low-level, threat to space based weapons and satellites appears to originate from background natural (meteoroids) and OD from previous space missions.

1. Introduction

Deployment of space-based interceptor (SBI) weapons in low Earth orbit (LEO) using mechanical impact kinetic kill vehicles (KKVs) to destroy ballistic missile warheads (BMWs) will generate debris fragments. There is concern regarding the potentially deleterious effects of this debris on existing satellites and SBI platforms. In addition to the potential hazard from SBI impact on BMWs are impact effects from long-term exposure to background (man-made) orbital debris (OD) and meteoroid collisions. To address these concerns geometrically based calculations estimating collisions from long-term OD and meteoroid exposure in the LEO environment as well as short term effects from SBI launched KKVs impact-generated transient sub-orbital debris (SOD) eject on satellites and SBI platforms are presented. Conclusions are drawn regarding the viability for exercising options to deploy and effectively use SBIs for post-boost phase and mid-course interception in terms of background meteoroid and OD and transient SOD effects.

2. Assumptions and Caveats

Very high speed impact phenomenology is an extremely complex subject due primarily to the high kinetic energy interaction of several materials properties parameters in a nonlinear manner. To achieve tractable analytic approaches to estimate collision rates and hit probabilities on assets in LEO, assumptions regarding distributed (normative) responses of materials as described by the equations of state, energy transport under very high loading (strain) rates, and energy partitions into solid and vapor (plasma) phases must be made. Approaches to this problem have a long history in the twentieth century with substantial inroads. Further experimental work combined with (hydrocode) computer modeling and analysis is expected to make this problem more tractable.

Another uncertainty lies in accurately and reliably determining the background OD and meteoroid fluxes and their properties. Observational data regarding OD and meteoroid fluxes are uncertain over long time periods and are difficult above 1,100 km altitude. OD can be locally inhomogeneous and background meteoroid fluxes are regularly subjected to substantial intensity variations, i.e. meteoroid showers. While some of the observational uncertainties can be contained within a reasonable error range, transient effects such as intense meteoroid storms, disastrous impacts into a space station, or cataclysmic interaction with a close approaching near-Earth object can significantly alter the collision calculus. Calculations carried out in this work assume fluxes to be the long-term measured background that, unless otherwise specified, are uniformly distributed in LEO, as are satellites and SBI platforms. Density variations within LEO, impact velocity dispersions, latitude effects, inclination, variation with solar activity, and other considerations which affect density distributions are not taken into account. But non-uniform effects can be incorporated into the analytical framework as needed.

This report makes no assumptions regarding technical feasibility or operational effectiveness of SBIs as counters to perceived ballistic missile (BM) threats within the foreseeable future. Assumptions regarding SBI mass, flyout and divert velocities, lifejacket and guidance components, range, and other technical parameters are made only to carry through computations and are purely hypothetical and are not based on detailed design studies. Performance characteristics used in this computational study are not intended in any way to verify or even suggest the existence of such weapons or to support or encouragetheir construction, deployment, or use. It should be understood that deployment of SBIs under any circumstances is a geopolitically charged action that will significantly influence both national and international security policies. As such these actions can have unpredictable outcomes that may thwart the initial security objectives sought through emplacement of SBIs. Here technology could lead policy to an uncertain outcome. Nonproliferation and verifiable arms reduction combined with social justice in open and democratic societies are the keys to international security and world peace.

3. Background

Artificial space debris objects known as OD are derived from and include nonfunctional spacecraft, spent rocket bodies, discarded mission related objects, collision and explosion fragments from spacecraft and rocket bodies generated from processes either while achieving or during orbit. Most Orbital debris is confined to two regions of near-Earth space; LEO and geostationary orbit (GEO) (National Research Council 1995). Currently (August, 2003) there are ~ 9,000 cataloged objects in Earth orbit. The total number of tracked objects is > 13,000 (Johnson 2003). Because OD are fragments from objects whose orbits were dynamically designed to enter in an Earth orbit, OD orbit Earth and remain there until atmospheric drag or some other weaker perturbing force causes their orbits to decay into Earth's atmosphere. Since atmospheric drag is the principal mechanism for OD removal, debris on orbit above 600 km, where the atmosphere is tenuous, can remain there for tens, thousands, or even millions of years. OD above 600 km altitude are affected by solar-radiation pressure and solar-lunar gravitation perturbations. OD particles are subjected to a central (gravitational) force, traveling in elliptical orbits with higher velocities at perigee and lower velocity at apogee. OD with highly eccentric orbits will travel through the upper reaches of Earth's atmosphere (their perigee) at very high velocities and be rapidly de-orbited by drag effects. While traveling slowly far above the atmosphere, they encounter negligible drag. However, in 2002 a piece of OD ~ 20 - 50 cm in an eccentric orbit came off an old satellite at an altitude of 1370 km and decayed in only six weeks (Johnson 2003). Because of their large cumulative number, longevity, location, and potentially high impact velocities, the major hazard posed by OD is to spacecraft operations. The current hazard to most space activities is thought to be low especially above LEO. However, depending on non-warfare growth rates in commercial and military satellites the OD level may increase to the extent that it could threaten to make some important orbital regions (primarily GEO) hazardous to space operations. About 70 - 80 % of OD lie within 250 to 400 km and have velocities ~ 9 km/s. A rough estimate of the LEO OD population in terms of size and mass is provided in table 1.

OD Size (cm)	Number	% OD	% Mass
> 10	8,000	0.02	99.93
1 -10	110,000	0.31	0.035
0.1 - 1	35,000,000	99.67	0.035

Table 1. Estimated OD Population (Interagency Rept., 1995). Cataloged objectives make up ~ 99 % of the OD mass. Haystack detections are ~ 600 - 1,600 km and radar cut-off at ~ 0.6 cm. Estimated LEO averaged background collision cross-section for 1 cm, $\sigma_{1cm} \approx 4 \times 10^{-5}$ /y-m^2. Since LEO extends well above 1,000 km the Haystack numbers at higher altitudes may be too low (~2 x) because of radar resolution limits. For 0.5 cm particles, $\sigma_{0.5cm} \approx 10^{-4}$ /y-m^2, but may be higher. For OD$\geqq$ 0.1cm ($\sigma_{0.1cm} \approx 8 \times 10^{-4}$/y-m^2), structural damage and space erosion may become an important factor.

4. Low Earth orbit region

The current international definition of LEO is that region within 2,000 km of Earth's surface where OD speeds are ~ 3 - 15 km/s. The U.S. Department of Defense sometimes uses an older definition of 5,875 km, equivalent to < 225 minute period. The orbital period at an altitude of 2,000 km is ~ 127 minutes. The volume of LEO is usually taken as that of the whole sphere between given latitudes, i.e. a spherical symmetrical shell. Post- boost and mid-phase interceptions of BMWs for the most part will occur in LEO which theoretically extends up to ~5000 km, with a majority of objects from ~ 200 to 2,000 km altitude above Earth with orbital periods < 200 minutes. For LEO objects radars provide the most sensitive method of detection and size estimation. Because radar intensity echo diminishes to the fourth power of the distance (altitude), very strong pulses are required for high altitude OD detection. The Haystack radar can see objects as small as 0.5 cm but only at a very low altitude, ~ 500 km.

At 1,000 km the sensitivity is probably closer to 1.0 cm and at 1,600 km the sensitivity is even less. For small debris detection operations the maximum range of Haystack ~ 2,000 km (Johnson 2003). The limiting diameters which the Haystack radar can detect depends on the type of reflecting material as well as their distance. The detection limit of the Goldstone bi-static radar operations is estimated to be about 2-3 mm. Because the radar assets are limited these measurements are only regional snapshots. From direct impact measurements of recovered areas exposed in space a very large number of OD particles ~ 0.01 to 0.001 cm in size were found from chemical analysis on the LDEF (Long Duration Exposed Flight) satellite panels which never achieved an altitude above 480 km. The overwhelming majority of (large) objects tracked as of Nov. 1, 1995 had ~ 5747 cataloged objects including the International Space Station (ISS). The peak population is ~ 1,000 km. LEO has an average flux of material > 1 cm in size ~ 4 x 10-5 particles/m^2-y (Johnson et al 2002) and peaked ~ 800 to 1, 000 km. At ~ 1,500 km the OD travels at 7-8 km/s with widely varying inclinations. Skimming velocity atop Earth's atmosphere is ~ 7 km/s at 2,000 km. Theoretically, collision velocities in LEO can vary from 0 - 15 km/s. However, when discussing total population numbers for very small objects one refers to the fluxes at specific altitudes and/or inclinations rather than a generalized region. For example, the flux of 100 micron particles in the ISS orbit, normally held between 350 and 400 km, is ~ 19/m^2-y (Johnson 2003). Because many of these particles have highly elliptical orbits discussion of total populations is less useful than assessing fluxes in specific orbits.

It has been suggested that in near-Earth space one must be concerned with OD accumulation and perhaps localized chain reaction effects. But there has not been any convincing evidence or models to support this conclusion. Computational results suggest BMW trajectories that either skim the upper reaches of the Earth's atmosphere or penetrate deeper into LEO and explode or collide with a SBI can indeed generate a considerable amount of transient SOD within a volume swept out along the axis of BMW center of mass trajectory. It is shown that a self-sustaining chain reaction is highly unlikely even if numerous break-ups occur because LEO is so large and fragment debris volumes are relatively small and transient, e.g. < 2,000 s. SOD fragments have minimal short-term and virtually no long term effects. A very small number of fragments may achieve true OD status. If several break-ups occur in the narrow band satellites occupy along exact GEO or GPS orbits results could be different.

The ubiquity of OD in LEO is underscored by pitting and micro-cratering on spacecraft surfaces recovered from lower regions of LEO, ≤600 km. After six years of continual exposure, 32,000 impact craters large enough to be visible to the naked eye were found on the LDEF panels, the largest of which was 0.5 cm in diameter. Subsequent analysis indicated that ~ ½ of the larger craters were of OD origin and ~ ½ were thought to be caused by meteoroids. These results are supported by observations of pitting on the U.S. space shuttle and Salyut and Mir space stations. Other spacecraft that had their surfaces marred by OD include the Solar maximum Mission (Solar Max). Nonetheless, uncertainty remains regarding intensity levels and particle size distributions of OD flux as a function of altitude above Earth. The US Air Force (USAF) Space Command (Colorado Springs), whose primary role is to monitor US space assets and ICBM activities uses ~ 30 radar and optical sensors to track ~ 10,000 OD objects, and maintains a catalog of tracked OD. Although this facility provides close approach determination and warnings for a few high-risk satellites, their systems would have to be substantially augmented (phased array and visible sensor upgrades) to manage the large number of fragments from SBI of ICBMs. A difference between the USAF and NASA approaches to OD is that the USAF considers OD to be significant if it is trackable while NASA considers smaller OD (often non-trackable) objects in its assessment models.

5. Twelve hour and geostationary orbits

When discussing so-called "12 hour orbits", it is important to distinguish between circular and highly elliptical geometries. One high asset concentration band is the GPS satellite circular orbital period of ~ 12 hours at a mean altitude of 20,200 km. The other is composed of families of satellites using highly elliptical 12 hour orbits with perigees in LEO and apogees near 40,000 km. The official GEO altitude is 35,786 km and a nominal operating band is +/- 200 km, including the transfer corridor. The normal operating band is +/- 75 km (Johnson 2003). If the volume of GEO is constrained to about +/- 15 degrees latitude (the maximum natural drift of an uncontrolled satellite at GEO) and GEO altitude of +/- 200 km, higher OD values can be obtained. Because GEO altitudes are so high it is militarily disadvantageous for BMWs to traverse this region unless deliberately targeted.

GEO's orbital period of ~ 24 h (~ 36,000 km) is synchronous with Earth's rotational period, giving these orbits enormous commercial and military importance because large Earth-based facilities are not required to track transmitting satellites. Most objects in GEO are spread along the 0 degree latitude (equator) geostationary band at very small inclinations, < 5 degrees. Most OD in GEO are too far away from Earth to be detected by radar. For altitudes > 1,000 km optical telescopes are used to detect reflected sunlight during the brief periods before sunrise and after sunset, assuming clear skies. Radar is not constrained by cloudy weather as are optical telescopes. As of Nov. 1 1995 there were ~ 601 objects in GEO. The average velocity in GEO is ~ 3.075 km/s. The average velocities between objects in GEO varies from ~ 100 to 500 m/s, with a maximum ~ 800 m/s. There are now just over 700 spacecraft in or near GEO and more than 200 nearby rocket bodies. The flux of objects > 1cm in GEO is not known for certain, and is highly dependent on how GEO is defined in terms of latitude and longitude. There are very few measurements between 20 ad 100 cm and no reliable measurements in the range 1 to 20 cm. Objects > 1cm can be reliably measured. However, as a rough estimate, the average OD material flux in GEO for > 1 cm is ~ 2 x 10^{-8} particles/m^2y (Johnson et al 2001). Although this is a very small number in terms of a baseline for establishing a sustained OD chain reaction, it is speculated that for satellites closely aligned along a common orbit, a synchronous series of explosions or collisions within a confined orbital region may lead to "orbital pile-up. But such a chain reaction scenario hasn't been analytically demonstrated for realistic conditions. Anti-satellite (ASAT) operations against valuable satellites in GEO orbits confined to narrow (crowded) bands extending from 34,850 to 36,550 km and peaked at 35, 550 km could be a problem. But GEO asset sabotage requires tremendous technical skill and substantial launch and tracking capabilities.

MEO or middle earth orbit is a sparsely populated region between LEO and GEO with only ~ 134 objects (Nov.1, 1995). This vast region from the end of LEO (2,000 km) to GEO (~ 37,000 km) (~ 257 x 10^{12} km^3) can sequester enormous amount of OD with low probability of damaging a satellite. Above and below GEO the flux is less than ~ 10^{-10} particles/m^{2-}y or even lower. There are few satellites and booster vehicles in these elliptical orbits. Other orbits traversing MEO are highly eccentric transfer orbits.

6. Comparison of LEO and GEO

OD flux and dynamic reactions to explosions, fragmentations, and BMW interceptions in LEO differ from those in GEO. In LEO, a densely populated region between 800-1,000 km (ICBM altitude range), radar tracks orbital velocities ~ 7.45 - 7.35 km/s, respectively, and an average collision velocity ~ 10 km/s, depending on inclination. High secular removal rates, especially in lower LEO regions, minimize effects of SBI/BM warfare. In GEO OD density is much lower and more uncertain than in LEO with a much lower collision velocity range than in LEO. On the other hand in GEO there are no secular removal mechanisms; OD can linger indefinitely. But the potential for a catastrophic event and long term disastrous outcomes from single point events exists. Survival of large strategically critical satellites in GEO may be vulnerable, under certain circumstances, to a single breakup such as at least one known Titan Transtage. While other breakups near GEO may have gone undetected there are no Delta second stages in or near GEO. Fragmentations induced by a deliberate act could cause severe problems depending on the magnitude. In general, OD will tend to migrate toward the stable points on the ring while their orbital inclinations would vary slowly and periodically. Disasters in GEO would be difficult because natural OD removal processes don't exists and the great distances at which (remedial) space operations must be carried out. Within the present context of space warfare GEO is unlikely to be affected by SBI/BM warfare, but is potentially vulnerable to direct ASAT attack.

7. The Meteoroid Flux

Meteoroids are natural particles, debris remnants from de-volatized comets and asteroids and are chemically analogous to the composition of comets and non-metallic meteorites, i.e. Fe, Mg, silicates. For the very fine particles meteoroid dust sizes range from ~ 1 to 1 mm with an average density of ~ 0.5 gm/cm^3 and, depending on their size, can be as high as 1 g/cm^3. Since meteoroids are derived from comet and asteroid materials their density range extends to meteorite densities, > 1 g/cm^3. Just above Earth's atmosphere meteoroids move much faster at ~ 11 to 72 km/s. A 0.3 cm diameter meteoroid can break a space shuttle wind screen or cause interior damage to a satellite. It is estimated ~ 40,000 metric tons of meteoroids enter Earth's atmosphere each year (Love and Brownlee 1993).

The probability a 1m^2 surface in LEO would be struck by a 1 cm meteoroid during a year is about 10^{-6}. Because of meteoroids small size and low density simple satellite design features can often protect spacecraft against some meteoroid threats. But during a periods of intense meteoroid bombardment the meteoroid threat may be significantly enhanced, rendering this protection useless.

8. Collision Rates from Background OD and Meteoroid Flux

The collision rate dN/dt of background OD and meteoroid flux is defined as

$$\text{Collision rate} \quad dN/dt\,(y^{-1}) = S\,\sigma\,A \qquad (1)$$

S = number of satellites, σ = orbital debris cross section (1/m^{2-} y) and A = average satellite area (m^2). Table 2 summarizes observations for three OD sizes and for meteoroid sizes > 0.03 cm in LEO. At the ISS orbit, meteoroid flux becomes greater than the OD flux for particles < 0.5 cm. Also listed are potential OD and meteoroid impact effects on satellites. Actual effects depend on where a satellite is hit and its protection.

OD Size	*(1 / m^2·y)	A(m^2)	Collisions/y	Result
$\geqq$ 1 cm	4×10^{-5}	10	0.2	
		50	1	severe damage
$\geqq$ 0.5	10^{-4}	10	0.5	
		50	2.5	damage
$\geqq$ 0.1	8×10^{-4}	10	4.0	
		50	20	degradation
Meteoroid size				
$\geqq$ 0.3	2×10^{-4}	10	1	
		50	5	damage

*Cross-sectional flux of a given size and larger (Johnson et al 2001).

Table 2. Orbital Debris Flux in LEO.

Table 2 provides the average annual collision rate for three OD sizes and one meteoroid size reference for 500 SBI platforms in LEO with areas of 1 and 50 m^2. Damage will depend on how well the satellite is protected and where and at what velocity the impact occurs.

9. Collision, Fragmentation and Vaporization

Enormous amounts of energy released during high speed impacts rapidly initiate a very complicated sequence of events depending on the relative density, mass (size), strength, and thermodynamic properties of the interactants. Because the energy per kilogram far exceeds the vaporization energy a plasma process evolves. Analysis suggests a 5 kg mass impactor undergoes massive vaporization at a relative impact velocity of 10-12 km/s. If the target is far more massive than the impactor, much of the impactor energy is partitioned into self-melting and vaporization (Lawrence 2003). It is convenient to assume for the purposes of this simple study to assume that if BMW and KKV materials are similar roughly equivalent BMW and KKV masses will be vaporized with the bulk of the more massive BMW remaining solid. One must also understand that if the BMW has a hardened, ablative coating, the amount of fragmentation may not be commensurate with the KKV. Also, one must take into account debris generated from impacting some of the decoys which would be dissimilar to the BMW materials. Table 3 describes impact phenomenology in terms of energy partition regimes.

3 - 5 km/s (4.5 - 12.5 x 10^6 J/kg): Solid fragmentation dominates with some melting and little vaporization.

> 5 km/s (> 12.5 x 10^6 J/kg) : Major portions are melted with some vaporization.

> 7 km/s (> 25.9 x 10^6 J/kg) : Vapor (plasma) dominates impact process.

Table 3. High Energy Density Impact Regimes. High speed impact processes are divided into three groups according to the amount of energy released at impact and the collective processes through which this energy is transformed.

Energy distributions for a 500 kg BMW target mass traveling at 7 km/s and five KKVs with masses of 0.001, l, 5, 10, and 50 kg impacted head-on at 3 km/s are given in Table 4.

KKV mass	**0.001**	**1**	**5**	**10**	**50**	**kg**
E_{Total}	12.25	12.28	12.37	12.50	13.48	x 10^{9} J
E_{Int}	0.05	49.9	247.5	490.2	2,272.7	x 10^{6} J
E_{Int}/MKKV	50	49.9	49.5	49	45.4	x 10^{6} J/kg
v_{rms}	2.61	2.60	2.59	2.57	2.43	km/s

Table 4. Fragment velocities from a 10 km/s impacts as a function of KKV mass. Total interaction energies, E_{Int}, interaction energies/kg, E_{Int}/MKKV, and rms velocities, v_{rms}, of fragments ejected from a KKV/BMW impact at a relative velocity of 10 km/s are listed as a function of KKV mass.

Increasing KKV mass slightly reduces available kinetic energy/kg and therefore the mean velocities of non-vaporized fragments. For 5 kg KKVs all but ~ 0.25 x 10^{9} J is of the total energy (49.5 x 106 J/kg) is available to fragment, melt, and establish a plasma vapor that propel fragments from the main BMW body. The respective average fragment velocities achieved from the 5 and 50 mass KKVs are 2.60 and 2.43 km/s. The highest velocity is achieved by a 1 g KKV at 2.61 km/s. Substantially increasing KKV mass only slightly reduces fragment velocities but generates an order of magnitude more SOD. If the KKV mass is kept below 5 kg, SOD flux will be low (i.e. it is arbitrarily assumed that there will be ~ 50,000 1g particles vs. 500,000 1 g particles for a 50 kg interceptor). A small and fast KKV can minimize SOD and enhance interception capabilities while minimizing lift costs. For M = 500, m = 5 kg, V = 7 km/s and v = 3 km/s, BMW trajectory perturbation is $\Delta V \approx$ 30 m/s. Over 1,000s target location is changed by ~ 30km. If equal amounts (5 kg each) of BMW target and KKV material are vaporized at ~ 8 x 10^{6} J/kg x 10 kg crushing, fragmentation, melting, vaporization energy, ~ 8 x 10^{7} J is extracted. Also, if it is assumed that high pressure shock waves generate fifty kg of fragments from the BMW, ~ 168 x 10^{6} J remain to accelerate fragments, at a root mean square fragment velocity of ~ 2.59 km/s.

10. Impact ejecta velocity and possible orbits

At extremely high impact velocities a very small fraction of plasma propelled ejecta may actually exceed the relative impact velocity, but generally remaining below 1.5 x impact velocity. The statistical distribution of this small fraction of particles can be determined by applying the error function to the root mean square velocity (rms) velocity. For a small impactor that does not break up the target, spray angles are likely to be more confined, there is generally a small angle of spray with most ejecta leaving the target along the opposite vector of the initial impactor. Impact between two commensurate bodies have large spray angles for both large and small OD particles. In cases where the impactor/target mass $<<1$ the center of mass will not significantly deviate from its trajectory and the impact (explosive) energy is derived from the reduced mass impact at the relative velocity. In these processes the higher the ejecta velocity, the smaller is the spray angle, although this last condition is not critical to calculating the rms velocity. The velocity of fragments, U, from an asymmetrical impact can be determined as a function the SBI impact velocity, energy reflection back into the SBI which ablates the impactor and energizes the vapor. A method (Remo 2003) estimate fragment velocity based on impact energy transmission, fraction of the (KKV) ablated, and Lagrangian plasma velocity and density profiles in the impact region suggests a KKV impact into a BMW at ~ 10 km/s yields a , v_{rms} ~ 2.5 km/s, in close agreement with the result in part 9.

A center of mass dominated (mass BMW >> mass KKV) radial type of impact fragmentation from an object on a sub-orbital trajectory, whether space or ground launched, confines lower velocity debris fragments within a small region of LEO defined by the sub-orbital BMW trajectory. Depending on the altitude, OD fragments are ejected over a range of angles and velocities, even if specially configured space charges are used. Some fragments at the very high velocity end of the spectrum could achieve eccentric orbits, hastening fragment de-orbiting from enhanced drag at perigee. High velocity fragmented materials directed radial away from Earth may achieve very eccentric orbital velocities and even achieve OD status. At sufficiently high velocities they may travel in a myriad of orbits, depending on their angle and velocity. It is possible that a statistically small number of higher velocity components achieve velocities ~ 11.6 km/s, depending on altitude allowing trajectories across (trans-orbital) weak instability boundaries .

11. SOD impacts on satellites in LEO

A straightforward and conservative approach is taken to compute upper limits to OD impact probabilities i.e. a "worst case scenario." For a sub-orbital trajectory, a linear model expresses the average satellite collision cross-section, σ_s,

$$\sigma_s = S\,A\,(\pi g^2 u_{rms}^2)\,v\tau^3 / (\mathrm{Vol}_{LEO}) \qquad (2)$$

S = number of satellites in LEO (S = 6,000 for the cataloged population; the number of operational spacecraft in LEO for all nations is closer to 300), A = average area of each satellite (1 m^2), u_{rms} = rms radial velocity of fragments = 2.5 km/s, g < 1 (~ ½) is a fragment trajectory factor associated with urms, v = velocity of the BMW (v = 7 km/s), τ = trajectory time of BM after being impacted by SBI, and Vol_{LEO} = volume of LEO .

$$\text{SOD flux} = F = 4 \;\; v / (\pi g^2 u_{rms}^2 \; v\tau^3) \qquad (3)$$

Where η= # fragments/ impact.

$$\text{Collision rate} = dN/dt = F\sigma = S\,A\,\eta\, v / \mathrm{Vol}_{LEO} \qquad (4)$$

Assuming η= 50,000 particles per SBI interaction with average mass of 1g.

$$DN/dt = 2.1 \times 10^{-9} \text{ collisions/SBI hit -s}$$

The total number of collisions, N, per SBI hit on a BMW during the entire BMW trajectory transit, τ, from 200 to 2,000 s, is (4.2 - 42) x 10^7/SBI hit. The collision probability, P, over τ = (4.2 - 42) x 10^7/SBI hit≈0. For 500 platforms with 10 SBI each, the total number of SOD collisions = (2.1 -21) x 10^{-3}. The total collision probability = 0.0021- 0.021 Even for 5,000 BMW hits and a 2000 s SOD trajectory, the total number of hits on all satellite assets in LEO is 21 x 10^{-3} and only ~ 0.001 for active satellites. The assumption is the fragmented particles are a single size; a logarithmic size distribution with more smaller particles and fewer larger particles is more likely.

12. Sub-orbital impacts on SBI platforms: fratricide

If the SBI platforms are confined to narrow operational regions of LEO from 7,000 km and 6,500 km altitude, the SBI volume, Vol_{SBI} ,= 276×10^9 km^3 . The SBI fragment sub-orbital volume swept out during the post impact trajectory is $V_{Frag,}$

$$Vol_{Frag} = \pi g^2 u_{rms}^{\ 2} v \tau^3 \qquad (5)$$

where U_{rms} = 2.5 km/s, Vol F_{rag} = $g^2\, 137 \times (10^6 - 10^9)$ km^3 for sub-orbital transit times of 100 and 1,000 s. A potential fratricidal scenario involves BMW destruction within a confined volume of LEO where SBI platforms reside. Here, the fragment flux is given by

$$F = \eta v / (\pi g^2 u_{max}^{\ 2} v \tau^3) \qquad (6)$$

The SBI platform collision cross section is $\sigma_{SBI} = S_{SBI} A$, where S_{SBI} is the number of SBI platforms of area A. SBI platforms that intersect the same LEO volume as the impact fragments maximize interaction. The collisions per SBI hit/s in this "space kill zone" is

$$dN/dt = F\sigma_P = 4\pi\, S_{SBI}\, A/\pi u^2 \tau^3 = 40 \times 10^{-8} \text{ hits/ SBI-s} \qquad (7)$$

The total number of collisions N during passage of the SOD for each interceptor hit during the BMW trajectory transit, τ= 1,000 s, is 40×10^{-5}/SBI hit. The probability, P, of a hit is 4×10^{-4}. Again, for the 500 platforms with 10 interceptors each the probability is 2 hits. The probabilities for two, three, or four SBI platform hits are respectively; P_2 = 0.27, P_3 = 0.18, P_4 = 0.09. Therefore, there is almost a 10% chance that an SBI platform be hit four times and could be lost to SBI fragment fratracide. Given that there are 500 SBI platforms, this number is quite low. Even if fragment velocities were twice as high, the impact probability would not change significantly. Ironically, the 500 SBI platforms at 50 m^2 surface area each provide a larger target than the passive satellite assets in LEO. For active satellites the numbers are significantly lower. However, if the SBI platforms are deliberately targeted, the calculus for the hit probabilities can dramatically change. But this is ASAT targeting and requires a different approach than outlined here.

The mean free path, λ is the distance traveled divided by the number of collisions occuring within a given time, t,

$$\lambda = \text{distance over time /\# satellite collision in this time} = v\, t / F \sigma t \quad (8)$$
$$= \text{Vol}_{LEO} / (S\, A\, \eta) \quad (9)$$

Determination of Vol_{LEO} is critical to because Vol_{LEO} establishes the confinement of the collision process. If $\text{Vol}_{LEO} = 10^{12}$ km^3, and S = 6,000 = active and inactive satellites, A = 1m^2, and 50, 000 one gram particles per KKV hit on a BMW, then = 33 λ 10^8 km, underscoring the how difficult it is to initiate random collisions in near-Earth space. However, if interactions are confined to a limited region in LEO where fragmentation processes occur and where SBI platforms are located, $\text{Vol}_{LEO} = 22 \times 10^6$ km$^{3.}$ The number of interacting satellites is also proportionally smaller. The cross-section of 500 SBI platforms, each with area ~ 50 m^2, $\lambda \sim 18 \times 10^3$ km.

13. Shielding against OD

Effects of OD can sometimes be mitigated to a certain extent through deployment of shielding, such as the well-known Whipple shield that typically consists of two thin, spaced, usually aluminum, walls. This configuration and variations thereof can provide some level of protection to spacecraft from the small but prevalent high speed OD impacts. Recently, enhanced protection shields have been developed utilizing exterior bumper layers composed of hybrid fabrics woven from a combinations of ceramic fibers and high density metallic wires. Other designs include completely metallic outer layers composed of high-strength steel or copper wires. These shields are designed to have reduced weights while providing protection against OD with mass densities up to ~ 9 g/cm3 without generating damaging secondary debris particles (NASA 2003). Other design options include lightweight woven polymer fabrics with special metallic coatings and the sue of geometric shapes to provide enhanced protection for particular orientations and projections.

Improvements in the deployment of OD shields include using sparsely distributed wires made from shape memory metals that can be stored in small volumes and be thermally activated into pre-determined shapes once in orbit. Another possibility is that sequestering several assets within an extended volume ill minimize an assets surface/volume and maximize shielding. Space maneuvers such as close-formation flying may further reduce risk and optimize shielding use against meteoroids, OD, and SOD.

14. OD and ASAT Issues

It can be assumed that if a space weapon is deployed its presence will be duly noted and countermeasures will be developed, tested, and deployed. The space based weapons systems would have a high level of vulnerability. Serious ASAT warfare among space powers could create enormous amounts of OD if explosions and mechanical fragmentation occurs with the center of mass of the debris field following the trajectory of the exploded satellite. Such an action would be counterproductive in symmetric warfare because space assets would be lost rapidly and indiscriminately by both sides. Parties with high asset exposure in space are not likely to engage in ASAT unless they became desperate and are left with very limited options. Given current missile technology proliferation it is quite plausible that rogue- or non-state entities with few or no space assets to defend could wantonly attack assets to initiate enough OD that additional satellites could be indiscriminately destroyed. If such an unlikely scenario were to occur, it may constitute a successful outcome for a rogue state. However, technologically advanced powers could use more sophisticated and subtle methods to disable ASATs without creating significant amounts of OD. Such methods include electromagnetic pulses, laser beams, foulants, low velocity penetrators, etc.

15. Summary of computational results

The first issue regarding OD/BMW interception issue involves fragment generation from kinetic impact into BMWs when the KKV interceptor impacts the BMW at a velocity of roughly 2.4 to 12 km/s. If BMWs are ~ two orders of magnitude in mass greater than the interceptor, it will be almost totally obliterated with of spall fragments unloading from the rear and accelerated by the plasma generated at impact. The BMW will have a crater but essentially remain intact. As KKV mass increases, more of the BMW is destroyed, but this does not necessarily indicate the impact fragments will have higher velocities.

The second point is that the overwhelming majority of fragments never achieve OD velocity but follow a transient SOD trajectory status that reduces impact probability because SOD lasts ~ 2,000 s or less. A few outlying fragments may achieve true OD status and even escape from Earth's gravity, but these outlying fragments are few and do not effect astrodynamic or strategic SBI issues.. The third point is the vastness of LEO where 50, 000 or 500,000 particles ~ 1 g each are quickly dispersed and have mean free paths ~ 10^{9} km. There may be local interaction in space where the particle densities are anomalously high and the mean free path is regionally reduced, but these are thought to be rare exceptions. Fourth, the chances of SOD satellite impact within the transient time frame, at most a few thousand seconds, are minimal.

16. Conclusions

The generation OD and SOD fragments from SBI impacts on BMWs will not cause a significant amount of damage to satellites and other SBI platforms in LEO. Under certain circumstances, when a concentration of SBIs is deployed, a possibility exists that some SBI platforms may be lost due to fragments ejected from BMWs impacted by KKVs. This would be a limited fratracide with only about three out of 500 platforms being lost. The reason for this limited effect from fragment debris is that almost all but a few of the fragments become SOD and are constrained to travel close to the original BMW (ballistic) trajectory because relative to the (sub-orbital) center of mass velocity the fragment velocity is small. This trajectory would have a lifetime < 2,000 s and occupy a relatively small volume in LEO since the fragmented particles have a relatively small spread velocity and short sub-orbital lifetime. The combination of occupying a relatively small volume of space within a small transient period substantially reduces SOD collision cross-sections. The few high velocity fragments directed away from Earth's surface may achieve OD status but are negligible compared to the existing OD and meteoroid flux.

The (constant) background OD and meteoroid flux by far poses the greatest threat to the SBI platforms and satellites. Indeed, one could expect to have at least two to five SBI platforms damaged each year from these background fluxes. Whether this damage is would be great enough to disable the platforms will depend on the size and velocity of the impact, where on the platform it hit, and how well protected the platform and its components are. But SBI platforms must be maintained, and that could substantially add to the lift costs. Ground based interceptors are not subject to such damage levels and are mush easier to maintain. One may conclude that neither the presence of background OD and meteoroid flux nor SOD fragment from BMW interception will substantially affect the integrity of either satellites or SBI platforms. There are special circumstances where OD and SOD can become hazardous to space assets in regions of space such as a cataclysmic fragmentation of the space station or deliberate ASAT warfare. Based on preceding analysis for a worst case scenario, the following conclusions are drawn for satellites, SBI and other assets deployed in LEO.

1. SOD is transient, sub-orbital, and generated in relatively small amounts during SBI impact in a vast volume of space. It is unlikely that fragments from SBI impacts on BMWs will significantly contribute to the OD population in LEO or collateral damage to satellites and/or SBI platforms. SOD does not pose long term threat to operations in LEO.

2. Background OD and meteoroid fluxes pose minor but real hazards to SBI deployment. Some protection against this background flux and SOD can be achieved though hardening and orienting satellite and SBI platforms.

3. There are some cases where collateral fragmentation can achieve anomalously high SOD and OD flux level in a very narrow volume of LEO.

4. Deployment of space based weapons introduces additional maintenance, reliability, and security factors that do not exist for interceptors that are sequestered on or within the earth or sea. Shielding may provide some level of protection for space assets.

17. Acknowledgements

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Errata

We regret errors appearing in Appendix E. They are the fault of the editor and printer and not of the contributing author.

Appendix E
P. 103, line 25: change “size range from ~ 1 to 1 mm” to “sizes range from ~1μ to 1 mm.”
P. 108, eq. (3): “$4\ v/(\pi g^2 u_{rms}{}^2 v\tau^3)$” should read “$4\eta v/(\pi g^2 u_{rms}{}^2 v\tau^3)$.”
P. 108, line 18: and 8 from the bottom:
P. 108, line 14: “10^7” should read “10^{-7}.”
P. 109, eq. (7): “$4\pi S_{SBI}A/\pi u^2\tau^3$” should read “$4\eta S_{SBI}A/\pi u^2\tau^3$.”
P. 110, line 3: change “Vol_{LEO} is critical to because” to “Vol_{LEO} is critical to λ because.”
P. 110, line 6: “$= 33\ \lambda\ 10^8$ km” should read “$\lambda = 33 \times 10^8$ km.”
P. 110, line 21: “~9g/cm3”should read “~9g/cm^3.”
P. 111, line 1: “ill” should read “will.”