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Analytic Model for Orbital Debris Environmental Management

David L. Talent*
Lockheed Engineering and Sciences Company, Houston, Texas 77058

A differential equation expressing the time rate of change of the number of objects on orbit has been developed. This approach, referred to as the "particles-in-a-box" (PIB) model, allows for the examination of orbital debris sources and sinks in a fashion that identifies the physical parameters of the low Earth orbit (LEO) environment with the coefficients of the differential equation. The PIB equation has at least two uses: 1) to test the stability of the LEO environment against runaway growth via a simple evaluation of the coefficients, and 2) as the basis for a numerical model of the environment. It has been determined, relative to the first of these two uses, that the present environment is slightly unstable to catastrophic growth—a condition that could be improved by the employment of active debris reduction techniques. Relative to the second of these uses, and under the simplest implementation of the PIB model—a single "equivalent" particle species in a single environmental box—the number of particles on orbit will continue to increase until approximately 2250 to 2350 A.D., reaching totals of 500,000 to 2,000,000. The model is expandable to the more realistic (complex) case of multiple species in a multiple-tier system.

Nomenclature

A = "deposition coefficient"
A_k = deposition term for the kth particle type
B = "removal coefficient"
B_{atm} = reduction fraction per year due to natural drag
B_k = drag and sweeper term for the kth particle type
C = "collision coefficient"
$D1$ = fraction of $P1$ meeting membership conditions
D_1 = average population object diameter
DE = fraction of FE meeting membership conditions
FE = fraction of launches resulting in an on-orbit (noncollisional) fragmentation
F_v = incomplete mixing factor
H_{ij} = collision frequency (yr^{-1}) between members of the population
$\dot{H}_{11}$ = collision frequency (yr^{-1}) between members of a population of similar objects
L = launches per year, worldwide
N = number of objects on orbit
$\dot{N}$ = time rate of change of this quantity as determined by the relative influences of A and B
PE = number of fragments produced per explosion
$P1$ = average number of pieces per launch
R_B = radius of the base of LEO shell from the Earth's center
REM = number of objects removed per year by deliberate retrieval
R_T = radius of the top of LEO shell from the Earth's center
S = reduction fraction per year due to use of "debris sweepers"
V_c = orbital speed at average population altitude
δ = number of pieces produced as a result of the collision less the two destroyed
$\delta_{(ij)k}$ = number of k-type particles produced during i-j collisions

Introduction

A FUNDAMENTAL characteristic of mankind's use of the low-Earth-orbit (LEO) environment is that the devices placed there to serve us usually result in the generation of orbital debris as a by-product. When payloads are launched, operational debris pieces and rocket bodies are also often placed in the environment. In some cases, these objects have not remained on orbit as inert hulks; spontaneous disintegrations[1] have often replaced a single large debris piece with up to hundreds of smaller pieces. Approximately 50%[2] of all objects currently tracked were generated in fragmentations of one type or another.

Even the payloads themselves tend first to become derelicts before they decay from the environment—presently about four out of every five such objects are useless hazards to navigation.[2] From this it may be concluded that the average orbital life of the typical payload is, at least, several times greater than its functional life. Finally, although not yet a significant contributor to the buildup of debris in the LEO environment, collisions may become more frequent as the environment becomes increasingly crowded.

Taken together, about 95%[2] of all tracked objects are trash, and a host of smaller, yet dangerous, objects[3] are suspected to be present. With the exception of very few cases of retrieval [e.g., Long Duration Exposure Facility (LDEF)], the only debris removal mechanism operating in the environment is drag due to the residual atmosphere. Even this mechanism was shown to be ineffective above an altitude of approximately 750 km by Petro and Talent[4] in their study of orbital debris removal methods.

Since the continued use of the LEO environment appears likely, and with an increasing level of activity,[5] a present desideratum would be the development of methods to assess the impact of mankind's activities on the environment and, in turn, the impact of the resultant evolution of the environment on mankind's further use. Presumably, if successful in this pursuit, the user community will be able to determine, with sufficient lead time, what activities and policies are most likely to lead to a stable and desirable environment over the long term.

With these concerns in mind, a method for modeling the LEO environment is presented in this paper that may be applied in forms ranging from the very simple PIB case to a complex multispecies, multitier system.

The Equation and Its Coefficients

In developing a mathematical model of an evolving system, we must first choose a relevant parameter as our "state" quantity. In the present development, the number of objects

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*Principal Scientist. Member AIAA.

resident in the LEO environment at any given time is selected. One reason for this choice is that if an object can be seen, it can be counted—the number of objects on orbit is a direct observable subject, of course, to an appreciation of possible incompleteness,[6] especially at higher altitudes and smaller sizes. The basic equation is presented here as

$$\dot{N} = A + BN + CN^2 \tag{1}$$

The form of the equation follows from the assumptions that 1) deposition reflects the rate at which users of the LEO environment choose to populate it with new objects, 2) decay due to atmospheric drag and/or random removal may be represented as a finite probability per unit time of the decay of any given LEO object, and 3) that the theory for collisions between members of the population may be developed along a line of reasoning similar to that for collisions between particles in a gas whose mean free paths between collisions may be calculated. Each of these coefficients will be described in turn.

A. Deposition Coefficient

It is an historical fact that objects are launched into the LEO environment and that an examination of available data[7] will reveal that it is not unusual, on the average, for more than one object to be placed in low Earth orbit per launch. This activity deposits objects, mass, and collisional "target" area on orbit. Launch activity is a planned, intelligent activity and the typical number of objects deployed per launch is a reflection of policies, procedures, and mission requirements.

Furthermore, it has been observed[1] that some objects, initially intact, later fragment on orbit. As a result of such accidents, no additional mass on orbit results; however, the environment is reduced by one large object and its area only to be replaced by a large number of smaller objects and their net target area. This implies that on-orbit fragmentations are a source of objects and area. Although not planned, the rate of fragmentations is a direct result of human activity and is included here with the "intelligent" deposition of objects in the LEO regime.

Finally, the capability to retrieve debris objects has been demonstrated (e.g., LDEF) and is also being discussed as a possible mode of debris reduction.[4] Thus this component of the deposition term is negative.

In general, for all of the following discussion, the base of LEO will be taken to be that altitude at which an average member of the population has only one year left on orbit. Furthermore, only objects deposited on orbit at an altitude greater than this base and remaining there for at least a year will be counted as members of the environment—hereafter this requirement will simply be referred to as the membership condition. With these provisions in mind the expression for A is

$$A = L[(P1)(D1) + (FE)(DE)(PE)] - REM \tag{2}$$

B. Removal Coefficient

In the absence of a retarding medium, all objects in LEO would remain on orbit for an indefinite period of time. However, the residual atmosphere is sufficient to cause the eventual decay and re-entry of some objects in this region. The efficiency of this mechanism to remove objects from orbit is dependent on the object's altitude, orbital and physical characteristics, the phase of the solar cycle, and so on. Other factors being equal, however, small objects tend to be more susceptible to the action of drag forces by virtue of their (typically) larger area-to-mass ratios. In addition, the possibility of using orbital debris sweepers or some equivalent process for cleaning up the orbital debris environment has been discussed.[4] For the sake of the present discussion, it is assumed that some device or system is possible that may be employed to remove debris objects of all sizes, with the same efficiency, and regardless of their inherent drag characteristics. For example, such a system, when deployed, might sweep up 1% of all orbital debris per year. Taken together with natural decay, the B term is written as

$$B = [B_{atm} + S] \tag{3}$$

The removal of BN objects per unit time results in the removal of numbers of objects, mass, and potential target area.

C. Collision Coefficient

To determine the number of objects created per unit time due to collision, the C term is expressed as the product of two quantities shown here as

$$C = (\delta)\dot{H}_{11} \tag{4}$$

The collision products factor δ is obtainable either from a sufficient base of experimental data or from theory. We will take δ to be a constant in this simplest possible PIB model of the environment in which the population, at all times, is assumed to be made up of equivalent particles whose characteristics, overall, may change as a function of time. A more sophisticated treatment of collision products is allowed for if the population is partitioned into a number of different particle size regimes as will be discussed in a latter section of this paper. The $\dot{H}_{11}$ term is developed along a line of reasoning similar to that of the kinetic theory of gases[8] and is expressed for members of a population of similar objects as

$$\dot{H}_{11} = (F_v)\left[\frac{(\sqrt{2}V_c)D_1^2}{(4/3)(R_T^3 - R_B^3)}\right]\left(\frac{1 - 1/N_1}{2}\right) \tag{5}$$

Strictly speaking, the expression in Eq. (5) is valid only for objects free to move at random in the specified volume. Also implicit in this formulation is the assumption that the orientation of the velocity vector of one particle with respect to all others is completely at random. It is clear that neither of these conditions completely obtain for orbital debris pieces in LEO.

The $\sqrt{2}V_c$ term, for a typical LEO orbit speed, yields about 10 km/s, not greatly different from that reported by Kessler et al.[9] However, the assumption implicit in Eq. (5) that every particle has access to all parts of the LEO volume cannot possibly be correct. An examination of orbital eccentricities is required to calculate F_v. Alternatively, one could determine F_v empirically by comparing the predicted collisions to date under the assumption of $F_v = 1.0$, with the actual number of collisions (if any) to date which would imply a value for $F_v \leq 1.0$.

In a fashion similar to fragmentations, a collision between two objects results in the reduction in the total number of objects in LEO by two along with their contribution to the total cross-sectional area for collisions. This reduction is more than compensated by the addition of the combined cross-sectional area of all of the fragments and a net increase in the total number of (smaller) objects.

Roots of the Equation

Equation (1) is a quadratic equation. As such, given the values of A, B, and C, it is possible to solve for the roots of the equation ($\dot{N} \equiv 0$) by the quadratic formula shown here:

$$N_{1,2} = \frac{-B \pm \sqrt{B^2 - 4AC}}{2C} \tag{6}$$

The quantity under the radical is identified as

$$q = B^2 - 4AC \tag{7a}$$

$$q = [\text{SINK TERMS}] - [\text{SOURCE TERMS}] \tag{7b}$$

It involves the difference between the A and C source terms and the B sink term. This quantity may exhibit the following three types of behavior:

$$q > 0: \text{[SINKS]} > \text{[SOURCES]: conditionally stable} \quad (8a)$$

$$q = 0: \text{[SINKS]} = \text{[SOURCES]: instability threshold} \quad (8b)$$

$$q < 0: \text{[SINKS]} < \text{[SOURCES]: unconditionally unstable} \quad (8c)$$

The first case, $q > 0$, for which two real roots exist (see Fig. 1), will be examined in detail. If the system state—specified by the total number of objects, N—is greater than zero but less than N_1, the system will grow in total number since $dN/dT > 0$; it will asymptotically approach N_1. If something should happen to place the system at a value of N between N_1 and N_2, the system will respond by regressing in total number since $dN/dt < 0$; again it will asymptotically approach N_1. In these two scenarios, the orbital debris system is seen to exhibit stable behavior—if disturbed from the equilibrium value N_1, the system returns to that value. However, stable behavior under perturbation does not necessarily mean that the environment is desirable from an operational perspective. If N_1 is so large as to interfere with important aspects of operations in LEO, the environment is undesirable even though stable. For example, if N_1 were so high that the mean time between collisions was less than or equal to the operational life of a typical payload, the environment would be unacceptable.

An acceptable environment will be one where the value of N_1 is reasonable from the collision probability perspective, and the N_1 to N_2 difference is large enough to render a transition to a value greater than N_2 by accident unlikely.

If the population count N should ever exceed N_2, the system will exhibit catastrophic growth. The implication from Fig. 1 is that the growth will be unbounded, but such a result does not make physical sense. Of course what will happen is that as N begins to grow, collisions will become important, the population will grind itself into smaller particles that will be more readily removed by natural drag. Thus, we would expect the system to undergo a catastrophic adjustment to a new equilibrium situation. During the course of this evolution, the values of A, B, and C will change continuously.

Regarding the evaluation of stability and solving for the roots of the PIB evolution equation, it must be remembered that any statement of stability is only valid for the present epoch of the A, B, and C coefficients.

Application to the LEO Environment

In all of the following examples, a set of specific values have been used for parameters such as launch rate, percentage of launches that produce a fragmentation, number of pieces produced by collision and explosion, etc. These are meant to be illustrative rather than definitive; however, effort has been made to be reasonable in their deduction from the sources listed at the end of the parameters section below.

As can be appreciated by an examination of the Civil Needs Data Base,[5] the anticipated growth in launch rate for the next several decades will be rather stepwise. For the sake of simplicity, a set of evolutionary cases have been adopted for discussion that start with the present launch rate and compound it at several rates of choice until the year 2020, at which time the number of launches is held constant.

The basic procedure employed in all of the evolutionary calculations was to establish the initial number of objects in LEO, an initial total mass in LEO, and an initial total cross-sectional area—taken to be the sum of radar cross sections for all objects in LEO. The sum of the radar cross sections divided by the number of objects provided an average cross section per object. This, in turn, was used to calculate a mean-population member radius. The quantities A, B, and C were then evaluated for use in calculating dN/dt.

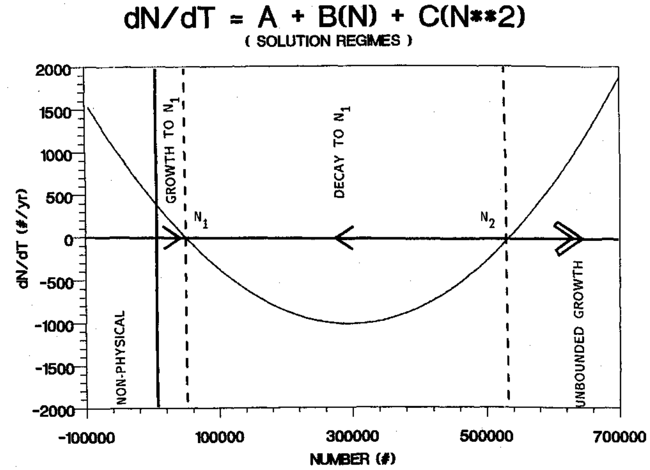

Fig. 1 Illustration of stability regimes as related to the roots of the evolution equation.

During each time step, changes in all quantities were accounted for and new totals for number, mass, and area were determined. These, in turn, were used to calculate new population particle characteristics and changes in the coefficients prior to the next time step.

Choice of Parameters

In the PIB evolutionary calculations the following parameters were used. These are listed below and grouped by association with the coefficients A, B, and C. In all cases, the subscript "i" indicates an initial value that was subject to change during the execution of a modeling run. These are given as follows:

A:

L_i	$= 120$
$P1$	$= 4$
$D1$	$= 0.63$
FE	$= 0.03$
DE	$= 0.82$
PE	$= 125$
REM	$= 0$

B:

B_{atm}	$= -6.0 \times 10^{-3}/R(\text{m})$
S	$= 0$

C:

δ	$= 200$
F_v	$= 0.55$
R_B	$= 6728$ (alt$_b$ = 350 km)
R_T	$= 8178$ (alt$_t$ = 1800 km)
$AREA_{exp}$	$= 5$ (area increase by explosion)
$AREA_{col}$	$= 15$ (area increase by collision)
$MASS_{dep}$	$= 800$ [mass (kg)/launched piece]

Others:

$YEAR_i$	$= 1989$
N_i	$= 6245$ (objects: 350–1800 km)
$ATOT_i$	$= 22{,}400$ (total area in m^2)
$TOTMASS_i$	$= 2.26 \times 10^6$ (total mass in LEO in kg)
V_c	$= 7.3$ (orbital speed in km/s)

These quantities were adopted based on examination of a number of references.[1,6,7,11,13,14] Of all of these quantities, the expression B_{atm} requires further explanation.

The expression for B_{atm} is intended to be representative for the LEO environment as a whole—not any one stratum. It was derived by assuming that the ratio of $ATOT_i$ to N_i, found to be 3.57 m^2, could be taken as an indicator of effective area for the average object in the environment. Using this value, and an expression for C_dA/M obtained by employing the results of Badhwar and Anz-Meador,[10] an effective $C_dA/M = 0.041$ was found. Using the distribution of objects with altitude illustrated in the Interagency Report[6] and a Jacchia[12] atmosphere appropriate for an assumed $F_{10} = 110$, an iterative decay program was executed until half of the entire population was decayed. This was taken as the half-life, about 500 years, of the LEO population corresponding to the derived effective value of C_dA/M. This suggests a baseline value of B of about -1.4×10^{-3}.

However, from an examination of data in the Space Surveillance Catalog,[13] it is apparent that the population mean radar cross section (RCS) is about four times larger than the population median RCS. Therefore, with a correction of a factor of four to allow for this effect, B becomes -5.6×10^{-3}. This is only appropriate for the baseline equivalent radius, derived here from the average RCS, as 1.07 m. The adopted expression, $B_{atm} = -6.0 \times 10^{-3}/R(\mathrm{m})$, assumes that changes in this population-average-effective drag term vary as $1/R$—consistent with area-to-mass for a solid sphere.

Simple Evolutionary Cases

Six evolutionary cases were generated; each is characterized by a rate of growth through the year 2020 followed by a steady launch rate thereafter. The simple compound growth cases examined were from 0% per year through 5% per year in steps of 1% between models. Figure 2 presents a montage illustrating the evolution of the LEO environment under the given assumptions.

Several general features immediately manifest themselves from an inspection of Fig. 2. These are 1) Catastrophic behavior is exhibited under all assumptions of growth rate from 0–5% as manifested by the fact that each of the curves (including the 0% case) reaches a peak number and peak mass before declining toward an asymptotic value. 2) With increasing growth rate the onset of catastrophic conditions is accelerated and intensified. 3) The typical time scale to achieve asymptotic behavior is 300–400 yr. 4) As is clear from an examination of the number and mass plots, illustrating the details of projected growth prior to 2050, significant dispersion in the cases is evident by 2020–2030.

A physical understanding of the growth, peak, and decline to asymptotic behavior illustrated in Fig. 2 is developed as follows. During the earliest phases of the evolutionary scenario large objects are placed on orbit at an ever increasing rate to the year 2020. As the number of objects increases, so also the total mass and total collisional cross-sectional area in the LEO environment is increased. Only fragmentations add objects and area by the conversion of a few large objects to small objects. Since the significance of collisions increases as N^2, and the product CN^2 is small in the early phases of the evolution, deposition with fragmentation (A) and drag with sweeping (B) dominate the behavior of the system.

Since the significance of the collisional term CN^2 increases by about a factor of four with each doubling of N (assuming C is nearly constant), collisional processes may be expected to become significant rather suddenly. That is, at some point the net number of objects added per year to the environment will be dominated by the addition of collisional fragments.

During this phase, large objects are processed into smaller objects and the average radius of a population member becomes smaller (Fig. 3). However, smaller objects are removed from the environment more readily by atmospheric drag—this tends to reduce the number of objects in the environment.

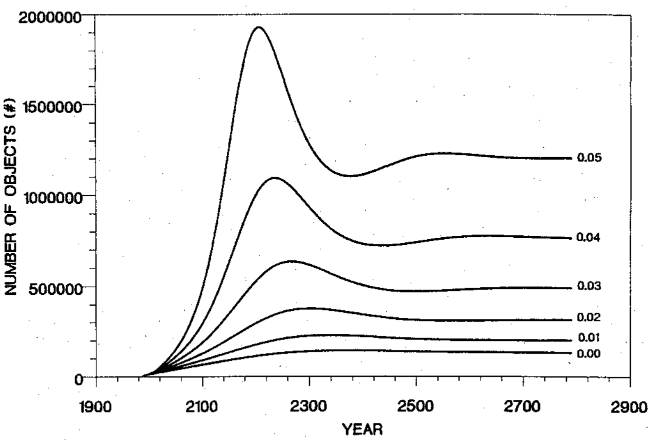

Fig. 2a Number of objects on orbit as a function of time as predicted by the PIB model for constant growth rates in the number of launches per year to 2020 A.D.; growth rates have been allowed to vary from 0–5% in 1% steps.

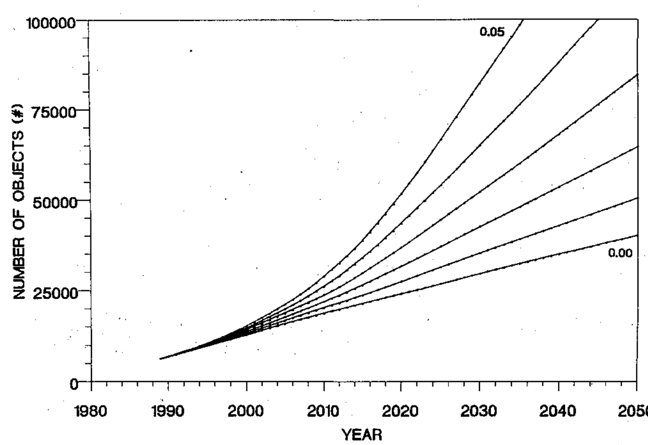

Fig. 2c PIB number data displayed to resolve the near-term growth in the number of objects on orbit.

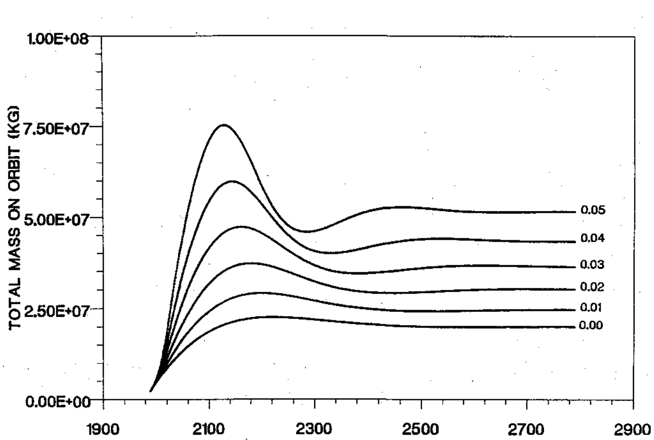

Fig. 2b Total mass on orbit as a function of time as predicted by the PIB model for the sequence of Fig. 2a.

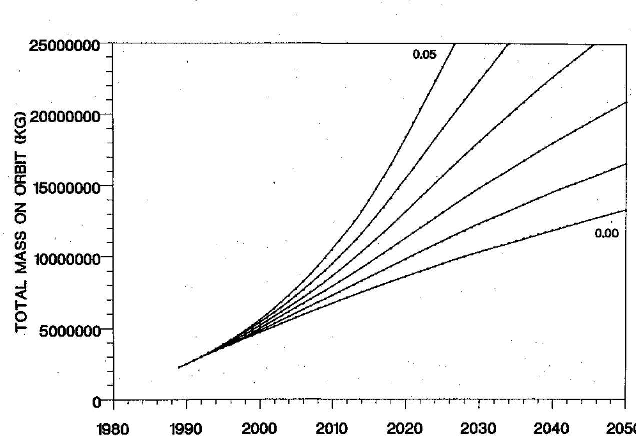

Fig. 2d PIB mass data displayed to resolve the near-term growth in the total mass on orbit.

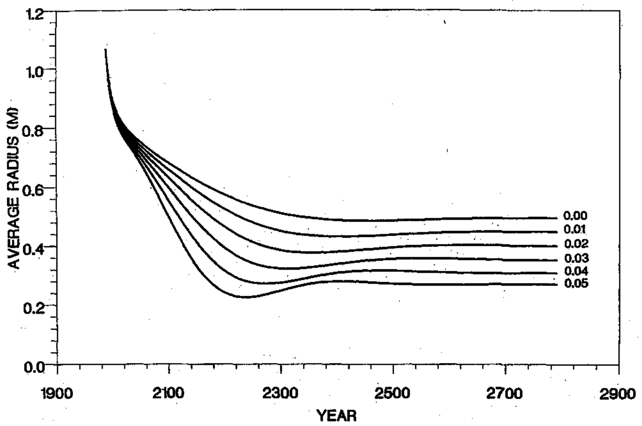

Fig. 3 PIB evolutionary scenarios for constant growth rates to 2020; from 0–5% in 1% steps. Evolution of average radius of a population member clearly exhibiting the effects of collisions.

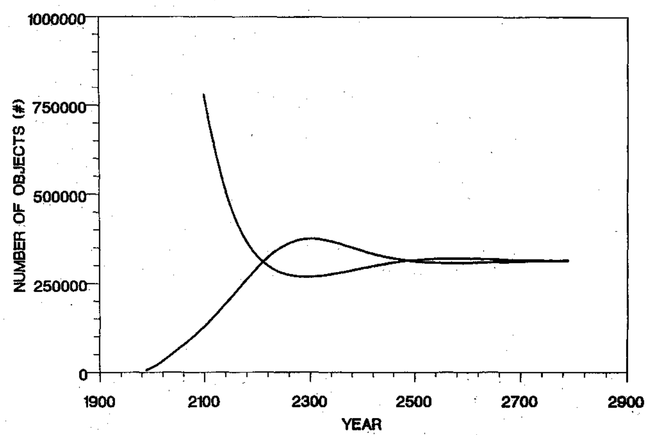

Fig. 4 Sudden enhancement of 2% PIB evolutionary case vs steady 2% growth.

Furthermore, since the average radius of a typical member of the population is becoming smaller, the value of the coefficient C, proportional to R^2, is reduced. Since N is also being reduced, the net result is that the product CN^2 is diminished and the "runaway" growth stops. The system has evolved to the point that a new evaluation of q would show that the environment is stable and asymptotically approaching the N_1 root of the quadratic equation.

The onset of a collisionally dominated environment for the two extreme cases shown in Fig. 2—0 and 5% growth—occurs in the years 2136 and 2054, respectively. An additional calculation, for the 10%-growth case, yielded the year 2032 for the onset of domination of the environment by collisional processes. For practical purposes, these dates may be considered the onset dates for runaway growth under the assumptions for each model.

These results, in general, are consistent with the collisional growth expectations put forward in earlier works such as that of Kessler and Cour-Palais.[15] In particular, for the 3%-growth case developed here, the cumulative number of collisions from 1990–2020, at five-year intervals, is 1.00, 1.42, 2.15, 3.32, 5.14, 7.87, and 11.89, respectively. When compared to Fig. 4 of Kessler and Cour-Palais,[15] the 3% case is seen to closely match their "510 Objects/Year" growth case.

Catastrophic Deposition

In the models of the last section, growth was considered to be smoothly increasing up to the year 2020 and to be maintained at a constant rate thereafter. Real growth is more likely to be stepwise[5] as new programs start.

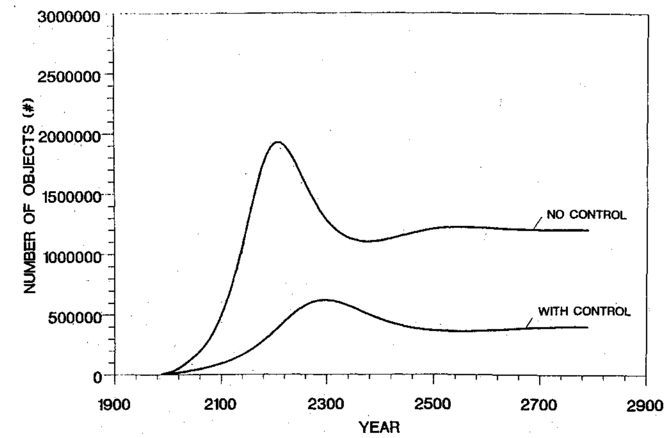

Fig. 5 Significant improvement in the evolution of the 5% case by virtue of the elimination of fragmentations and reduction of the deposition of operational debris by 50%.

Another possible stepwise addition of particles to the environment is that of a large number of particles through accidental or deliberate deposition.

To illustrate the use of the PIB model in the case of the sudden addition of a large number of small particles to the environment, the case shown as Fig. 4 was developed. In this scenario, the LEO environment is assumed to be evolving along the 2% curve when, in the year 2100, about 600,000 objects of radius 2.5 cm and having a total mass of about 100,000 kg are suddenly deposited in the environment. As can be seen from the figure, since these objects are rather small, they leave the environment relatively quickly due to drag, but not before they are involved in a significant number of collisions and thus drive the net population below the evolutionary curve it was previously following.

Control

To illustrate the usefulness of the PIB model in assessing the effects of different modes of orbital debris generation prevention, Fig. 5 compares the nominal 5%-growth case to a modified case wherein no fragmentations are allowed to take place in combination with a modification in operational procedures that, on the average, deposit only two objects on orbit per launch instead of the value of four used in the first evaluation of the 5%-growth case.

Other debris control procedures may be examined using the PIB model including the use of debris sweepers, collision avoidance, and others. Some of these would be best developed allowing the LEO population to be partitioned into multiple object species with placement in multiple environment tiers.

Multiple Species, Multiple Boxes

Equation (1) extended to the case of a single environmental box containing m species of particles is

$$\dot{N}_k = A_k + B_k N_k + \sum_{i=1}^{k} \sum_{j=i}^{m} \delta_{(ij)k} \dot{H}_{ij} N_i N_j \tag{9}$$

where the index k may take on values from 1 to m. Regarding the $\dot{H}_{ij}$ factor, Eq. (5) is appropriate if $i = j$; for dissimilar objects the appropriate form is

$$\dot{H}_{ij} = (F_{v_{ij}}) \left\{ \frac{(\sqrt{2}V_c)[(D_i + D_j)/2]^2}{(4/3)(R_T^3 - R_B^3)} \right\} \tag{10}$$

To extend to a multitier system, a set of equations such as Eq. (9) would be written for each tier with crossfeed terms being developed to accommodate particle migration from tier to tier and/or multitier, multisize deposition due to fragmentations and collisions. The details of such a formulation would be dependent upon the process models for these phenomena.

Conclusions

The PIB model has been developed and illustrated as a useful tool for the assessment of LEO environment stability and as a starting point for the development of evolutionary models. The model allows for a simple treatment of the gross features of environment evolution yet is consistent with expectations based on physical arguments.

Within the context of the model, evolutionary scenarios have been examined for the future state of the LEO environment and have been found to be very sensitive to growth rate—either simple percentage growth or the sudden deposition of a large number of particles in the environment.

On the other hand, a few simple changes in current operating practices relative to the deposition of operational debris and the allowance of fragmentations were shown to be effective in significantly reducing the maximum debris growth as well as the asymptotic behavior of the 5%-case model.

Although the PIB model is illustrative and useful as a modeling tool, the further development of the technique to the multispecies, multitier case is a reasonable next step.

Acknowledgments

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References

[1]Johnson, N. L., Gabbard, J. R., Kling, R. L., Jr., and Jones, T. W., "History of On-Orbit Satellite Fragmentation," U.S. Army Strategic Defense Command, A029, Huntsville, AL, Feb. 1986.

[2]Johnson, N. L., "Evolution of the Artificial Earth Satellite Environment," *Orbital Debris from Upper-Stage Breakup,* edited by Joseph P. Loftus Jr., Vol. 121, Progress in Astronautics and Aeronautics, AIAA, Washington, DC, 1989, pp. 15–24.

[3]Kessler, D. J., "Current Orbital Debris Environment," *Orbital Debris from Upper-Stage Breakup,* edited by Joseph P. Loftus Jr., Vol. 121, Progress in Astronautics and Aeronautics, AIAA, Washington, DC, 1989, pp. 3–14.

[4]Petro, A. J., and Talent, D. L., "Removal of Orbital Debris," *Orbital Debris from Upper-Stage Breakup,* edited by Joseph P. Loftus Jr., Vol. 121, Progress in Astronautics and Aeronautics, AIAA, Washington, DC, 1989, pp. 169–182.

[5]Guthrie, G., and Montgomery, S., "Civil Needs Data Base FY 1989 Version," Vol. IV, SRS Technologies, NASA Contract NASW-4341, Arlington, VA, 1989.

[6]Anon., "Report on Orbital Debris," National Security Council Rept., 1989, pp. 1–28.

[7]Anon., "Satellite Situation Report(s)," NASA Rept., Vols. 15–27, 1975–1987.

[8]Reif, F., *Fundamentals of Statistical and Thermal Physics,* McGraw-Hill, New York, 1965, Chap. 12.

[9]Kessler, D. J., Reynolds, R. C., and Anz-Meador, P. D., "Orbital Debris Environment for Spacecraft Designed To Operate in Low Earth Orbit," NASA TM 100-471, April 1989.

[10]Badhwar, G. D., and Anz-Meador, P. D., "Determination of the Area and Mass Distribution of Orbital Debris Fragments," *Earth, Moon, and Planets,* Vol. 45, 1989, pp. 29–51.

[11]Anz-Meador, P. D., private communication, NASA Johnson Space Center, Houston, TX, April 1990.

[12]Jacchia, L. G., "Thermospheric Temperature, Density, and Composition: New Models," Smithsonian Institution, SAO-SR, No. 375, Washington, DC, 1977.

[13]Anon., "Space Surveillance Catalog," U.S. Space Command Rept., Dec. 1989.

[14]King-Hele, D. G., Walker, D. M. C., Pilkington, J. A., Winterbottom, A. N., Hiller, H., and Perry, G. E., *The R. A. E. Table of Earth Satellites (1957–1986),* Stockton Press, New York, 1987.

[15]Kessler, D. J., and Cour-Palais, B. G., "Collision Frequency of Artificial Satellites: The Creation of a Debris Belt," *Journal of Geophysical Research,* Vol. 83, No. A6, 1978, pp. 2637–2646.

Paul F. Mizera
Associate Editor