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Orbital Debris Effects from Space-Based Ballistic Missile Interception

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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 affect significantly space-based (satellite) assets if the OD generated from ballistic missile warhead interception is limited in mass, velocity, and transit time and is essentially suborbital 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.

I. Introduction

DEPLOYMENT of space-based interceptor (SBI) weapons in low Earth orbit (LEO) with use of mechanical impact kinetic kill vehicles (KKVs) to destroy ballistic missile warheads (BMWs) will generate debris fragments. Concern arises regarding 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 (manmade) orbital debris (OD) and meteoroid collisions with the SBI platforms themselves, rendering them ineffective while also creating additional OD. To nontendentiously address these concerns, geometrically based calculations estimating collisions from long-term OD and meteoroid exposure in the LEO environment and short-term effects from SBI-launched KKVs impact-generated transient suborbital debris (SOD) ejecta 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 midcourse interception in terms of background meteoroid and OD and SOD effects. This analysis does not address effects associated with high-energy radiation effects from the detonation of a nuclear explosive in space or the long-term effects from high-intensity solar activity, which can also present substantial hazards to satellites.

II. Assumptions and Caveats

Very high-speed impact phenomenology is an extremely complex subject due to the high kinetic energy interaction of several materials properties parameters in a nonlinear manner. To achieve tractable analytic approaches that estimate collision rates 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. Experimental work combined with (hydrocode) computer modeling and analysis are expected to make this problem more tractable in the future.

Another uncertainty lies in accurately and reliably determining background OD and meteoroid fluxes and properties. Observational data regarding OD and meteoroid fluxes are uncertain over long time periods, especially above 1100-km altitude. OD can be locally inhomogeneous and background meteoroid fluxes are regularly subjected to substantial intensity variations, that is, meteoroid showers. Whereas 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. These calculations assume fluxes to be 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 that effect density distributions are not taken into account, but can be incorporated into the analytical framework as required.

This study makes no assumptions regarding the 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 hypothetical and 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 encourage their 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. Such actions can have unpredictable outcomes that may thwart initial security objectives sought through emplacement of SBIs. Here technology could lead policy to an uncertain outcome.

III. 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 OD is confined to two regions of near-Earth space: LEO and geostationary orbit (GEO).[1] Currently (August 2003), there are ∼9000 cataloged objects in Earth orbit. The total number of tracked objects is >13,000 (N. Johnson, personal communication, 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. Because 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

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Table 1 Estimated OD population[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

velocities and be rapidly deorbited 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, personal communication, 2003). Because of their large cumulative number, longevity, location, and potentially high impact velocities, the major hazard posed by OD is to spacecraft operations. Current hazards to most space activities are thought to be low, especially above LEO, where particle density is low. However, depending on nonwarfare growth rates in commercial and military satellites, OD levels may increase to the extent that some important orbital regions (primarily GEO) could threaten to become hazardous to space operations. About 70–80% of OD lie within 250–400 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. Cataloged objects make up ~99% of the OD mass. Haystack detections are ~600–1600 km, and radar cutoff is at ~0.6 cm. Estimated LEO averaged background collision cross section for 1 cm is $\sigma_{1\mathrm{cm}} \approx 4 \times 10^{-5}$/year · m^2. Because LEO extends well above 1000 km, the Haystack numbers at higher altitudes may be too low (~two times) because of radar resolution limits. For 0.5-cm particles, $\sigma_{0.5\mathrm{cm}} \approx 10^{-4}$/year · m^2, but may be higher. For OD ≥ 0.1 cm ($\sigma_{0.1\mathrm{cm}} \approx 8 \times 10^{-4}$/year · m^2), structural damage and space erosion may become an important factor.

IV. LEO Region

The current international definition of LEO is that region within 2000 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 5875 km, equivalent to <225-min period. The orbital period at an altitude of 2000 km is ~127 min. The volume of LEO is usually taken as that of the whole sphere between given altitudes, that is, a spherical symmetrical shell. Postboost and midphase 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 2000-km altitude above Earth with orbital periods <200 min. 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 1000 km, the sensitivity is probably closer to 1.0 cm, and at 1600 km the sensitivity is even less. For small-debris detection operations, the maximum range of Haystack is ~2000 km (Johnson, personal communication, 2003). The limiting diameters that the Haystack radar can detect depend on the type of reflecting material, as well as their distance. The detection limit of the Goldstone bistatic 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 ~0.01–0.001 cm in size were found from chemical analysis on the Long-Duration Exposed Flight (LDEF) satellite panels, which never achieved an altitude above 480 km. The great majority of (large) objects tracked as of 1 November 1995 had ~5747 cataloged objects including the International Space Station (ISS). The peak population is ~1000 km. LEO has an average flux of material >1 cm in size ~4×10^{-5} particles/m^2 · year (Ref. 2) and peaks at ~800–1000 km. At ~1500 km, the OD travels at 7–8 km/s with widely varying inclinations. Skimming velocity atop Earth's atmosphere is ~7 km/s at 2000 km. Collision velocities in LEO may vary from 0 to 15 km/s. However, when discussing total population numbers for very small objects, one refers to fluxes at specific altitudes and/or inclinations rather than generalized regions. For example, the flux of 100-μm particles in the ISS orbit, normally held between 350 and 400 km, is ~19/m^2 · year (Johnson, personal communication, 2003). Many of these particles have highly elliptical orbits, making discussion of total populations 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. However, there has not been any convincing evidence or models to support quantitatively this conclusion. However, computational results do suggest that BMW trajectories that either skim the upper reaches of the Earth's atmosphere or penetrate deeper into LEO and explode or collide with an 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 breakups occur because LEO is so large and fragment debris volumes are relatively small and transient, for example, <2000 s. SOD fragments have minimal short-term and virtually no-long term effects, although a very small number of fragments may achieve true OD status. However, if several breakups occur within a narrow band of satellites that occupy along exact GEO or global positioning satellite orbits, results could be different.

V. Meteoroid Flux

Meteoroids are natural particles, debris remnants from devolatized comets and asteroids, and are chemically analogous to the composition of comets and nonmetallic meteorites, that is, Fe, Mg, silicates. For the very fine particles, meteoroid dust sizes range from ~1μ to 1 mm with an average density of ~0.5 g/cm^3 and, depending on their size, can be as high as 1 g/cm^3. However, because meteoroids are derived from comet and asteroid materials, the larger meteoroids density range may extend to meteorite densities >1 g/cm^3. Just above Earth's atmosphere, meteoroids move much faster at ~11–72 km/s, and a 0.3-cm-diam 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.[3] The probability that a 1-m^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. However, during a period of intense meteoroid bombardment, the meteoroid threat may be significantly enhanced, rendering this protection useless.

VI. Collision Rates from Background OD and Meteoroid Flux

The collision rate $\mathrm{d}N/\mathrm{d}t$ of background OD and meteoroid flux is defined as

$$\text{collision rate} \equiv \frac{\mathrm{d}N}{\mathrm{d}t} = S\sigma A \tag{1}$$

S is the number of satellites, σ the OD cross section (per square meter per year) and A the average satellite area (square meters). Table 2

Table 2 OD flux in LEO

Size, cm	σ*(1/m^2 − yr)	A, m^2	Collisions/yr	Result[a]
		OD		
≥1	4×10^{-5}	10	0.2	
		50	1	Severe damage
≥0.5	10^{-4}	10	0.5	
		50	2.5	Damage
≥0.1	8×10^{-4}	10	4.0	
		50	20	Degradation
		Meteoroid		
≥0.3	2×10^{-4}	10	1	
		50	5	Damage

[a]Cross-sectional flux of a given size and larger.[2]

summarizes observations for three OD sizes and for meteoroid sizes >0.03 cm in LEO. Average annual collision rate is provided for 500 SBI platforms in LEO with areas of 10 and 50 m^2. 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 damage will depend on how well the satellite is protected and where and at what velocity the impact occurs.

VII. Collision, Fragmentation, and Vaporization

The enormous energy released during high-speed impacts rapidly initiates 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, plasma processes evolve. Analysis suggests a 5-kg mass impactor undergoes massive vaporization at a relative impact velocity of 10–12 km/s. For targets more massive than the impactor, much of the impactor energy is partitioned into self-melting and vaporization (J. Lawrence, personal communication, 2003). It is convenient 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. If the BMW has a hardened, ablative coating, the amount of fragmentation may not be commensurate with the KKV, nor would debris generated from impacting decoys be dissimilar to the BMW materials. Table 3 describes impact phenomenology in terms of energy partition 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-, 1-, 5-, 10-, and 50-kg impacted head-on at 3 km/s are given in Table 4. Total interaction energies E_{int}, interaction energies per kilogram $E_{\text{int}}/M_{\text{KKV}}$, 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 in Table 4. Increasing KKV mass slightly reduces available kinetic energy per kilogram and, thus, the mean velocities of nonvaporized fragments. For 5- and 50-kg KKVs, all but ~0.25 and 2.27×10^9 J, respectively, are in the center of mass system. Relatively small amounts of specific (internal) energy (49.5 and 45.4×10^6 J/kg) in the reduced mass system are available to fragment, melt, and establish a plasma vapor that propel fragments from the main BMW body. Respective average fragment velocities achieved from the 5 and 50 mass KKVs are 2.59 and 2.43 km/s. The highest fragment velocity is achieved by a 1-g KKV at 2.60 km/s. (The 0.001-kg is not a practical interceptor.) Substantially increasing KKV mass only slightly reduces fragment velocities but generates significantly more SOD. If the KKV mass is kept below 5 kg, SOD flux will be low, that is, it is arbitrarily assumed that there will be ~50,000 1-g 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 also minimizing lift costs. For $M = 500$ kg, $m = 5$ kg, $V = 7$ km/s, and $v = 3$ km/s, the BMW trajectory perturbation (to first order) is $\Delta V \approx 30$ m/s. Over 1000 s, the target location is changed by ~30 km. Starting with a total reduced mass impact energy of 2.5×10^8 J, if equal amounts (5 kg each) of BMW target and KKV material are vaporized at $\sim 8 \times 10^6$ J/kg × 10 kg, then crushing, fragmentation, melting, vaporization energy extracts $\sim 8 \times 10^7$ J. Also, if it is assumed that high-pressure shock waves generate 50 kg of fragments from the BMW, $\sim 168 \times 10^6$ J remain to accelerate fragments, at an rms fragment velocity ≈2.59 km/s

Table 3 High-energy density impact regimes

Group	Process
3–5 km/s ($4.5–12.5 \times 10^6$ J/kg)	Solid fragmentation dominates with some melting and little vaporization.
>5 km/s (>12.5×10^6 J/kg)	Major portions are melted with some vaporization.
>7 km/s (>25.9×10^6 J/kg)	Vapor (plasma) dominates impact process.

Table 4 Fragment velocities from a 10-km/s impact as a function of KKV mass

Energy distributions and rms velocities	KKV mass, kg				
	0.001	1	5	10	50
E_{Total}, $\times 10^9$ J	12.25	12.28	12.37	12.50	13.48
E_{Int}, $\times 10^6$ J	0.05	49.9	247.5	490.2	2,272.7
$E_{\text{Int,}}/M_{\text{KKV}}$, $\times 10^6$ J/kg	50	49.9	49.5	49	45.4
v_{rms}, km/s	2.61	2.60	2.59	2.57	2.43

VIII. 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, generally remaining below 1.5 times the impact velocity. The statistical distribution of this small fraction of particles can be determined by applying the error function to the 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 v_{rms}. The velocity of fragments, U, from an asymmetrical impact can be determined as a function of the SBI impact velocity and the energy reflection back into the SBI, which ablates the impactor and energizes the vapor. Estimates[4] of fragment velocities based on impact energy transmission, fraction of the (KKV) ablated, and Lagrangian plasma velocity and density profiles in the impact region suggest a KKV impact into a BMW at ~10 km/s yields a $v_{\text{rms}} \approx 2.5$ km/s.

A center of mass-dominated (mass BMW ≫ mass KKV) radial-type of impact fragmentation with an object on a suborbital trajectory, whether space or ground launched, confines lower velocity debris fragments within a small region of LEO defined by the suborbital 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 deorbiting from enhanced drag at perigee. High-velocity fragmented materials directed radial away from Earth may achieve highly eccentric orbital velocities and may even achieve OD status. At sufficiently high velocities, the fragments 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 (transorbital) weak instability boundaries.[5]

IX. SOD Impacts on Satellites in LEO

A straightforward and conservative approach is taken to compute upper limits to OD impact probabilities, that is, a worst-case scenario. For a suborbital trajectory, a linear model expresses the average satellite collision cross section σ_S

$$\sigma_S = N_S A_S (\text{vol}_{\text{frag}}/\text{vol}_{\text{LEO}}) \tag{2}$$

where

$$\text{vol}_{\text{frag}}\left(\pi g^2 u_{\text{rms}}^2 / 4\right) v \tau^3 \tag{3}$$

N_S is the number of cataloged satellite targets (~6000), A_S is the average satellite target area (~1 m^2), vol_{frag} is the volume of the fragment cloud in the (primarily) suborbital trajectory, and vol_{LEO} is the operational volume of LEO ($\sim 10^{21}$ m^3). Note that the number of operational spacecraft in LEO for all nations is closer to 300, rms radial velocity of fragments $u_{rms} = 2.5$ km/s and $g < 1$ ($\sim\frac{1}{2}$) is an associated fragment trajectory factor. Velocity of the BMW, v, $\sim$7 km/s, and $\tau \approx 1000$ s is the BM trajectory time after being impacted by SBI. The SOD flux dispersed within the fragment volume after a single impact on a BMW is

$$\text{SOD flux} \equiv F = 4\eta v \big/ \left(\pi g^2 u_{rms}^2 v \tau^3\right) \tag{4}$$

where η is the number fragments/impact,

$$\text{satellite collision rate} \equiv \frac{dn}{dt} = F\sigma_S = \frac{N_S A \eta v}{vol_{LEO}} \tag{5}$$

Assume $\eta = 50{,}000$ particles per SBI impact interaction with average mass of 1 g,

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

The total number of collisions, n, per SBI hit on a BMW during the BMW trajectory transit τ, from 200 to 2000 s, is $(4.2 - 42) \times 10^{-7}$. The probability P of a satellite being hit by OD over time τ is $(4.2 - 42) \times 10^{-7}$/SBI hit. For 500 platforms with 10 SBI each, the total number of SOD collisions with all satellites is $2.1 - 21 \times 10^{-3}$ and $\sim$0.0001–0.001 for active satellites. The assumption is the fragmented particles are a single size. A logarithmic size distribution with more small particles and fewer large particles is more probable, but this assumption will not significantly affect the results of this study.

X. Suborbital Impacts on of SBI Platforms: Fratricide

Here OD effects are considered from the destruction of SBI platform(s). If the SBI platforms are confined within narrow LEO operational regions from 7000 to 6500 km altitude, the SBI volume $vol_{SBI} = 2.9 \times 10^{20}$ m^3. The SBI fragment suborbital volume swept out during the postimpact trajectory is once again vol_{Frag}. A potential fratricidal scenario involves BMW destruction within a confined volume of LEO, where SBI platforms reside. The SBI platform collision cross section is

$$\sigma_{SBI} = N_{SBI} A_{SBI} (vol_{frag}/vol_{SBI}) \tag{6}$$

where N_{SBI} is the number of SBI platforms of area A_{SBI} within the SBI volume. The ratio of the fragment volume to the SBI volume will be much higher than for LEO because SBIs operate within a smaller volume than operational and nonoperational satellites.

The SOD fragment flux dispersed within the fragment volume after a given (single) SBI platform is destroyed is

$$F = \eta v \big/ \left(\pi g^2 u_{max}^2 v \tau^3\right) \tag{7}$$

The collisions per SBI hit per second on BMW within this space kill zone is

$$\text{SBI collision rate} = \frac{dn}{dt} = F\sigma_{SBI} = \frac{N_{SBI} A_{SBI} \eta_{SBI} v}{vol_{SBI}} \tag{8}$$

$N_{SBI} = 500$, $A_{SBI} = 60$ m^2, $\eta_{SBI} = 50{,}000$ particles of 1 g, and $v = 7000$ m/s,

$$\frac{dn}{dt} = 3.6 \times 10^{-8}/s$$

The total number of SBI collisions by OD from 1 and 10 BMWs hit by KKVs during a transit, $\tau = 1000$ s are 3.6×10^{-5} and 3.6×10^{-4}, respectively. These numbers are quite low. Even if fragment velocities were twice as high, the impact probability would not change significantly. Ironically, the 500 SBI platforms at 60-m^2 surface area each provide a larger target than the passive satellite assets in LEO. As each SBI platform is destroyed, more OD is generated and will enhance the OD flux while diminishing σ_{SBI}. However, if SBI platforms are deliberately targeted, the calculus for hit probabilities can dramatically change. However, this massive antisatellite (ASAT) targeting would likely precipitate a strategic response and requires a different approach than outlined here.

XI. Mean Free Path of SOD

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

$$\lambda = \text{distance over time/number of satellite collisions in this time} = vt/F\sigma t \tag{9}$$

$$\lambda = vol_{LEO}/(N\,A\,\eta) \tag{10}$$

Determination of vol_{LEO} is critical to λ because vol_{LEO} establishes the confinement of the collision process. If $vol_{LEO} = 10^{12}$ km^3, and $S = 6000 =$ active and inactive satellites, $A = 1$ m^2, and 50,000 1-g particles per KKV hit on a BMW, then $\lambda = 33 \times 10^8$ km. This large value of λ underscores 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, $vol_{SBI} = 3 \times 10^{11}$ km^3. The number of interacting satellites is also proportionally smaller. The cross section of 500 SBI platforms, each with area $\sim$50 m^2 yields a mean free path $\lambda \sim 2 \times 10^8$ km.

XII. 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 provide some level of protection to spacecraft against 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 $\sim$9 g/cm^3 without generating damaging secondary debris particles.[6] Other design options include lightweight woven polymer fabrics with special metallic coatings and the use of geometric shapes to provide enhanced protection for particular orientations and projections. Implementation of these shields could substantially enhance survivability of satellites. Additional 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 predetermined shapes once in orbit. Another possibility for mitigating against the effects of OD is sequestering several assets within an extended volume to minimize 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.

XIII. OD and ASAT Issues

It must be assumed that if a space weapon is deployed its presence will be duly noted and countermeasures will be developed, tested, and deployed. Compared to Earth-sequestered weapons, space-based weapons systems have a high level of vulnerability. Determined ASAT warfare among space powers could create enormous amounts of OD if explosions and mechanical fragmentation occurs with the debris field following an expanded trajectory of the exploded satellite. Such an action would be counterproductive in symmetric warfare because space assets would be lost rapidly and indiscriminately by all sides. Thus, 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. If attacked, there is no option other than vigorously defending the space assets. Given current missile technology proliferation, it is plausible that rogue- or nonstate entities with few or no space assets or homeland to defend could wantonly attack assets to initiate enough OD that additional satellites could be indiscriminately destroyed. Such a scenario, were it to occur, may constitute a successful outcome for a rogue in the throes of demise. On the other hand, technologically advanced powers using sophisticated and subtle methods could disable space assets without creating significant amounts of OD. Such methods include electromagnetic pulses, laser beams, foulants, and low-velocity penetrators.

XIV. High Relative Velocity On-Orbit Collision of Spacecraft

A deliberate high relative velocity on-orbit collision between two U.S. spacecraft provided empirical insight to the longevity of OD from a satellite collision, which in some aspects mimics a KKV BMW interception.[7] On 5 September 1986 two U.S. satellites, one (U.S. 19) a cylindrical cone 1.2 m in diameter and 4.6 m in length and the other (U.S. 19 R/B) a cylindrical Delta second stage with an auxiliary payload, collided at a very high velocity at 200-km altitude. Both satellites were thrusting at the time of impact. It appears, based on the (limited) available data, that most of the debris from this high-speed impact reentered the atmosphere before being officially cataloged. Radar signals from the event indicate particle clustering at 200 km and small velocity dispersion. Also, the number of surviving OD fragments was small. Extrapolating this result to a SOD collision will further reduce the small number of surviving fragments. Refer to Refs. 8 and 9 for a detailed study of on-orbit breakups.

XV. Summary of Results

The first issue regarding OD/BMW interception involves fragment generation from kinetic impact into BMWs when the KKV interceptor impacts the BMW at a velocity of roughly 2.4–12 km/s. If the BMWs are about two orders of magnitude in mass greater than the interceptor, it will be almost totally obliterated with spall fragments unloading from the rear and accelerated by the plasma generated at the impact interface. The BMW will have a crater and related damage 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 significantly higher velocities.

The second point is that, because of the low reduced mass impact energies, the overwhelming majority of fragments will never achieve OD velocity but follow a transient SOD trajectory status that reduces impact probability because SOD lasts $\sim$2000 s or less. Because of the statistical nature of the fragmentation process, 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 $\sim$ 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. The deliberate on-orbit, high-velocity collision of two spacecraft by the United States in 1986 generated a minimal amount of OD and velocity dispersion. Most OD was found to reenter the atmosphere before being officially cataloged.[7] These results support the analysis presented.

XVI. 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 3 of 500 platforms being lost. With the appropriate shielding, this number would be even lower. 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 (suborbital) center of mass velocity the fragment velocity is small. This trajectory would have a lifetime <2000 s and occupy a relatively small volume in LEO because the fragmented particles have a relatively small spread velocity and short suborbital 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. If this OD has a high eccentricity, it will be rapidly deorbited at perigee.

The (constant) background OD and meteoroid flux appears to pose the greatest threat to the SBI platforms and satellites. Indeed, without shielding, one could expect to have at least two to five SBI platforms damaged each year from these background fluxes. Whether this damage 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 are the platform and its components. In any event, SBI platforms must be at least routinely maintained, and that substantially adds to lift costs. Ground-based interceptors are not subject to such damage levels and are mush easier to maintain. It appears 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, however, special circumstances in which 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 the 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, suborbital, 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 induce 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 large numbers of deployed SBIs. Protection against background fluxes and SOD can be achieved though hardening components and overall shielding and orienting satellite and SBI platforms.

3) In some cases, 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.

This study is deliberately limited to effects arising from the interception in LEO of BMWs that travel in a suborbital trajectory. A future study should consider OD effects from a direct ASAT attack on passive satellites and SBI platforms. In such cases involving ASAT warfare, a considerable amount of the debris will be orbital and will, therefore, persist indefinitely in augmenting the background OD and meteoroid flux. This effect presents a serious limitation on ASAT warfare that does not appear to constrain antiintercontinental ballistic missile warfare.

To limit the deployment of space-based weapons, states must agree to nonproliferation and verifiable arms reduction combined in a fair and equitable manner with social justice.

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