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SIMULATION MODEL OF SPACE STATION OPERATIONS IN THE SPACE DEBRIS ENVIRONMENT

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ABSTRACT

A discrete event simulation model was developed to analyze the effect of space debris on the Space Station operations. The space environment model includes elements contributing debris (e.g., launches) and the dynamics of the elements (e.g., explosions and decay). The model simulates the Space Station operations and interaction with the debris environment. The resulting data describe the number of Space Station encounters with debris as a function of the buffer zone. These results are translated to fuel requirements for avoidance maneuvers. Sensitivity analysis results caused by varying the initial conditions, system dynamics and operations philosophy are discussed.

INTRODUCTION

Past practices by all nations utilizing space since 1958 have created a cluttered space environment. Satellites now operate with increasing risk of colliding with space debris. Ironically, the realization of the increasing magnitude of this problem comes at a time when many nations are becoming increasingly dependent on their space assets for communications, military, research, and future production needs.

While scientists disagree as to the rate of debris growth, all agree that it is large and is increasing. Such a scenario brings to question the reliability, cost-effectiveness, and safety of present and future satellites and manned spacecrafts.

There has not been a lack of analysis on the satellite collision hazard problem. However, many studies have contradictory results on the criticality of the situation, and almost all have considered only small satellites when calculating collision probabilities. Indeed, scientists concur that the acceptable level of risk will decrease with time, altitudes higher than the Shuttle, and large structures (1; 2; 3:285). One large structure that has received little attention with regards to debris hazard analysis is the proposed Space Station. The Space Station Program Description Document prepared by the Space Station Task Force acknowledges the collision hazard only twice. First, the document discusses the impact resistance of the spacecraft, but only in terms of the meteoroid flux (4: Sec 6, 3). Second, the document expresses concern over the interaction of composite materials with both man-made and meteoroid debris particles. (5: Sec 5, 18)

The establishment of a permanent manned presence in space puts increased importance on debris hazard for several reasons. First, the Space Station will be many times larger than any other manned spacecraft previously put into space. Therefore, it is more likely to be hit by debris. Second, this larger target will be manned, therefore increasing concern over system survivability. Third, the Space Station will be permanent. Therefore, it will more likely be hit by debris because of its constant exposure to such an environment. Fourth, the Space Station will be the most concentrated effort and probably the most expensive effort since Apollo, so great care will be taken to ensure the program's success. Finally, the Space Station will be open to international and commercial use. Overall, many countries and commercial firms have a very real stake in the success of a Space Station which will exist in a hazardous environment.

A complete model was developed that describes the elements and dynamics of the space debris environment. A discrete event simulation using SLAM was used to analyze the operation of the Space Station. The resulting data gave the number of Space Station encounters with debris as a function of the buffer zone. The data was also used to calculate the fuel required to execute avoidance maneuvers. The sensitivity of the results due to different assumptions and parameters of the debris elements, system dynamics and the operations philosophy were also analyzed.

CONCEPTUAL MODEL

A causal diagram, shown in Figure 1, describes the elements in the system and the interactions. The causal diagram shows that the probability of collision increases if there is an increase in the exposure time to the space debris environment, the relative velocity between the satellite of interest (SOI) and the colliding debris object, the cross-sectional area of the SOI, or the space debris density. These parameters correspond to those used by other researchers when calculating the collision probability calculations (6:280; 3:281; 7:103, 107, 119; 8:361).

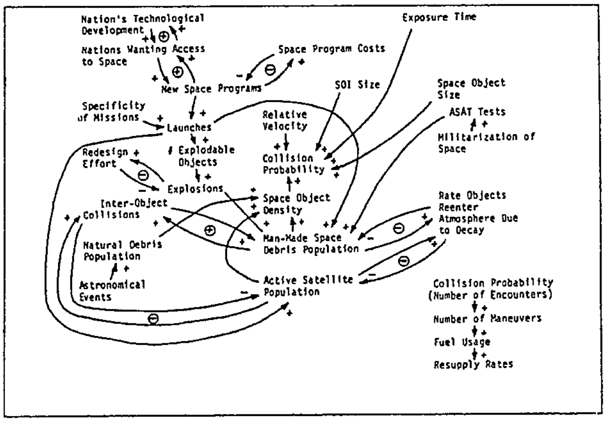

Figure 1: Causal Diagram

The longer an SOI is exposed to the space debris environment, the more likely it will collide with debris. Likewise, a higher relative velocity indicates that the debris will cross the path of the SOI more often, and hence have more opportunities to collide with it. An increase in the cross-sectional area of the SOI will cause the probability of collision to increase simply because the SOI will sweep out a larger volume of space where debris may be located. Finally, an increase in the spatial density of orbiting objects with which the SOI may collide will increase the probability of collision because of more objects available for collision.

A parameter not considered in many derivations of the collision probability equation deals with the cross-sectional area of the debris. The causal diagram indicates that an increase in this parameter would have the same effect on the collision probability as the SOI cross-sectional area.

Debris spatial density is a primary determinant of the probability of collision. The system elements affecting spatial density consist of space launches, unintentional explosions, ASAT test explosions, inter-object collisions, the natural debris population, and the orbital decay of active satellites and debris into the atmosphere.

The causal diagram shows that there are several system elements which influence the number of space launches which significantly contribute to the active satellite and debris populations. The 1983 TRW Space Log listed fourteen nations involved in sponsoring launches (9:120). As nations develop their technology, their desire for access into space will increase. This has been true for the United States and the USSR. This increased desire will create more incentives to develop technology, forming a positive loop as indicated by the causal diagram. Again, the American and Russian space programs verify this condition. The technological development, desire to access space, and the space program positive loops are tempered by the costs associated with the space programs, which the causal diagram indicates with a negative loop. While the number of new space programs may be constrained somewhat by cost, an increase in their number will likewise increase the number of space launches.

As the mission of satellites becomes more specific, more space launches will be required to achieve broad space program objectives. An increase in the number of launches, in turn, directly increases both the active satellite and debris populations. Finally an increase in these populations naturally increases the spatial density of objects in orbit. Unintentional explosions such as defective spent boosters, and intentional explosions as a result of ASAT tests are also primary contributors to the space debris population. However, analysis of unintentional explosions have resulted in redesign efforts thereby creating a stabilizing negative loop between the two elements. However, as the number of explosions from defective items still in orbit increases, the debris population will continue to increase. An increase in the number of ASAT tests also increases the debris density. The number of ASAT tests, in turn, is dependent on the intent of nations to militarize space.

Two additional sources of debris, inter-object collisions and the natural debris flux, are not major contributors to the debris spatial density but do contribute to the apparently destabilizing nature of the space debris environment system. The causal diagram shows that inter-object collisions and the space debris population form a destabilizing positive loop. As inter-object collisions increase, the debris population increases. As this population increases, however, the probability of elements of this population colliding increases also. The number of inter-object collisions forms a "stabilizing" negative loop with the active satellite population. As the number of inter-object collisions increases, the probability of collision between an active satellite and another SOI increases, thereby decreasing the number of active satellites. As the active satellite population increases from launches, on the other hand, the spatial density of orbiting objects increases and thus the probability that two objects will collide increases. This negative loop, while stabilizing from a causal diagram perspective, is obviously destabilizing to those interested in the survivability of all active satellites.

Natural debris flux is the second minor contributor to the debris spatial density. It primarily consists of meteorites traversing the orbits of active satellites and man-made debris. This flux is dependent on astronomical events whose increase causes the total debris spatial density to temporarily increase. As many researchers agree, the growth of the man-made flux lessens the importance of the natural debris flux in the collision probability problem (10).

Orbital decay at this time is the only element that contributes directly to stabilizing the space debris population. The causal diagram shows that the rate at which objects reenter the atmosphere due to decay forms negative loops with both the active satellite and debris populations. The decay rate depends on the altitude of the object, the state of the atmosphere, and the object's size and density (7: 121-127). While orbital decay does contribute to the stabilization of the orbiting object populations, its contribution is overwhelmed by the destabilizing contributions of debris sources.

The causal diagram indicates a one-way, positive relationship between the probability of collision, the number of maneuvers required, the amount of fuel used, and the required resupply rates. An increase in the number of close encounters with debris will require the Space Station to perform more avoidance maneuvers and to use more fuel. Should this fuel usage exceed original plans, additional Space Shuttle resupply missions would be required. This sequence of events will directly increase the cost of the Space Station and Space Shuttle programs. Increased costs could constrain the development of new space programs. Therefore, the causal diagram shows a link between the probability of collision and the ability of man to use the resource of space.

SPACE STATION DESCRIPTION

The Space Station will consist of separate manned and unmanned orbiting satellites. A manned "core" element will be the first element of the system deployed. It will contain research and development laboratory facilities, pilot production capability, servicing facilities for satellites and other space vehicles, logistics support for other elements of the Space Station system, and transportation capability to those elements.

The Space Station core element should become operational in 1992 and will grow in size and capability until 2000. The Space Station will be assembled and serviced by the Space Shuttle, with servicing missions occurring on a 90-day basis (11: 132). The core element is currently planned to be deployed in a circular orbit at an inclination of 28.5 degrees and at an altitude of 500 kilometers. There is the possibility of another core element being deployed at a later date at 400 kilometers altitude and 90 degrees inclination (12:23). The remainder of the Space station system will consist of unmanned space platforms where scientific experiments and production facilities will be located.

COMPUTER MODEL

The debris population is divided into three altitude bands, or concentric shells, surrounding the earth: 200 to 400 kilometers, 400 to 600 kilometers, and 600 to 900 kilometers. The system elements for the model are launches, ASAT tests, orbital decay, unintentional explosions, and inter-object collisions. The objects in each altitude band are assumed to be uniformly distributed. Additionally, the average cross-sectional areas of the objects within each altitude band and the average orbital velocities remain constant.

The run length of the model was designed for 30 years, starting in 1984. This time interval would give data for the period leading up to the deployment of the Space Station, during its growth to maturity, and after it reached maturity.

The parametric model is a discrete event simulation using the SLAM simulation language. The space debris environment system elements included in the simulation model are individual subroutines. Other subroutines initialize the variables, calculate the Space Station collision probabilities and the number of encounters with debris requiring avoidance maneuvers, periodically check the system parameters, and present the results.

Initialization Subroutine

This subroutine sets initial values for all variables in the simulation model. The simulation starts in 1984 and runs for thirty years to 2013. Although the Space Station will not become operational until 1992 a 1984 start allows the use of known parameters.

Since this model does not keep track of each object's orbital parameters, average velocities for each altitude band are used in the collision probability calculations. The circular orbital velocity equation is:

$$v_c = (\mu/a)^{1/2}$$

where

a = altitude from earth's center (km)
μ = universal gravitational constant (km^3/sec^2)

This equation reflects the assumption of predominantly circular orbits in LEO. The velocities used in the model were the averages of the velocity calculations at the middle and boundaries of each altitude band.

The August 1984 CLASSY catalog established the initial tracked debris populations. For the altitude bands of interest, 2,593 objects were found, with approximately 12% found in the low altitude band, 32% in the medium band, and 56% in the high band (13). The tracked debris was divided into large objects, those having an average RCS greater than 1.0 m^2, and small objects. The untracked population was assumed to be three times as large as the tracked population. This was based on survey results from experts in the space debris environment field (14:33).

For orbital decay, the decay constants represent the percentage of objects decaying out of a particular altitude band in one week's time (14:34). Since the largest percentage of objects is found within the altitude bands modeled, and since objects at higher altitudes take hundreds of years to decay, it is assumed that no objects decay from higher altitudes into the high altitude band.

Survey responses obtained by Penny and Jones (14) were used to establish 1400 total explodable objects in low earth orbit. Using 50.9%, the proportion of total tracked population in the CLASSY catalog of interest, there are 713 explodable objects in orbit between 200 and 900 kilometers. It was assumed that the number of explodable objects at a particular altitude was proportional to the total number of objects in that altitude band (15).

The remaining variables involve system elements which are sources of debris: launches, ASAT tests, and unintentional explosions. The current total number of launches range between 120 and 150 (9). The model uses these values as minimum and maximum launch rates and 135 launches as the yearly mean rate. The exponential distribution with these parameters was used to generate inter-arrival times between launches because of the independent scheduling of launches among all nations.

An exponential distribution with a mean of two ASAT tests per year was selected to generate inter-arrival times between the occurrence of these tests. Again, like launches, ASAT tests are assumed to occur independently of one another. For unintentional explosions survey responses estimated that one out of every 500 explodable objects exploded each year (14). This parameter is the mean of an exponential distribution used to generate the time between explosions. The "memoryless" property again describes the independent nature of these occurrences.

Event-Scheduling Subroutine

The EVENT subroutine calls the appropriate event subroutines. Figure 2 is a flowchart depicting the major elements of this subroutine.

ASAT Test Subroutine

The subroutine determines the altitude band and the quantity of debris deposited in that band. Based on Soviet ASAT studies, 50% of the tests occur in the medium altitude band (16). It is assumed that the debris generated stays in the same altitude band where the ASAT test occurred (17:114), and the debris has a normal distribution (14:107). The parameters for this distribution were obtained from an analysis of the historical data collected by Johnson on the Soviet ASAT test program. The total debris population is then recalculated.

Orbital Decay Subroutine9

The DECAY subroutine performs two major functions. First, it updates the debris populations in each

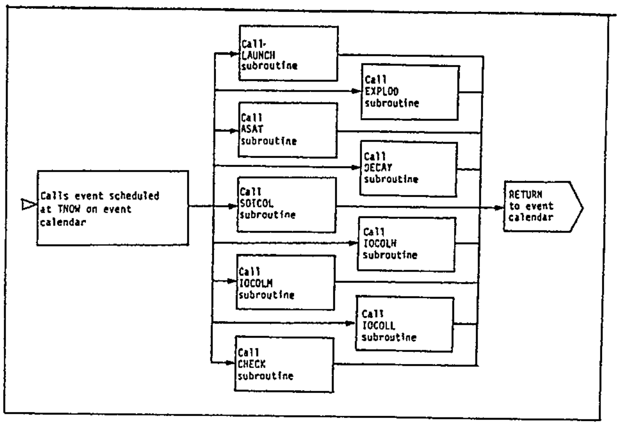

Figure 2: Event-Scheduling Flow Diagram

altitude band weekly to account for orbital decay. Second, because this subroutine is scheduled on a weekly basis, the debris and explodable object populations are recorded to obtain averages of these populations over the year.

Unintentional Explosion Subroutine

The subroutine EXPLOD, handles the time, location, and dynamics of an unintentional explosion in space. The primary functions of this subroutine are to (1) schedule the next unintentional explosion, (2) determine the altitude band where the explosion occurred, (3) determine the quantity of debris generated from the explosion, (4) decrement the appropriate explodable object population to account for the explosion, and (5) update the debris populations based upon the debris added.

The altitude band in which the explosion occurs is based on the relative percentage of the number of explodable objects in a particular altitude band to the total number of explodable objects. The gamma distribution is used to generate the amount of debris. This was based on survey results obtained by Penny and Jones (14:102-103). Also coming from that survey are the parameter values of 500 objects for the mean and 140 objects for the standard deviation.

Orbital Launch Subroutine

The subroutine LAUNCH performs the functions associated with a launch of a spacecraft. These functions include determining the altitude band where the spacecraft enters into orbit, the amount of debris deposited from the launch, the number of new potentially explodable objects added to the environment, and the updating of the debris populations. The subroutine also schedules the next launch using an exponential distribution with a mean of 135 launches per year. The TRW Space Log indicates that, for those launches targeted at the altitude bands of interest, approximately 69% of the payloads were put in the low altitude band, 15% were put in the medium altitude band and 16% were put in the high altitude band (9). A normal distribution with a mean of 13 and a standard deviation of three, was used to generate the amount of debris (18:97-98). Also, no less than 9 and no more than 18 objects can result from a launch (14:97). According to the survey, each launch deposits two explodable objects in the same altitude band as the payload (14:99).

SOI Collision Probability Calculation Subroutine

The subroutine SOICOL calculates the Space Station collision probability and the number of encounters with debris. The Poisson distribution was used to calculate the Space Station collision probabilities. With respect to the space debris environment model, an "event" is the collision between a debris object and the Space Station. Given small enough intervals of time where the debris densities do not change, the occurrence of a collision in these intervals of time is equally likely. Finally, the collision with one object in no way affects the possibility of the Space Station colliding with another object. Therefore, the Poisson distribution was used in the calculation of collision probabilities.

Since an "event" can only occur when an object and the Space Station are at the same place at the same time, this is equivalent to determining the number of objects found within the volume swept out by the Space Station over a year's time. This value is a function of several parameters: the debris spatial density, the Space Station cross-sectional area, the relative velocity between the colliding debris and the Space Station, and the length of time the Space Station is exposed to the environment. The parameter can be written as:

$$1 = d\ A(0.6 \times v)t$$

where

d = debris spatial density (objects/km^3)
A = Space Station cross-sectional area (km^2)
v = Space Station circular orbital velocity (km/sec)
t = time of measurement (sec)

The overall Space Station probability of collision calculation therefore becomes:

$$P\ (X \geq 1) = 1 - \exp(-d\ A0.6vt)$$

The debris spatial densities were calculated using the current debris populations from each altitude band. The cross-sectional area of the Space Station from 1992 through the year 2000 was incremented to correspond to the planned growth in the Space Station (19). The value of 0.0000004 is the weekly increase in growth.

The number of objects the Space Station encounters was a different calculation because it involved a shorter time period of measurement and a different SOI cross-sectional area. Avoidance maneuvers will be required when an object lies in the Space Station's path and when it is in close proximity to a collision path. A buffer zone is required because of the present inaccuracies of the ground-based tracking facilities. These inaccuracies may be up to ten kilometers of error when tracking certain space objects (20:21).

Based on a ten kilometer diameter circular buffer zone with the Space Station at the center, the volume swept out by the Space Station for one revolution is 13,576,628 km^3. The circular orbital period is 94.613372 min/orbit, which is 106.53885 orbits/wk. The volume swept out by the Space Station buffer area per week becomes $1.4464383 \times 10^9\ \mathrm{km}^3$/wk. This number was multiplied by the debris spatial density to obtain the number of objects encountered per week.

Inter-Object Collision Subroutines

The inter-object collision event periodically checks whether an inter-object collision occurred in any of the altitude bands. This event was divided into three separate subroutines corresponding to the three altitude bands. The probability of collision between any two objects other than the Space Station for each altitude band was calculated using parameter values found at that instant in time. The inter-object collision subroutines next determined whether a collision actually occurred, the type of objects involved in the collision and the amount of resulting debris. Figure 3 shows the flow chart for the medium altitude band. Except for the SCHEDULE function, the flow chart is identical to the low and high band charts.

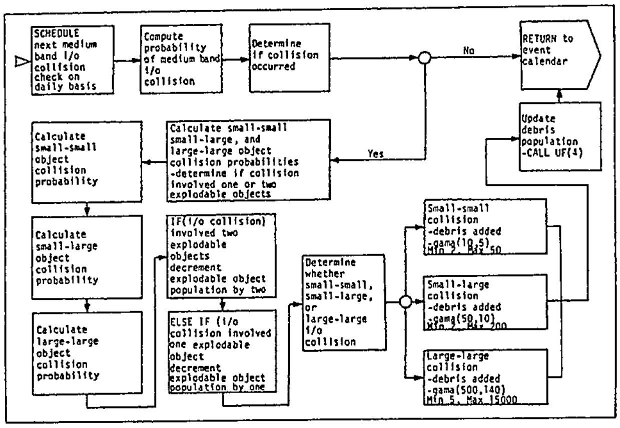

Figure 3: Medium Altitude Band Inter-Object Collision Flow Diagram

EXPERIMENTAL DESIGN

The most critical unknown directly affecting the model output is the size of the untracked debris population. The baseline model uses three times the tracked population as the starting untracked population. Additionally, the starting debris populations were varied to account for untracked debris populations five and eight times the amount of tracked objects. A factor of eight was chosen to correspond to recent observations performed with the U.S. Air Force GEODSS telescope system in estimating the amount of trackable debris (21:16). The factor of five provides a middle range for analysis.

The safety or buffer zone around the Space Station depends on the confidence in the exact location off the orbiting debris. To avoid the possibility of colliding with debris, the Space Station would need to maneuver. A trade-off exists between the level of confidence and the fuel required for avoidance maneuvers. Therefore, an analysis was done for different buffer zones (radii): 1, 3, 5, 7, and 10 kilometers.

It was determined that nine replications of the parametric model will give collision probabilities of the desired accuracy with 97.5% confidence (22:427).

ANALYSIS

Table 1 presents the collision probability over the 22 years of analysis for the three different starting untracked debris populations. The Space Station collision probabilities using untracked debris populations three times the tracked populations yielded an average value of 0.0335 with a sample standard deviation of 0.0082 over the first 22 years after initial deployment of the spacecraft. This translates to at least one collision within a 29 year period. The average collision probability over the years of interest when considering an untracked debris population five times as large as the tracked debris population is 0.0392 with a sample standard deviation of 0.0107. This probability indicates that at least one collision will occur in 25 years, which is expected considering the increased magnitude of the untracked debris population. However, the average collision probability for an untracked debris population eight times the number of tracked objects is 0.0366 with a standard deviation of 0.0132, which translates to at least one collision occurring in a period of 27 years. This discrepancy apparently can be attributed to orbital decay counteracting the larger, initial debris population of small, untracked objects.

YEAR	UNTRACKED DEBRIS POPULATION 3X	5X	8X
1992	.04417984	.05004029	.06086987
1993	.04948522	.05049875	.06216294
1994	.04559287	.05495163	.05849797
1995	.04469331	.05539890	.05242787
1996	.04213160	.05388026	.05156042
1997	.03347091	.05229689	.04698096
1998	.03599253	.04581250	.04350626
1999	.03342433	.04311085	.03893839
2000	.03807677	.03845693	.03874352
2001	.03743685	.04408584	.03530629
2002	.03762065	.04284479	.03089205
2003	.03377774	.04039241	.02822994
2004	.03084769	.03629503	.03015987
2005	.02849567	.03537226	.02941474
2006	.02679938	.03297165	.02961808
2007	.02537565	.03051218	.02772455
2008	.02467216	.02876923	.02580383
2009	.02407048	.02722227	.02411659
2010	.02358310	.02597688	.02294796
2011	.02370759	.02543776	.02253946
2012	.02366490	.02484992	.02186278
2013	.02687203	.02443635	.02467285
$\bar{x}$	.0333624	.0392552	.0366808
σ	.008222	.0107317	.0132783

TABLE 1: Collision Probabilities

The general trend of the collision probability calculations is an initial increase in value within the first four years of interest, followed by a general decrease over the remaining years. Since the collision probability as calculated depends exclusively on the changing debris spatial density, an analysis of the medium altitude band debris population over the years of interest yields the same general trend. Figure 4 illustrates the similarity of these trends. It should be noted that the x-axis corresponds to the year of the simulation run, with year number one corresponding to 1984, year number nine corresponding to 1992, the first year of Space Station operations, and year number 17 corresponding to Space Station maturity in the year 2000. Certain system elements

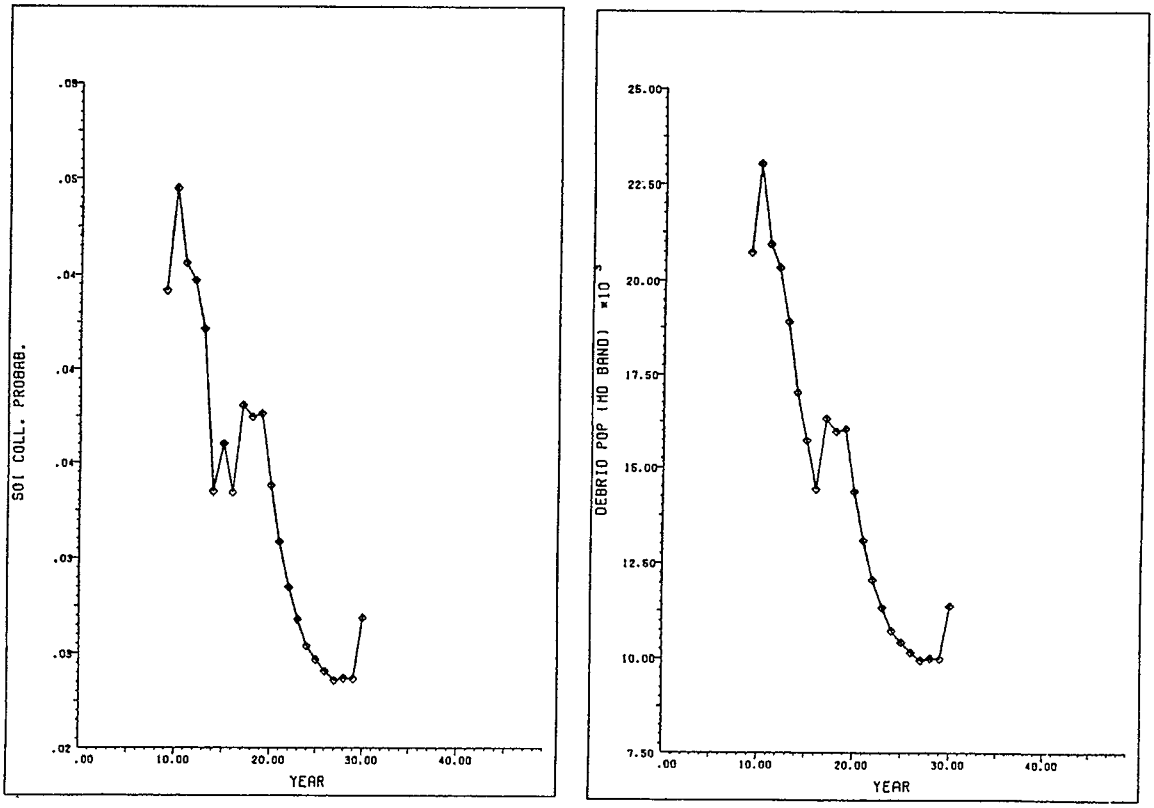

Figure 4: Trend of Collision Probabilities and Debris Population for 3x1 km Model

are primary contributors to this model behavior. First, only 15% of the space launches enter the medium altitude band, so launch debris and, more importantly, explodable objects are not added to that band. In addition, the relatively high orbital decay rate in the medium band compared to the high altitude band decay rate depletes both the debris and explodable object populations faster than they are added.

Analysis of the maximum and minimum collision probabilities for each model of varying untracked debris populations provides a more accurate picture of the impact caused by this parameter. The maximum probability of 0.0494 occurs in 1993 for the model incorporating an untracked debris population three times the tracked population. The minimum value of 0.0235 occurs in the year 2010. These probabilities translate to at least one collision occurring in 20 years and 42 years, respectively. From the model incorporating an untracked debris population five times the tracked population, 1995 yields the maximum collision probability of 0.0553, or at least one collision in only 18 years of operations. The minimum value of 0.0244, or at least one collision in 40 years, occurs in the last year of analysis, 2013. The model using a starting tracked population eight times the tracked population results in the maximum probability occurring in 1993, with a value of 0.0621 or at least one collision in 16 years. The minimum probability of 0.0218 occurs in the year 2013. This value translates to at least one collision occurring in 45 years.

A comparison of the above values indicates that, as might be expected, the highest untracked debris population yields the greatest probability. However, only a total of four years separates all three maximum collision rates. The minimum probabilities of collision values occur in roughly the same time period, again illustrating the general trend of changes within the middle altitude debris population. The minimum value actually occurs in the model with the highest starting untracked debris population. The interaction of orbital decay with these large numbers of small objects more susceptible to decay may explain the higher rate at which the middle altitude band debris density decreases.

The most important point to make about the Space Station collision probabilities does not concern trends in their growth, but rather the absolute magnitude of their values with regard to Space Station survivability. For an untracked population that is three times that of the tracked population, at least one collision can occur in 20 years.

The following notation is used to describe the different models incorporating varying buffer zones and starting untrackable debris populations. For example, 3x1km describes the model incorporating a starting untracked debris population three times the tracked debris population and a one kilometer radius buffer zone surrounding the Space Station. Therefore, 15 models comparing the debris encounters along with the untracked debris populations are identified as follows: 3x1km, 5x1km, 8x1km, 3x3km, 5x3km, 8x3km, 3x5km, 5x5km, 8x5km, 3x7km, 5x7km, 8x7km, 3x10km, 5x10km, 8x10km.

The baseline value of a 10 kilometer radius buffer zone corresponds to initial NASA estimates. The smaller buffer zones were used to check the sensitivity of debris encounters.

Since the debris encounter calculation used hinges upon the debris spatial density, the trend observed matches that found for the collision probability calculations.

The analysis of tracked and untracked debris encounters in a debris environment initially containing untracked debris three times the tracked debris population yields startling results, as shown in Table 2. The baseline 3x10km model generates an average of around 9,251 encounters with tracked and untracked debris per year, compared to 4,520 for the 3x7km model, 2,293 for the 3x5km model, 810 for the 3x3km model, and only 67 for the 3x1km model. Approximately the same order of magnitude between the average number of encounters per year for each buffer zone occurs for the models using five times and eight times the tracked debris. In all cases, the models with the starting untracked debris population five times the tracked population yield the highest average number of encounters per year averaged over all years of interest.

YEAR	BUFFER ZONE RADIUS (KM)				
	1 km	3 km	5 km	7 km	10 km
1992	105.56	1153.44	3248.89	6391.22	13073.00
1993	117.00	1283.56	3612.78	7106.44	14529.56
1994	104.33	1165.89	3283.67	6458.89	13208.33
1995	97.11	1132.33	3186.44	6271.22	12825.00
1996	94.00	1051.67	2962.67	5831.44	11928.56
1997	84.00	940.78	2664.78	5248.67	10738.00
1998	69.33	868.78	2460.11	4845.00	9914.78
1999	66.78	796.89	2253.22	4442.89	9095.78
2000	79.78	902.89	2553.33	5028.78	10289.78
2001	78.67	885.56	2497.89	4922.44	10074.22
2002	71.22	886.67	2510.22	4944.67	10116.89
2003	69.11	790.00	2241.44	4422.56	9050.89
2004	60.44	719.00	2039.22	4027.22	8242.89
2005	57.78	660.00	1879.89	3707.67	7598.67
2006	51.56	621.33	1763.44	3483.11	7134.33
2007	40.56	583.67	1667.89	3290.44	6749.22
2008	40.44	566.00	1619.11	3201.78	6554.89
2009	40.44	553.44	1578.56	3121.78	6394.67
2010	39.67	543.33	1547.00	3054.78	6260.00
2011	34.67	541.56	1556.78	3070.56	6296.22
2012	34.67	545.78	1549.44	3069.00	6284.56
2013	40.11	617.33	1774.11	3495.56	7163.22
$\bar{x}$	67.15	809.54	2293.22	4519.82	9251.07
σ	25.51	235.59	654.74	1283.14	2619.03

TABLE 2: Debris Encounters Per Year for 3s.. Models

As is believed to be true for the collision probabilities, the apparent discrepancy between the 5x.. and 8x.. model encounters is probably caused by increased flow out of the medium band of smaller particles characterizing the higher untracked debris populations. Overall, the number of encounters between the models for each buffer zone are quite similar. On the average, the number of encounters per year for the 3x.. models are 84.4% of the 5x.. models. The 8x.. models maintain an average yearly number of encounters 93.6% of the 5x.. models.

Fuel Requirement Analysis

The number of objects invading the established buffer zone determines the fuel requirement over the 90 days between scheduled refuelings. Encounters translate into Space Station avoidance maneuvers. The maneuver can either be a change in altitude or a change in velocity, thereby eradicating the possibility that the particular debris object and the Space Station orbits intersect at the same time. Only change in velocity manuevers are considered (33).

The magnitude of the maneuver is a function of the desired miss distance and the time the maneuver is initiated before the predicted collision. For this analysis a 10 kilometer miss distance and a one day advance notification of a close encounter were chosen. Shorter miss distances and longer periods of time to perform the maneuver would decrease the required magnitude of the maneuver. Using the above parameters, the required change in velocity is 0.1157407 m/sec. The maximum allowable change in velocity for the Space Station when it is initially deployed is 20.01327 m/sec/90-day. At system maturity it is 6.3860886 m/sec/90-day. Using the required change in velocity the maximum allowable number of maneuvers at initial system deployment is 172.91471 encounters/90-day. The same type of calculation yields 55.175825 maximum allowable encounters per 90-day basis at system maturity.

Table 3 presents the quarterly maximum debris encounters for each year for the 3x.. model with varying buffer zones and initial untrackable debris populations. While all models were run, the one kilometer radius buffer zone is the only zone in which avoidance maneuvers do not impact the amount of fuel required. The apparent unreasonableness of the debris encounters

YEAR	BUFFER ZONE RADIUS (KM)				
	1 km	3 km	5 km	7 km	10 km
1992	42	449	1257	2471	5048
1993	52	526	1471	2888	5902
1994	52	490	1373	2700	5515
1995	61	564	1576	3099	6325
1996	52	508	1423	2795	5710
1997	39	416	1166	2290	4681
1998	34	346	975	1917	3919
1999	40	451	1266	2487	5082
2000	39	434	1213	2384	4873
2001	52	526	1472	2888	5905
2002	52	475	1334	2622	5359
2003	39	399	1119	2201	4498
2004	26	334	941	1851	3784
2005	26	283	796	1566	3202
2006	26	245	685	1352	2764
2007	13	210	603	1189	2434
2008	13	208	580	1143	2338
2009	13	195	559	1092	2241
2010	13	194	535	1061	2169
2011	13	182	528	1040	2128
2012	13	195	546	1082	2221
2013	26	324	912	1793	3666
$\bar{x}$	33.45	361.55	1015	1995.95	4080.18
σ	16.06	130.14	361.96	709.37	1447.16

TABLE 3: Maximum Encounters Per Quarter for 3x.. Models

as calculated warranted further study. Alternate methods of calculating the number of debris encounters were addressed and will be reported separately.

Sensitivity Analysis

Sensitivity analysis was also done for two other system elements affecting the probability of collision. The elements of launches and potentially explodable objects were chosen because the first is the major factor controlling the debris distribution and the second is the primary contributor to the debris populations. As the causal diagram indicates, these system elements are linked together since launches are the only sources of potentially explodable objects.

Besides selecting these system elements for sensitivity analysis based on their importance in the space debris environment system, the parameters associated with these elements could change over the years. The growing interest of many nations in space may in fact cause the launch rate to increase in the future. Also, experience and better engineering over the years may decrease or completely eradicate the placement of potentially explodable objects in space.

The average launch rate was adjusted upward by two each year as well as the corresponding maximum and minimum number of launches allowed for that year. The number of explodable objects was varied using a uniform distribution to generate zero to three explodable objects for each launch. The above changes were combined with the varying number of starting untracked debris populations. Either (1) the launch rate was held constant and the explodable objects added was allowed to vary, (2) the launch rate increased and the explodable objects added remained constant, or (3) both were allowed to vary. Discussion of sensitivity analysis results incorporates certain notation describing each of these models. Examples are 3x1iec and 8x1cev. The "3x" and the "8x" indicate the magnitude of the starting untracked debris populations above the tracked populations. The "1" and "e" represent launches and explodable objects deposited, respectively. The "c" indicates that the parameters associated with that particular system element remain unchanged from the baseline model. Finally, an "i" indicates an increasing launch rate and a "v" represents a varying number of explodable objects being deposited.

The results of the sensitivity analysis models are quite significant in showing the impact of launches and potentially explodable objects on the probability of collision. Table 4 presents the collision probabilities by year for the baseline, 3x1iec, 3x1cev, and 3x1iev models. The 3x1iec average collision probability of 0.0578 translates to a collision rate of at least one in only 17 years. This is 12 years sooner than that predicted by the baseline model. Keeping the launch rate constant while varying the number of potentially explodable objects deposited results in a collision rate over two times greater than that for the baseline model. This is approximately another two times greater than that for the 3x1iev model, which predicts an average of at least one collision in approximately 76 years.

The results underscore the significance of the explodable object population and bring to light the relative unimportance of launches in contributing to the debris population. Figure 5 compares the explodable object medium altitude band populations for the 3x1iec and 3x1iev models, and Figure 14 presents

YEAR	MODEL TYPES			
	BASELINE	3x1iec	3x1cev	3x1iev
1992	.04417984	.04710845	.03765426	.01600658
1993	.04948522	.05081905	.03271499	.01483373
1994	.04559287	.05215969	.02867474	.01402144
1995	.04469331	.05619323	.05466592	.01360019
1996	.04213160	.05274885	.04701716	.01296066
1997	.03347091	.06033363	.04086820	.01244894
1998	.03599253	.05535555	.03564259	.01221952
1999	.03342433	.05533770	.03164308	.01228196
2000	.03807677	.05586892	.02870997	.01221768
2001	.03743685	.05395369	.02572057	.01222774
2002	.03762065	.05675412	.02349717	.01215591
2003	.03377774	.05518003	.02187713	.01236752
2004	.03084769	.05425863	.02036143	.01231636
2005	.02849567	.05202202	.01898672	.01219805
2006	.02679938	.05458822	.01788025	.01220383
2007	.02537565	.06073925	.01761306	.01217938
2008	.02467216	.06569868	.01733582	.01247737
2009	.02407048	.07237769	.01690777	.01226209
2010	.02358310	.06594069	.01659968	.01206763
2011	.02370759	.06417050	.01607260	.01258639
2012	.02366490	.06316163	.01603832	.01287449
2013	.02687203	.06733568	.01601283	.01286330
$\bar{x}$	.0333624	.0578229	.025304	.0130518
σ	.008222	.0063027	.0121622	.0015964

TABLE 4: Collision Probabilities for Varying Launch Rate and Explodable Objects Added

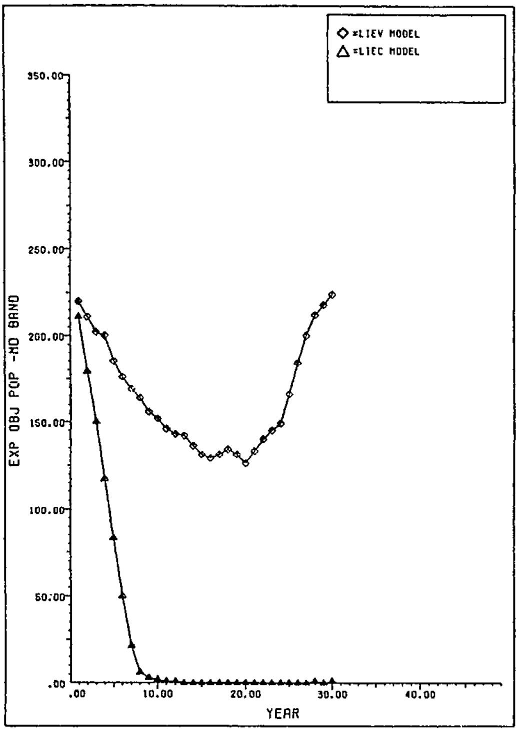

Figure 5: Medium Altitude Band Explodable Object Populations for 3x.. Varying Explodable Objects

the corresponding changes in the debris populations. It is apparent that controlling the potentially explodable objects deposited in space stabilizes the debris population even with increasing launch rates.

Tables 5 and 6 present the results for the sensitivity analysis models using starting untracked debris populations five and eight times the number of trackable objects. The same general relationships between the models exist as they did for the 3x.. models, with the average collision probabilities for the 5xliec and 8xliec models being 50.8 and 63.2% greater than their respective baseline models. As for the 3x.. models, the 5xlcev, 8xlcev, 5xliev, and 8xliev models demonstrate the tremendous effect unintentional explosions have on the debris population, and hence on the Space Station collision probability.

CONCLUSIONS

Any attempt to model a system depends on what is known or can be reasonably assumed about that system. The remaining unknowns concerning the space debris environment are critical in obtaining an accurate assessment of its impact on man's use of space. While the accuracy of this analysis is open for discussion, the results provide a baseline for assessing the severity of the debris problem for the Space Station operations. Individuals interested in this field must decide whether the results are optimistic or pessimistic. Should they prove to be optimistic, efforts to increase the survivability of the Space Station would be required. The combination of the unknown magnitude of the untracked debris population, the known lethality of these small particles, and the constant exposure of the Space Station to such an environment over extremely long periods of time points to a very real problem. Should the collision rate prove to be even greater than calculated, the Space Station will barely reach system maturity until it is in great danger.

While the collision probabilities are probably representative of the actual situation and possibly even a bit optimistic, the debris encounter calculations appear high even for the predicted severity of the environment. Even if the untracked debris could be factored out of the calculations, the numbers would most probably suggest a totally unsurvivable situation. The space debris environment model as designed may be sufficient to calculate realistic collision probabilities, but may not provide enough detail to accurately assess the occurrences of encounters requiring avoidance maneuvers.

However, the debris encounter results have some merit until a more convincing calculation method is developed. Unless new results totally discount the calculations, the number of debris encounters indicate that the tracking ability of ground-based facilities must drastically improve if the Space Station is going to survive without constantly maneuvering and being resupplied with fuel. Even with increased tracking capability, a serious trade-off exists between the financial costs and logistical problems associated with increased resupply rates and the degree of risk acceptable for potential collisions.

The significance of the sensitivity analysis results lies not in the actual numbers obtained but in the realization that acting upon system elements under human control can tremendously lessen the severity of the problem.

	MODEL TYPES			
YEAR	BASELINE	5xliec	5xlcev	5xliev
1992	.05004029	.03570102	.02103356	.02006035
1993	.05049875	.03557548	.01897977	.01791552
1994	.05495163	.04147403	.01758615	.01638609
1995	.05539890	.04371885	.01689145	.01553045
1996	.05388026	.04213362	.01612138	.01466239
1997	.05229689	.04426603	.01522600	.01397903
1998	.04581250	.05127300	.01477087	.01333304
1999	.04311085	.04880160	.01477970	.01323771
2000	.03845693	.04801654	.01466458	.01309173
2001	.04408584	.04901629	.01432328	.01288789
2002	.04284479	.04910424	.01384612	.01268475
2003	.04039241	.04567255	.01383038	.01269663
2004	.03629503	.05471144	.01396916	.01255862
2005	.03537226	.06317230	.01385267	.01271845
2006	.03297165	.06831674	.01362259	.01269280
2007	.03051218	.07271446	.01359463	.01273246
2008	.02876923	.08078532	.01384843	.01289954
2009	.02722227	.08920792	.01350881	.01264357
2010	.02597688	.09068515	.01323668	.01240971
2011	.02543776	.08612528	.01355856	.01288972
2012	.02484992	.08061361	.0138769	.01323562
2013	.02443635	.08131743	.01391745	.01325088
$\bar{x}$	.0392552	.0592001	.0149365	.0138408
σ	.0107317	.0185103	.002022	.0019699

TABLE 5: Collision Probability Per Year

	MODEL TYPES			
YEAR	BASELINE	8xliec	8xlcev	8xliev
1992	.06086987	.04290534	.02282761	.02318599
1993	.06216294	.04544861	.02060896	.02080575
1994	.05849797	.05023121	.01907370	.01924406
1995	.05242787	.05096405	.01913648	.01804488
1996	.05156042	.04997551	.02030964	.01687457
1997	.04698096	.04593803	.01876058	.01602542
1998	.04350626	.04726157	.01764678	.01537640
1999	.03893839	.04278838	.01675337	.01497128
2000	.03874352	.04196701	.01622864	.01479690
2001	.03530629	.04605224	.01553587	.01461445
2002	.03089205	.05407100	.01497739	.01417562
2003	.02822994	.05641016	.01488182	.01421574
2004	.03015987	.06859242	.01462150	.01412831
2005	.02941474	.07523348	.01429685	.01418390
2006	.02961808	.07694914	.01392298	.01423437
2007	.02772455	.07711538	.01399043	.01405779
2008	.02580383	.07567819	.01410709	.01427273
2009	.02411659	.06977523	.01385568	.01399219
2010	.02294796	.06324328	.01375846	.01384897
2011	.02253946	.06746732	.01419161	.01436684
2012	.02186278	.07431063	.01447270	.01503700
2013	.02467285	.06941000	.01442261	.01519107
$\bar{x}$	.0366808	.059853	.01629	.0157111
σ	.0132783	.014743	.0026884	.0024811

TABLE 6: Collision Probability Per Year

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