Man-Made Debris in Low Earth Orbit—A Threat to Future Space Operations

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Man-man debris in orbit represents a potentially serious threat to satellites residing in low-Earth orbit, a threat which may become sufficiently large to serve as an operational constraint. Previous work has focused on presenting the hazard as a function of altitude. In this paper a path integral formulation for calculating hazard levels is presented. This formulation enables specific spacecraft orbits and debris deposited in specific orbits to be considered in determining hazard levels. Two cases are presented: for the Space Shuttle in 160 nm (300 km) orbit and for spacecraft in sun-synchronous orbit. The previous work is found to be in good agreement with the path integral results. The sensitivity of the hazard to spacecraft orbital inclination is presented in tabular form.

Nomenclature

A = cross-sectional area, cm^2
$\dot{C}$ = frequency of collisions between a member of a debris population and a specific object, s^{-1}
$\bar{\dot{C}}$ = time-averaged collision frequency, s^{-1}
C_D = drag coeficient $= F_D / \tfrac{1}{2}\rho_A v^2 A$
$d^3 v$ = volume element in velocity space
$f(\vec{r},\vec{v},t)$ = phase space number density function for the debris population, s^3/cm^6
F_D = atmospheric drag force, dyne
m = mass, g
$n(\vec{r},t)$ = number density of debris particles, cm^{-3}
$\bar{n}(h)$ = number density of debris particles averaged over latitude, cm^{-3}
P_C = probability of at least one collision occurring between an object and a member of the debris population
P_{NC} = probability of no collision occurring between an object and a member of the debris population
v = speed relative to the atmosphere, cm/s
$\vec{v}_p$ = velocity of an object moving through a debris population, cm/s
$v_R(\vec{r},t)$ = relative speed between an object and the members of the debris population, cm/s
β = ballistic coefficient, $cm^2/g = C_D A/m$
ρ_A = atmospheric density, g/cm^3
σ_{tot} = collision cross section, averaged over aspect, cm^2

Introduction

OBJECTS in orbit in the vicinity of the Earth, which will be referred to as "debris," present a collision hazard to spacecraft conducting operations in orbit. The level of hazard to a given spacecraft depends on its size and time on orbit and on the number and size of debris objects in its operating environment.[1-3] The debris may be meteoroids passing near the Earth or man-made objects generated during space operations. In this paper the focus will be on man-made debris since it is this debris which presents the dominant and controllable collision hazard to operating spacecraft. It is imperative that those involved in the use of the near-Earth environment become concerned with this hazard, as the growth of this debris may in the near future begin to have a significant and adverse effect on space operations. Even now there is mounting evidence that orbiting spacecraft have experienced collisions[4]; it is certain that such events will occur with greater frequency in the future as the debris population grows and/or the space activity expands.

The occurrence of a collision between man-made objects in orbit will be a catastrophic event, both for the objects directly involved in the collision and for other spacecraft. The speed at which objects will collide will be on the order of the orbital speed—roughly 8 km/s for low-Earth orbit (LEO)—making it likely that the impact will produce a very large number of new debris particles, most of them too small to be seen with ground-based detectors, and leading to an enhancement of the probability that collisions with other spacecraft will occur. If one of the colliding objects is a functioning spacecraft, the resulting damage, even from the smaller, untrackable objects, might impair, if not terminate, its operational capability. Hence on-orbit collisions will adversely affect future space operations by causing an increased likelihood of additional collisions occurring and by presenting a failure mechanism for operating spacecraft which will have to be factored into the cost of operation.

To exercise effective control of man-made debris, the number of objects being placed in long-life orbits without their having an onboard mechanism for removal from orbit must be minimized. Once debris is deposited in orbit it is extremely expensive, if not impossible, to retrieve. Orbit decay by atmospheric drag will eventually cause the debris to reenter the Earth's lower atmosphere, but this mechanism will take a very long time to remove all but the very smallest debris pieces or debris deposited in low-perigee-altitude orbits. Therefore control of the problem must come by adopting procedures which prevent the deposition from occurring.

Operations which violate such procedures, whether they are antisatellite operations or debris released during normal operations, might, if they are maintained, lead to a state where the near-Earth environment is so heavily populated by debris as to be virtually impossible to use. Even with the current debris levels, there are some regions of space which would be very hazardous for some of the larger proposed spacecraft to use if they had no collision protection. Since the large relative speeds of objects in LEO make even very small objects a danger, sophisticated detection and avoidance systems would be required onboard all operating spacecraft if avoidance was to be attempted. Such systems would cost payload, both for the detection hardware and for the extra fuel, and are considerably beyond the current technology. The alternative to avoidance would be to employ bumpers which could accommodate the impact without allowing it to damage the operating systems on the spacecraft. However, there are

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essential parts of a spacecraft, e.g., the solar panels, which are difficult to shield; moreover, the fact that much of the man-made debris is of large mass would require very massive or complex bumpers.

In this paper, a model is presented which can be used to calculate collision hazard levels based on a knowledge of the set of orbital parameters for a debris population. The model is similar to the model first presented by Kessler and Cour-Palais[1] and discussed further in a series of papers by Kessler. A conceptual difference from the Kessler model is the use of path integral formulation for calculating collision probabilities; a significant sophistication in this model involves the inclusion of the debris population velocity distribution function in the probability calculations. These features allow collision hazard levels to be calculated for specific orbital planes and for debris deposited into specific orbital planes, the latter an important capability for analyzing the hazard increase introduced by a specific debris deposition event.

The discussion is divided into two parts. The first part is an assessment of the current hazard levels, with a discussion of the problems associated with controlling future hazard levels. The hazard model used in this part of the discussion employs the traditional approach of using particle density as a function of altitude. In the second part, a path integral formulation for calculating collision probabilities is introduced. This formulation takes into account the velocity distribution of the debris population as a function of position and is suitable for developing models for hazard minimization and for calculating the contribution to the hazard level introduced by the deposition of debris in specific orbits. A comparison of results of the two formulations verifies their essential compatability.

Discussion

The significance of the orbital debris problem depends primarily on the number and size of objects on orbit. When considering objects large enough to damage most spacecraft, man-made debris constitutes the dominant threat.[1] In the past, man-made debris had two sources: routine space operations, which include the deposition of spent stages as well as hardware released during normal maneuvers, and on-orbit explosions, both intentional and accidental. More recently, there have been several unusual events involving debris generation which might be attributed to collisions rather than explosions.[3,4] An additional debris source which may be significant for optical devices is particulate matter ejected in solid rocket motor exhaust.

The number of objects which are large enough to be tracked by NORAD detectors is about 4500 and consists of about 35% objects released during normal operations and 65% objects associated with on-orbit explosions.[3,5] In addition to the tracked objects, there is a population of uncertain size consisting of objects too small to be seen with currently used detectors.

In theory, the debris hazard could be controlled by limiting the rate of debris deposition or by balancing deposition and growth with debris removal. However, only the institution of programs to control (minimize) the rate of debris deposition is an effective alternative since an active debris removal program, which would require many thousands of feet per second of propulsion capability to acquire each debris object, is not feasible with the present propulsion technology, and removal by atmospheric drag is generally ineffective on short time scales. The inability to introduce controllable and effective debris removal into the problem increases the possibility for catastrophic debris growth, in which the onset of debris with debris collisions would introduce an extremely large and uncontrollable source of debris objects which could remain in the environment sufficiently long to trigger a runaway collision process. The circumstances under which this might occur have not yet been determined.

However, the evolution of the debris population under plausible conditions can be sketched. In this scenario, normal operations and on-orbit explosions, which might result from correctable design flaws, insensitive operational procedures, inadequate preventive design characteristics, or antisatellite operations, which represent controllable debris sources, would continue to contribute to the population of man-made objects in orbit. These objects, being generally large, would populate long-life orbits and increase the size of the population, characterized by N, its number of members. In consequence, the expected time between debris-debris collisions, which has a $1/N^2$ dependency, would decrease (as will be seen, this time is already unacceptably short, ~50 yr, for the current population levels). With the advent of debris-debris collisions, an uncontrollable debris source, which for some events might produce many thousands of debris objects, would be introduced. If the removal time for the collision debris proved to be greater than the expected time before experiencing another collision, collisions could become the dominant debris source and would yield a rapidly escalating growth rate in the number of debris objects.[1,5] The increasing number of debris objects would also decrease the time between collisions as experienced by a particular spacecraft since this time has a $1/N$ dependency.

The rise in the number of debris objects would continue until debris removal by atmospheric drag balanced the debris being generated by collisions. This method of removing debris will become more effective as debris undergoes successive fragmentations, since the smaller particles will generally have a larger ballistic coefficient. However, the inefficiency of debris removal by atmospheric drag, as seen in Fig. 1, which shows the length of time in years required for debris deposited in circular orbit to decay to 200 km altitude as a function of ballistic coefficient, indicates that the debris population might become very large before this debris sink became effective.

Most man-made debris will have a ballistic coefficient lying in the range shown. For tumbling debris particles the drag coefficient will be very nearly 2 for all altitudes above 200 km and the area will be on the order of the square of the largest linear dimension. For example, an empty Shuttle Orbiter will have a ballistic coefficient of about 0.02 cm^2/g (average cross-sectional area), a tumbling aluminum fragment 1 cm × 1 cm × 5 mm a ballistic coefficient of 1.5 cm^2/g, and a tumbling mylar fragment 1 cm × 1 cm × 0.5 mm a ballistic coefficient of 15 cm^2/g. Decay times are shown for the Earth's atmosphere at maximum solar activity (dashed lines) and at minimum solar activity (solid lines) and clearly show that, while most of the orbital decay will occur during the period of maximum solar activity, many solar cycles will be required to remove massive objects deposited as low as 700 km.

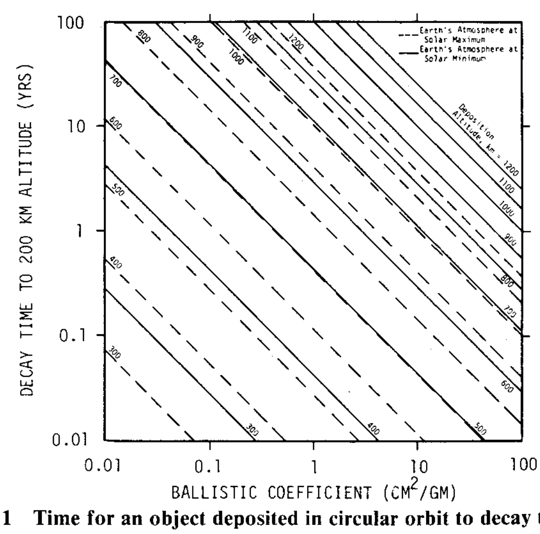

Fig. 1 Time for an object deposited in circular orbit to decay to 200 km altitude.

The qualitative statements made in the above discussion can be stated more precisely in the development of a model for assessing the hazard levels. Perturbations, arising from the complex mass distribution of the Earth, from the time varying positions of the sun and moon, and from drag induced by the Earth's upper atmosphere, are constantly acting to alter the velocity and hence the orbital path of each debris object. The presence of these perturbations, which rapidly change the epoch of each orbit by time lengths much longer than the interaction times between objects, make a deterministic model of the debris environment unsuitable for calculating collision hazard levels. Instead, a model combining celestial mechanics with kinetic theory concepts has been developed to describe the interaction between debris particles and between a debris particle and an operating spacecraft.[1,2] In this paper the hazard level is characterized by the expected time between collisions.

For a given object, the frequency with which it experiences collisions with an ensemble of particles is

$$\dot{C}(\vec{r},t) = \sigma_{\text{tot}} \int d^3v \, |\vec{v} - \vec{v}_p| f(\vec{r},\vec{v},t) \tag{1}$$

The kinetic theory properties of the model enter through the use of the number density distribution function as the descriptor of the debris population. The celestial mechanics aspect of the model arises in the reduction of debris orbital data to density and velocity distribution functions and, for the calculations which require the path followed by a spacecraft, a means of describing the kinematics of the spacecraft.

The collision cross section, σ_{tot}, is a difficult quantity to handle with the highly irregularly shaped objects of various sizes that constitute the population of man-made objects in orbit. For the model at this stage of development it is sufficient to assume that objects in orbit are randomly oriented, so that each object can be assigned an "effective cross-sectional area," which is its true cross-sectional area averaged over aspect. In this work the stronger assumption is made that the collision between a spacecraft and any member of the debris population can be modeled using a single collision cross section. This assumption is correct if most of the debris population is of about the same size or if the spacecraft is much larger than the debris objects, in which case the effective cross-sectional area of the spacecraft approximates the collision cross section.

Although more effort could be invested in improving the handling of the collision cross section and therefore lead to a "better" collision rate, the presence of unobserved debris, to be discussed later, introduces much greater uncertaintly into the calculation; thus, until the contribution from this unobserved debris is well understood, the simplifying assumptions for the collision cross section appear adequate. A further discussion of the collision cross section is presented in Kessler and Cour-Palais.[1]

The number density of debris objects is

$$n(\vec{r},t) = \int d^3v f(\vec{r},\vec{v},t) \tag{2}$$

The mean speed of the object relative to the debris is

$$v_R(\vec{r},t) = [1/n(\vec{r},t)] \int d^3v \, |\vec{v} - \vec{v}_p| f(\vec{r},\vec{v},t) \tag{3}$$

so that

$$\dot{C}(\vec{r},t) = \sigma_{\text{tot}} n(\vec{r},t) v_R(\vec{r},t) \tag{4}$$

The collision frequency is related to the time rate of change of the collision probability by

$$\frac{dP_C(\vec{r},t)}{dt} = -\frac{dP_{NC}(\vec{r},t)}{dt} = P_{NC}\dot{C}(\vec{r},t) \tag{5}$$

Therefore the probability that a given object will experience a collision while following a path through the debris is given by integrating Eq. (5) over the path. That is, using time as the path parameter,

$$P_{NC}(t_0) = \exp\left[-\int_0^{t_0} dt \dot{C}[\vec{r}(t),t]\right] \tag{6}$$

where the initial time is taken to be 0 and the elapsed time to be t_0. Further,

$$P_C(t_0) = 1 - P_{NC}(t_0) \tag{7}$$

so that for cases where the travel time is short compared to $\dot{C}^{-1}$ everywhere on the path,

$$P_C(t_0) \simeq 1 - \left[1 - \int_0^{t_0} dt \dot{C}(\vec{r},t)\right] = \int_0^{t_0} dt \dot{C}(\vec{r},t) \tag{8}$$

The collision probability can be used to define a mean collision rate by

$$P_C(t_0) = \bar{\dot{C}} t_0 \tag{9}$$

Equations (4) and (7) are most useful for describing the debris hazard. To use them to calculate hazard levels based on observed, hypothesized, or projected debris populations or on spacecraft operation definitions, some discretization operation must be performed. There are many such operations which might be employed; two will be used in this discussion.

One approach is to deal only with the altitude dependence in the problem,[1,2,5,6] and involves calculating a number density distribution having only an altitude dependency. Calculating this number density distribution requires an averaging of debris properties over latitude and removes the possibility of consistently defining a relative speed based on the debris distribution function; instead, some value for the relative speed must be assumed. The virtue of a latitude-averaged form for the problem is that it gives a reasonably accurate assessment of the debris hazard in an easily digested form.

Alternatively, both latitude and altitude dependence can be retained with averaging occurring only over the azimuthal angle.[2] In this approach a velocity distribution function can be consistently defined, and therefore other types of information on the hazard levels can be recovered. In particular, it is possible to calculate hazard levels for specified spacecraft orbits as well as marginal hazard levels for debris deposition into specific orbits. Moreover, the development for determining the hazard with correlated debris motion (to be presented in a subsequent paper) will require such an approach. While the simplicity of describing the hazard with a few numbers is lost, these new aspects of the problem can be addressed.

In this work, the reduction of the debris population properties to the distribution functions was performed in a manner which accommodated both types of analyses. An Earth-centered, two-dimensional, spherical grid was defined, consisting of surfaces of constant radius spaced every 50 km from 150 to 4000 km in altitude and surfaces of constant polar angle (latitude) spaced every 5 deg. The apogee and perigee altitude and orbital inclination of each debris object was reduced to a contribution to the number density, based on what percentage of time the object spent in each cell that it traversed, and to the debris velocity distribution function, also defined for each cell. The reduction procedure is discussed in more detail in Reynolds and Fischer.[2]

Symmetry arguments were introduced to reduce the amount of computation. Symmetry between cells in the Northern and Southern hemispheres, which occurs if there is a random distribution in the argument of perigee in the debris population, was assumed. More important, independence in the azimuthal coordinate (right ascension) was assumed, reflecting a random distribution in the orientation of the

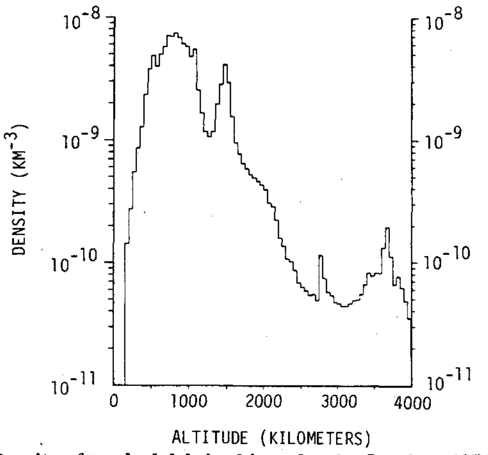

Fig. 2 Density of tracked debris objects for the October, 1976 debris population.

orbital planes in the debris population, an assumption supported by the observed distributions.[3] This effect was expected, since differential precession rates of the line of nodes and argument of perigee introduced by the multipole moments of the Earth's mass distribution and by drag introduced by the Earth's atmosphere, the dominant perturbations for low-Earth orbits, will randomize quite rapidly both orbital plane orientation and argument of perigee, even for debris with motion initially correlated by deposition from a single event.

The debris population used as a basis for this work was the debris being tracked and cataloged by NORAD for the October, 1976 Satellite Situation Report. There were 4271 objects being tracked at this time. This compares with 4557 objects contained in the February, 1980 Satellite Situation Report, plus 170 objects which had not entered the official NORAD catalog, reflecting a similar state for the debris environment as recently as mid-1980.

Debris Hazard as a Function of Altitude

The reduction to simple altitude dependence from distributions defined on the two-dimensional grid is quite simple. Only the mean density at a given altitude, $\bar{n}(h)$, need be calculated, and it can be done exactly since the density, $n(h,l_i)$, and volume, $V(h,l_i)$, of each cell at a given altitude was calculated. The relation determining $\bar{n}(h)$ is, of course,

$$\bar{n}(h) = \sum_i n(h,l_i)\,V(h,l_i) \Big/ \sum_i V(h,l_i) \tag{10}$$

where the sum is over latitude. This method is equivalent to that used in Refs. 1, 5, and 6. These data are presented in Fig. 2 for the October, 1976 debris population and compare favorably with other authors.[1,5,6]

The significance of these debris densities is best appreciated by translating them into collision frequencies using Eq. (4). Assuming a value of 7 km/s for v_R, time between collisions ($\dot{C}^{-1}$) as a function of collision cross section is presented in Fig. 3 for a series of circular LEO altitudes. The type of spacecraft corresponding to the different collision cross sections is shown along the top of the figure. The left-hand scale provides times for the current population, the right-hand scale gives times for a population experiencing a uniform annual growth of 5% for 20 years.

The varied character of the collision problem is clearly illustrated in this figure. The time between collision for objects the size of the Shuttle Orbiter will be very large, even in regions of greatest debris density. However, larger objects, such as the large astronomical mirrors or other large space structures, will certainly collide during their operational lifetime with man-made debris large enough to be tracked from the Earth if they operate at these altitudes. Collisions with such large objects will not only jeopardize the continued functioning of these spacecraft, they will also act as sources of additional man-made debris and contribute to an elevation of the collision hazard level.

Since the data contributing to Figs. 2 and 3 come only from objects being tracked by NORAD, a correction should be made for objects not being tracked, most of which are those too small to be seen by NORAD detectors. The minimum size of an object which is detectable by NORAD is 4 cm at lowest altitudes[5] and increases with altitude. Since this size is much larger than that required to cause extensive damage in collision with a spacecraft, there is a potential segment of the debris population which represents a hazard but which cannot be seen.

The contribution of unobserved debris to the collision hazard represents the major uncertainty in current collision hazard assessments. Kessler[5] has proposed a correction factor to account for this debris. If this correction is included, the times between collision shown in Fig. 3 are reduced to those shown in Fig. 4. Clearly, future programs will introduce systems/structures large enough to collide frequently with man-made debris, a conclusion which may indicate there will be severe constraints on the use of LEO space in the future.

The results shown in Fig. 3 allow an estimation of the frequency of debris-debris collisions for the current tracked population. Accepting a mean collision cross section of 5 m^2 for these objects, the time between collisions as experienced by a given object will be about 200,000 years. The mean time between collisions involving any two objects will be this time divided by the number of objects in the population, which is about 5000. Therefore the expected rate of collisions between objects in LEO large enough to be tracked is about one collision every 50-100 years if the present population level is maintained.

Debris Hazard with Latitude Dependence

The limitation in the above discussion is that it necessitates a smoothing of debris properties over latitude. In the process, not only is information on the density distribution averaged out, but the velocity distribution as a function of spatial location loses its meaning. If the latitude dependence is maintained, neither of these consequences arise. As will be seen, the results from this form of the model lead to the conclusion that calculations assuming latitude averaging will provide answers which are quite good.

The pertinent expressions in this form of the problem are, principally, Eq. (8) for the collision probability and Eq. (9) for the mean collision rate.

An object in orbit and passing through the grid can be viewed as moving through regions of constant debris conditions as it passes from cell to cell. In consequence, the path integral of Eq. (8) may be replaced by a sum over the cells traversed, yielding

$$P_c(t_0) = \sigma_{\rm tot} \sum_i n(i)\,v_R(i)\,t_i \tag{11}$$

where i is the index running over the cells traversed, t_i is the time spent traversing cell i, and $t_0 = \Sigma t_i$.

Both i and t_i depend on the orbit chosen to define the path integral. Once a spacecraft orbit is chosen the orbit geometry will determine which cells will be traversed and the transit time in each. The orientation of the velocity vector in each of the cells combines with the debris particle velocity distribution for the cell to yield a relative speed in that cell.

This form of the model has been applied to the evaluation of the collision hazard for the Space Shuttle Orbiter and for sun-synchronous spacecraft.

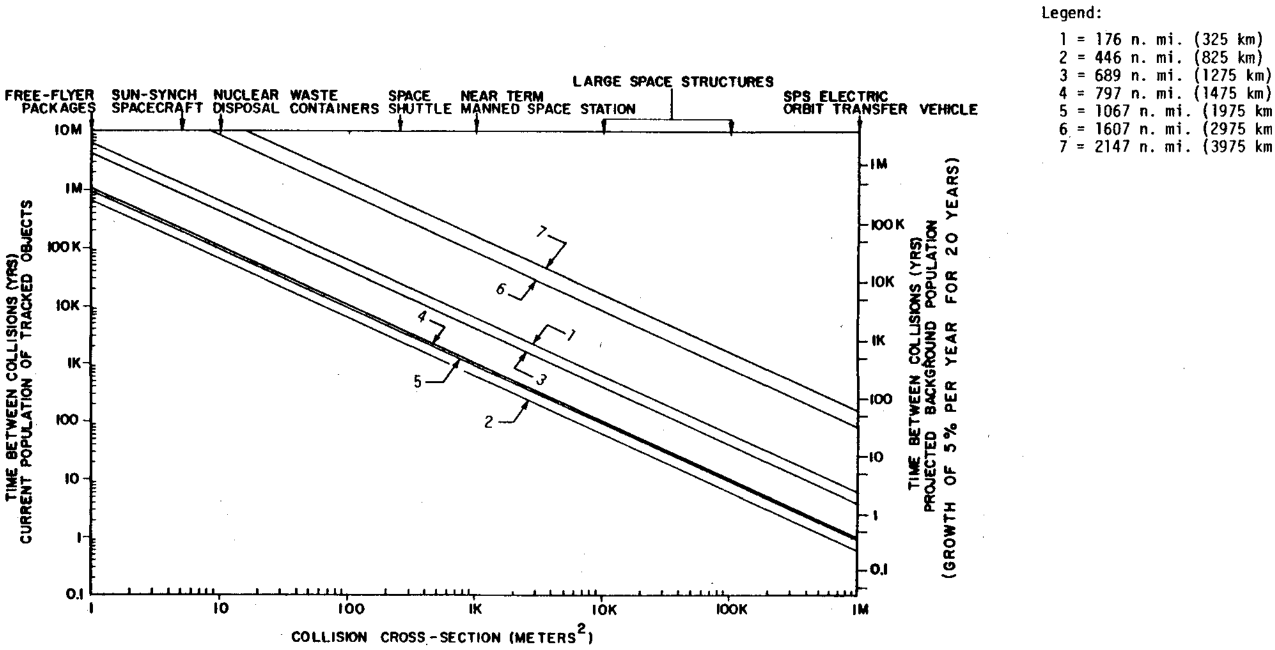

Fig. 3 Expected time between collisions for the October, 1976 population of tracked objects and for that population of tracked objects propagated by a 5% annual growth rate for 20 years.

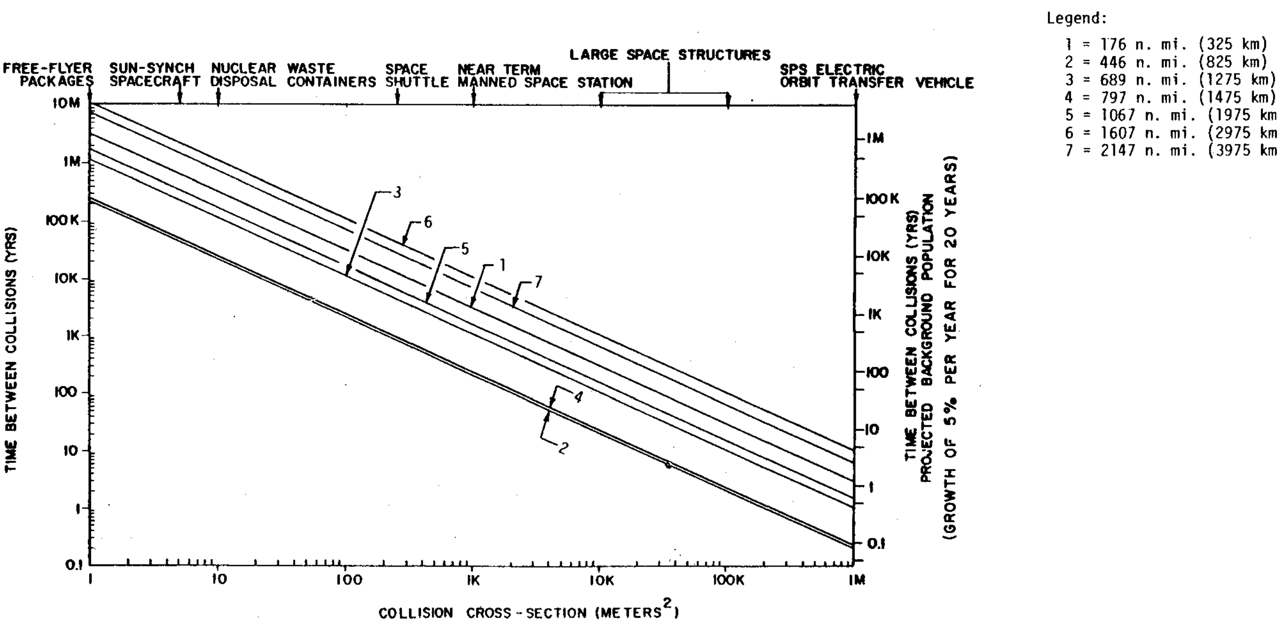

Fig. 4 Expected time between collisions for the populations of Fig. 3 corrected to size 4 cm for unobserved objects.

Table 1 Times between collisions ($\dot{C}^{-1}$) (in years) between the Shuttle Orbiter and man-made debris (orbital altitude = 300 km)

Shuttle orbit inclination, deg	Present population of tracked particles	Present population of tracked particles corrected for unobserved particles to size 4 cm	Corrected population with 5% annual growth for 20 years
28.5[a]	2.7×10^4	1.4×10^4	4.6×10^3
56	2.0×10^4	1.0×10^4	3.3×10^3
82	1.6×10^4	8.0×10^3	2.7×10^3
90	1.5×10^4	7.5×10^3	2.5×10^3
98	1.4×10^4	7.0×10^3	2.3×10^3
Latitute averaged[b] debris properties	2.5×10^4	1.3×10^4	4.3×10^3

[a] Path integral formulation. [b] Results based on analyses equivalent to those used in Ref. 1.

Debris Hazard for the Shuttle Orbiter

The Orbiter will nominally operate in a circular orbit with an altitude of approximately 300 km. Because it is so much larger than the objects comprising the debris population, the Orbiter's mean cross-sectional area can be used to define the collision cross section. The cross-sectional area nose-on is approximately 50 m^2, while the area in the plane of the wings is approximately 500 m^2. A mean cross-sectional area of 250 m^2 was used in performing the collision calculations. As stated earlier, the assumed independence of debris size and the use of a mean cross-sectional area for collision cross section serve to introduce some uncertainty into the calculations.

Given the orbital altitude and collision cross section, the collision hazard as a function of orbit inclination can be computed. The results are presented in Table 1 in the form of time between collisions. The debris populations are 1) the objects contained in the October, 1976 Satellite Situation Report ("Present Population"), 2) the October, 1976 population corrected for unobserved particles, using Kessler's correction factors,[5] and 3) the October, 1976 population, corrected for unobserved particles and augmented by a 5% annual growth rate for 20 years. The corresponding quantities for the latitude-averaged debris values, assuming a relative speed of 7 km/s, are also shown.

The large values for the times between collisions contained in Table 1 indicate that man-made debris of size 4 cm and larger will not present a significant hazard to the Shuttle Orbiter. In fact, the times are large compared to times for collisions involving the Orbiter with a meteoroid of sufficient mass to severely damage a TPS title, as shown in Table 2. These times are based on the meteoroid population model of Cour-Palais.[7] The sensitivity of the LEO environment to man-made debris deposition is clearly illustrated by comparing the meteoroid population particle densities with fragment producing operations, such as antisatellite tests, which migh occur on orbit. At any time there are about 100 kg of meteoroid material of mass greater than 0.01 g in the volume of space up to 4000 km altitude. Therefore a single incident which explosively fragmented 100 kg of material into the same mass distribution as displayed by the meteoroids would, if these fragments were dispersed uniformly up to 4000 km altitude, match the meteoroid debris levels.

The problem of preferential deposition of debris into the Orbiter environment, as would occur if an explosion occurred on a stage still in the low-Earth parking orbit or if debris was routinely deposited during normal Shuttle operations, can also be examined using the path integral formulation. One of the conclusions of Reynolds and Fischer[2] was that observations of fragments resulting from explosions of Delta second stages were consistent with the production of about 500 debris fragments. If such an explosion occurred at the Shuttle parking orbit altitude, the debris deposited from a 28.5-deg orbit would lead to a time between collisions of about 600 years. This result assumes the particles have relaxed to having a random distribution in right ascension of ascending node and in argument of perigee. While the motions are correlated, the hazard level is higher. The relaxation time for the transition of correlated to uncorrelated motion is on the order of a year. A model to calculate collision probabilities while correlated motion exists is being developed. This collision time is based upon a fixed increase in deris and does not consider debris decay.

Table 2 Time between collisions between the Shuttle and a meteoroid of mass greater than a given minimum mass

Minimum meteoroid mass, g	Time between collisions, yr
10	350,000
1	25,000
0.1	1,800
0.01	130

Debris Hazard for Sun-Synchronous Payloads

A greater debris hazard might be expected for sun-synchronous spacecraft than for the Shuttle because lifetime and stationkeeping requirements for such payloads favor placement at higher altitude, in the range of from 600 to 1200 km, where debris densities are largest. However, the increase in debris density, as shown in Fig. 2, is compensated for by the characteristically smaller size of sun-synchronous spacecraft, as shown in Fig. 3. The net effect is that the hazard level to sun-synchronous spacecraft, at least of the type presently in use, is nearly the same as for the Orbiter.

Because the sun-synchronous payloads must reside in retrograde orbits, the speed of the spacecraft relative to the debris should be larger than 7 km/s, the speed assumed in generating Figs. 3 and 4. Table 3 presents a set of collision times: for the October, 1976 population of tracked debris, smoothed over latitude and assuming $v_R = 7$ km/s, and for the spacecraft in a sun-synchronous orbit using a path integral formulation with the same debris populations used to generate Table 1. A collision cross section of 5 m^2 was used.

The elevation of the hazard level from debris augmentation by explosion of a Delta second stage in sun-synchronous orbit is less pronounced for sun-synchronous spacecraft than it was for the Orbiter at 300 km because the debris density is already so much higher at the sun-synchronous orbit altitudes. If the explosion produced 500 particles, the time between collisions

Table 3 Time between collisions ($\dot{C}^{-1}$) (in years) between sun-synchronous payloads and man-made debris (collision cross section = 5 m^2)

Orbit altitude, nm	Correction factor for unobserved particles	Present population of tracked particles, smoothed over latitude	Present population of tracked particles	Present population of tracked particles and factor for unobserved particles	Corrected population with 5% annual growth rate for 20 years
350	2.5	1.8×10^5	1.2×10^5	4.9×10^4	1.9×10^4
400	2.7	5.3×10^5	9.3×10^4	3.4×10^4	1.3×10^4
450	2.9	4.8×10^5	7.9×10^4	2.7×10^4	1.0×10^4
500	3.0	6.1×10^5	9.6×10^4	3.2×10^4	1.2×10^4
550	3.15	7.5×10^5	1.3×10^5	4.0×10^4	1.5×10^4
600	3.25	1.5×10^6	2.2×10^5	6.8×10^4	2.6×10^4
650	3.5	3.5×10^6	4.8×10^5	1.4×10^5	5.2×10^4

involving one of these particles and a sun-synchronous spacecraft would be about 50,000 years.

Conclusions

The problem of man-made debris on orbit has a varied character, depending on the size of the object on orbit, on the operating altitude, and on the length of time it remains on orbit. The debris population will certainly be sufficiently large that collisions will occur on some of the larger structures being considered for use in future programs. The effect of such collisions on the operation of the spacecraft, the implications which the deposition of the resultant debris has on the evolution of the debris population, and its effect on space operations must be understood before such events begin to occur. If not, it is conceivable that a debris population will be created which will make the near-Earth environment unusable for any extensive space program. If this occurs there will be very little that can be done except wait for atmospheric drag to clean out the lower-altitude regions.

The use of a path integral formalism for the calculation of collision hazard levels allows more information on the properties of the debris population to be used than can be accommodated with a latitude-averaged model. It is well suited to analyzing the effect of debris augmentation from a specific event. Collision times calculated with the path integral formalism are generally shorter (Table 1), indicating a collision is more likely to occur than is shown by an analysis using a smoothed population with relative velocity 7 km/s.

The hazard presented to spacecraft as large as the Space Shuttle is seen to be small, as long as they operate at low altitude. Much smaller spacecraft can operate with little danger even in the regions of maximum debris density, as can be seen for the sun-synchronous spacecraft. These conclusions would remain valid even if a significant (greater than a factor of 10) increase in the spatial densities of debris should occur.

However, for large structures in space, such a comfortable margin is not available. Large astronomical instruments, space stations, or large vehicles such as the SPS Electric Orbit Transfer Vehicle would have to be flown assuming a considerable risk that collision with man-made debris would occur. Increases in the population size in the future will only serve to make that risk greater.

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