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A Methodology for Estimating the Uncertainty in the Predicted Annual Risk to Orbiting Spacecraft from a Current or Predicted Space Debris Population

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ABSTRACT

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I: INTRODUCTION

I.1: Objective

The objective of this research is to investigate and present a better methodology for approaching and analyzing environmental problems. This will be accomplished by focusing on a specific environmental problem of current interest, the proliferation of space debris. Environmental problems have a number of characteristics in common. They tend to occur as the result of human development. They affect large segments of the Earth. They are too big to analyze completely. The data available for analysis and decision making usually exhibit a significant amount of uncertainty. And finally, any effective solution generally requires some public action.

The number of objects floating in near Earth space has grown significantly since the dawn of the Space Age. (OSTP,1996) Some of these objects present a hazard to the utilization of near Earth space for many human activities. The problem is truly a global one affecting any individual that draws some benefit from man made systems operating outside the atmosphere. Large objects in Low Earth Orbit(LEO) can have a more dramatic effect on future space activities, such as the International Space Station(ISS), than small objects in similar orbits or large objects in more distant orbits.(NRC,1997) All objects and effects can't be analyzed, so it makes sense to concentrate on those that will have the major effects. The data on debris objects in space is very uncertain, and this makes the risk to the ISS presented by these objects very uncertain. Addressing this risk and uncertainty are the major thrusts of this effort. A number of public policy documents have been written recommending public action to address this risk, and in the end, policy actions will be taken.

The purpose of this research is to investigate the uncertainty in what we know about the risk to the ISS due to space debris, and clarify the uncertainty in this knowledge. In so doing, it is hoped that a better public understanding can be obtained of the risk, and the inevitable actions that will be required to manage this risk. It is also hoped that this research will demonstrate a methodology for addressing other environmental problems.

I.2: The Space Debris Problem

The beginning of the space age

The space age began with the launching of SPUTNIK-1 on 4 October 1957. It, and the last stage booster that went into orbit with it, were the first objects to orbit the earth as man-made satellites. They established similar orbits, with a 227 km perigee and 945 km apogee. The upper stage returned to earth on 1 December 1957 and SPUTNIK returned on 3 January 1958. The first US satellite was Explorer-I. It achieved an initial orbit of 183 km perigee and 215 km apogee on 1 Feb 1958. It returned on 31 Mar 1970. The second US spacecraft to orbit the earth was Vanguard-I. It achieved a 649 km perigee, and a 3866 km apogee, on 17 March 1958. It remains aloft to this date and has become one of the oldest pieces of man-made space junk called space debris. (US Space Command, 1996) These four satellites exhibit a number of the phenomena that characterize the space debris problem. Almost everything that goes up into orbit eventually returns to earth. Low altitude objects(low perigee) with a lot of surface area return faster than heavy objects with little surface area. Orbit lifetimes grow exponentially as the altitude of perigee exceeds several hundred kilometers.

Of the more than 23,776 trackable objects that have been recorded in space by the US Space Command Space Surveillance Network, fewer than 8,000 remain aloft. (US Space Command, 1996) Most of the rest have returned to earth. Some have escaped as interplanetary probes. Some of these objects were created in space as a result of explosions of larger objects, usually spent boosters. These explosions also created smaller objects that are difficult to track with the UHF radars that make up the Space Surveillance Network(SSN).

By the late 1980's it became obvious that enough spent boosters, dead satellites, and explosion remains were hanging around in near earth space that this space debris could present a collision hazard for future spacecraft. The initial document to receive wide distribution addressing this problem was the seminal text by Nick Johnson and Darren McKnight, Artificial Space Debris. (Johnson, 1991) It brought the problem to the attention of a national audience and identified many of the facets of the space debris problem.

The dominant concern that has evolved concerning space debris is its potential impact on the International Space Station. The International Space Station will be by far the largest object ever assembled in space and therefore the biggest target for orbiting debris. The inertial velocity for a satellite in low earth orbit is slightly over 7 km/sec. If the debris particles are moving in the same direction as the Space Station at its orbital altitude, they do not present a collision hazard as they will have zero relative velocity.

They are essentially flying in formation with the Station as it orbits the earth. However, if they are moving in an orbit with a different inclination to the equatorial plane, at the Station's altitude, they could achieve relative velocities approaching 15 km/sec. At these speeds even very small particles have extreme penetrating power. But that is the subject for another paper.

Prior to the orbiting of SPUTNIK there were essentially no trapped objects in the earth's gravitational field, other than the moon. (NRC, 1995) There were occasional meteor showers that presented a source of debris entering the upper atmosphere, but unlike the Van Allen radiation belts, there are essentially no natural trapped objects to produce a hazard to space flight. There is a natural debris hazard due to small sub-millimeter size objects entering the earth's potential well from interplanetary space, but it can be shielded against much easier than some of the larger objects that man has launched into the well. Thus, if every object launched or released in space could be accounted for, it would be possible to exhaustively describe the space debris population. This is impossible due to the shear number of objects that have been launched, released, or generated by explosions in near-Earth space.

An environmental problem

The space debris problem is an "environmental" problem. It is too big to solve. The actual debris population and its probable future evolution can not be completely quantified. There are too many objects to deterministically predict individual behaviors and there are too few objects to achieve a good statistical characterization. The sizes and locations of the objects make it very difficult to make very accurate measurements. Yet the space debris issue has become a political concern, primarily due to its impact on the International Space Station. Some political and programmatic decisions will have to be made based on the imperfect information that is currently available and likely to be available in the future.

Like many environmental problems, “sides” have developed. One “side” has developed that claims space is a big place, and the satellites launched by man are so dilute that debris does not constitute a significant hazard. We have operated over 8,000 satellites in space over a period of 40 years, and we have never observed a collision. (At least we had not observed a collision before last August when a piece of debris from an Ariane launch appeared to sever the gravity stabilization boom of the CERISE satellite, a French spy satellite.) Therefore collisions are not very likely now and will not be in the near future. (Canavan, 1996c)

The “other side” takes the approach that with all of those launches there are thousands of pieces of junk floating out in near Earth space waiting to run into each other. This is an environmental concern and if we publicize it enough some action will be taken and we will be given credit for alerting the world to a potential hazard. To support this they have generated plots of the debris floating about a picture of the globe. In order to make the debris visible, it has been enlarged in size by several orders of magnitude. Of course if it isn’t enlarged in size, the pieces are invisible to the naked eye, and it is apparent that “there is not a problem”. There have been collisions observed with the Space Shuttle, on an almost microscopic level. Over 60 windows have been replaced on the Shuttle Orbiters due to impacts with microscopic debris. The Long Duration

Exposure Facility(LDEF) experiment did record numerous small impacts. There is reason for concern. (NRC, 1995)

At times these "sides" have devolved into arguments that end with the participants verbally reflecting on the inability of the "other side" to perform any creditable technical work or speak in a truthful manner. The object of the effort here is to show that there is probably an element of truth in both sides, and that *estimates of reality under the influence of large uncertainties in the data are very difficult, and can best be made by including estimates of the uncertainty in the final answer based on the data uncertainties and a reasonable system model.* To say that one's answer is uncertain is a very difficult statement to make. However, it does provide a clearer picture for policy makers attempting control the environment as to the risks involved. It can also lead to more funding for research in the areas that will reduce uncertainty in predictions.

This type of problem is not unique to the space debris issue. The issues here are characteristic of most environmental problems. The approach used here probably has validity for other environmental problems also. Consider a slight diversion into two much better publicized environmental problems, the population explosion and global warming.

The population explosion problem has been around at least since the time of Malthus. However, in recent time it was raised again in 1968 by Paul Erhlich's "The Population Bomb". (Ehrlich, 1968) The Prologue begins with the statement *"The battle to feed all humanity is over. In the 1970s the world will undergo famines-hundreds of millions of people are going to starve to death in spite of any crash programs embarked upon now."* The problem was that based on extrapolated population growth rates and extrapolated food production growth rates, increased food production could not keep up with the increased population. Yet, today global per capital calorie availability is up by 33% since the 1930's and per capita food supplies have risen by 40 percent in Africa, Asia and Latin America. (Eberstadt, 1995a) What happened? Ehrlich had a very simple model and he did not consider or describe where his data came from. The US has a fairly effective census program. Most countries in the underdeveloped world do not. To quote Eberastadt in 1995,

> "Although the capabilities for enumerating the world's population have improved markedly during our century, especially over the past generation, it would be unwise to exaggerate them. By now almost every recognized country has conducted at least one census. But some have held only one census to date, and governments that routinely conduct censuses commonly do so at ten-year intervals. Birth and death registration systems are even more problematic. In the estimate of the United Nations Statistical Office, fewer than a dozen developing countries of a million or more field statistical systems with near-complete coverage of local births and deaths. These states account for only a tiny fraction of the 'Third World's' population-no more than 3 or 4 percent of its total." (Eberstadt, 1995b)

Had Ehrlich estimated the uncertainty in his prediction, he would be considered a lot more credible today.

One might point to the famine in Somalia as an example of the famines that he predicted. However that famine was brought on by the harsh actions of the Somalia government on a population only slightly above the subsistence level, as was the Soviet famine of 1934 in the Ukraine, the Bengal famine in 1943, the Chinese famine in 1960 following Mao's Great Leap Forward, and probably the North Korean famine of 1997. Government actions show a very strong correlation with famine onset, but that is an entirely different model. To accurately predict that population growth will overtake agricultural production on a global scale requires much better data and models than are currently available. The analytic approach used here to analyze space debris could be applied to this problem to highlight fertile areas for future research or data collection to reduce uncertainties, but it is not likely that they would be of any more than academic interest.

The global warming problem is even more interesting. Observations of the planet Venus have found a lifeless, very hot surface covered with a dense atmosphere of carbon dioxide. Since Venus is similar in size and only slightly closer to the Sun than the Earth is, it is surprising that it is so much hotter with an average surface temperature of 480°C compared to the Earth's 22°C. (Adjusting for the differences in distance from the sun would predict Venus' surface temperature should be about 77°C.) The best scientific explanation for the very hot surface temperature is that sunlight is trapped by the Venusian atmosphere and not reradiated back to space. (Murray, 1981)

Observations of the concentration of CO_2 in the Earth's atmosphere have recorded a steady increase since at least 1850. Data taken at Mauna Loa, Hawaii record an increase of from 285 parts per million in 1850 to slightly over 355 parts per million by 1990, with the increase per year growing exponentially. This is often blamed on the increased consumption of fossil fuels since the industrial revolution. Based on this change, a predicted increase in average global temperature of 0.3°C per decade could be expected currently. An total increase of 0.54°C has been observed from 1861 to 1984, if the recorded global temperature measurements over this period are averaged spatially. The uncertainty associated with this process has not been quantified. The averages were based on representative data in 5-degree latitude by 10-degree longitude sections over both land and water. Two problems with the data were identified. First, many of the recording stations were relocated over time. Some of the effects of the station relocation could be removed statistically, but not all. Second, ships have been getting larger and the measurement thermometers were moving up in height over the oceans. This and other configuration changes make it hard to maintain a very accurate baseline over time.

However, satellite based measurements over the period 1979 to 1994 indicated a linear cooling of -0.13°C over this period. Estimated uncertainty in these measurements was 0.01°C for each month. These measurements were made by a microwave sensor on a 2.5-degree by 2.5-degree grid across the globe. They measured the thermal emissions of oxygen in the troposphere, and are not subject to many of the uncertainties that other measurements are. Obviously there are some discrepancies here. (Balling, 1995)

It seems obvious that if any of the direct measurements of temperature are correct, the models that predict global warming based on the amount of CO^2 in the atmosphere do not appear to work very well. So to extrapolate from these models and conclude that the use of fossil energy must be cut back is a very risky public policy decision. There are probably other phenomena that need to go into the models including the increased human population that exhales CO^2 as a natural by product of breathing, or the increased removal of CO^2 from the atmosphere by an increase in the quantity of plant life on the planet. Better measurements need to be made over the appropriate regions of the atmosphere. But most importantly the uncertainties inherent in the data and the models must be tracked. Only if we have estimates of the certainty of our conclusions, can we make good public policy decisions on actions to take to control the environment. And if we have performed the uncertainty analysis, and are very uncertain of our answers, then it will provide insight into where the data or models need to be improved in order to make a better decision.

Space Debris And the International Space Station

The specific environmental problem addressed here is the survival of the International Space Station(ISS). The ISS is expected to fly starting in late 1997 and remain viable until 2015. It will fly at an altitude of 350 km to 550 km and an inclination of approximately 51.6°. It will be the largest object ever placed in orbit with a mass of 419,000 kgm and an exposed surface area of 11,000 square meters. Critical components will present a surface area of approximately 2,230 square meters and will require shielding of some sort. The remaining area is primarily solar panels and can tolerate debris damage with a gradual degradation in performance.

Large objects in space are tracked by the US Space Command Space Surveillance Network(SSN). This consists of a series of tracking radars, optical tracking devices, and an electronic "fence". The tracking radars and optical devices are scattered around the globe. The electronic fence stretches across the southern United States with an inclination to the equator of approximately 33°. The tracking radars are the most important for the characterization of space debris. They operate at a frequency of approximately 440 MHz and provide information on the relative size of debris objects as well as locations. All measurements of space objects are sent to the USSPACECOM Space Surveillance Center(SSC) at Cheyenne Mountain AFB, Colorado. Here the objects and their tracks are analyzed for national defense considerations. The SSC publishes a catalog of space objects that are being tracked or have decayed extending back to SPUTNIK-1. Most of the published analysis of space debris is based on this catalog.

The UHF radars that make up the SSN record many measurements of the radar returns from space objects. Based on these measurements, they are able to determine an average radar cross section for each object. In some sense this radar cross section is a measure of the size of the object. Since the return from the object is due to the reflection of an electromagnetic wave, the relationship of the size of the object to its radar return will be a function of the size of the object relative to the wavelength of interrogation. If the wavelength of the radar is small relative to the size of the object, the measurement is said to be in the optical range and the radar cross section is representative of the projected area of the object in the direction of the radar. If the wavelength of the radar is large relative to the size of the object, then the return is said to be in the Rayleigh region and the radar cross section is significantly less than would be estimated based on the projected area of the object. NASA has developed an approximate response curve, called the Size Estimation Model(SEM), that relates the size of the object to the average radar return of that object. (This effort is discussed in more depth in Appendix B.) Two important issues are worth emphasizing with respect to this curve and its use. First, the curve is an average response for an average set of fragment-like objects. At any given frequency, the radar cross section of a particular object can be very significantly smaller or larger than this average curve. Stealth technology is based on making the return very small. Corner reflectors can produce very large returns for tracking small objects. In general though, fragments from an explosion or collision are not likely to emerge with just the right characteristics for significantly enhanced or significantly reduced returns. On average the SEM curve should be approximately correct.

The UHF radars of the SSN operate with a frequency of approximately 440 MHz. This corresponds to a wavelength of approximately 0.68 meters, or 68 cm. The smallest recorded radar cross section in the current SSN catalog is 0.0002 square meters. This corresponds to a value of -37.0 dBsm(decibels referenced to 1 square meter). If the cross section is assumed to represent a disk with the equivalent projected area, then this corresponds to a disk with a diameter of 1.6 cm. If the SEM model is used this corresponds to a diameter of 6.2 cm.. Based on the spread in the SEM curve and an estimate that the lowest usable radar cross section that can be reliably returned is 0.0004 sqm(-34 dBsm), the SSN catalog should be reliable down to approximately 10 cm equivalent diameter objects.

An impact of a 10 cm object on the ISS would be disastrous if it hits a critical area. So the plan is to maneuver out of the way of objects of this size or larger. It is anticipated that 10 such maneuvers will be required per year for the ISS. This can be done as the track files will be available from the SSN catalog. Below 10 cm equivalent diameter, the collisions will have to be allowed to occur. It is possible to shield against small debris particles up to about 1 cm in size, and the current ISS designs include this type of shield. The major risk then is to particles in the 1 to 10 cm size range. Very little can be done against these particles and the risk must be taken or mitigated externally.

The external mitigating actions can vary from prohibiting all future launches while the ISS is up, to doing nothing. The policy question is, *"What is the appropriate action given that increasing restrictions on launches will meet with increasing political(national and international) resistance?"*

From the Department of Defense(DOD) perspective, there is not as much concern for the growth of debris at Low Earth Orbit(LEO) altitudes. DOD has no current or planned manned vehicles in space and most of the satellites in this regime have much lower cross sectional areas than the ISS. DOD satellites may experience degradation of function and a low probability of a massive collision, but these hazards are small relative to other failure mechanisms for LEO satellites. Eventually, however, if the debris risk continues to grow it will be comparable with and eventually exceed the risks of failure from other mechanisms. It is probably better to plan ahead and develop a strategy for minimizing this risk consistent with the long term benefits to be obtained. So LEO debris may become a concern to DoD for the completion of its future missions.

I.3: Analysis History

The analysis that has gone into modeling and predicting the effects of space debris has been rather fragmented. In many ways it is one of those problems that the space development community would like to ignore. Space debris is a hazard that has grown as a result of space operations and has the potential to restrict future space operations. Quantitative estimates of the problem are needed to plan future space activities.

A government focal point for modeling space debris and predicting its effects has developed at Johnson Space Center. This group, led by Don Kessler, is attempting to describe the magnitude of the space debris problem and analyze its implications. In his early publications, Kessler developed a number of analytic models for describing the physics of space debris generating events and the resulting debris belts that are formed. His major contributions have been to the evolution of a debris cloud produced by an explosion of a spent booster, or the collision of two space objects, and the development of a collisional cascade as the density of space objects grows in a narrow altitude range. His model of the evolution of the debris cloud appears to match observed events reasonably well. No cascades of debris impacting other debris and creating larger fluxes of smaller fragments have been observed. He has predicted that the conditions are about right for this type of a cascade to occur in the 900 to 1000 km altitude range and possibly in the 1000 to 1400 km altitude range. If such cascades were to occur, they would render these altitude ranges unusable for tens to hundreds of years.

In order to better understand all of these effects and to more closely scrutinize the evolution of space debris generating events, the modeling effort was moved to the computer. JSC has funded the development of the EVOLVE code. EVOLVE is a state of the art modeling code that predicts the evolution of space debris from discrete events. It is capable of using all known past events as input, and extrapolating their effects into the future along with projected future launch activity. It is a discrete event code, and therefore it can model the details of the development of debris clouds fairly well. It is also designed to interpolate between measured data based on good physics and orbital mechanics to provide data in regions where measurements are impossible or at least very difficult. It was used for the analysis performed here primarily to predict the debris environment for International Space Station Altitudes during the period of time that the ISS is expected to be operating. A more detailed description is provided in Section II.

When the concern over the risk due to 1 to 10 cm equivalent diameter particles became obvious, JSC developed a measurement program based on the Haystack radar at Lincoln Labs. Haystack is an X-Band(10 GHz) radar that is used by USSPACECOM to perform space object identification(SOI) on orbiting objects of interest. NASA and the USAF negotiated a trade that allowed NASA to use the Haystack radar for approximately three months of the year in return for NASA funding the construction of a new smaller tracking radar call HAX, or Haystack Auxiliary, for the USAF. Since 1990, the Haystack radar has logged over 3068 hours on the small debris observation problem.

Due to the massive disk antenna on Haystack, the only way it can be used for low altitude orbital debris observations is to park it in a known direction and let the debris fly through the beam. This works reasonably well, though at a due south, 10-degree above the horizon, parked position, Haystack can barely observe 530 km altitude orbits at the 28.5-degree inclination characteristic of most Space Shuttle flights. Since the ISS will fly at about the same altitude and with an inclination to the equator of 51-degrees, Haystack does a reasonable job of observing most of the debris that will be of concern to the ISS.

Both the output from the EVOLVE code and the measured data from Haystack are too unwieldy and fragmentary to be useful for defining a design specification for the ISS. The NASA group at JSC led by Don Kessler have developed an engineering model of the orbital debris environment suitable for engineering design. The first version of this model was published in 1991. This version was based on a variety of sources including analysis of panels returned from the Solar Max satellite, Arecibo radar measurements, Goldstone radar measurements, the USSPACECOM catalog, an MIT experimental test site telescope measurements, and some Ground-Based Electro-Optical Space Surveillance(GEODSS) telescope measurements(National Research Council,1997). This model was updated in 1994 for altitudes between 350 and 600 km and 51.6 degree inclinations. The update is based on new data primarily from the Haystack radar, but including an analysis of the Goldstone radar data, preliminary data from surfaces returned from the LDEF, and a recalibration of the SSN radars. An improved model was released in November of 1996 called ORDEM96(Kessler, 1996). It covers the altitude range up to 2000 km and breaks the debris population down into six inclination bands, two eccentricities, and six size ranges or types of objects. It includes additional data from the Haystack measurements, more analysis of the LDEF impacts, analysis of several Space Shuttle impacts, and a theoretical treatment of solar radiation.

It agrees well with the Haystack data in the 1 to 10 cm range at 500 km and has been accepted as the approved model for ISS safety evaluations after May 1966(National Research Council, 1997). ORDEM96 provides a fast computational tool that will specify the flux on a spacecraft based on the best calculations and measurements available.

It is not particularly useful for predicting the future with different assumptions as to the numbers of launches, effectiveness of procedures for minimizing explosions on orbit, or the development of a collisional cascade. It extrapolates the current environment by 4% per year for all inclinations except the near equatorial debris. The debris in this inclination category is expected to grow at 8% per year.

At least two other efforts have attempted to estimate the debris environment based on the catalog data, available measurements, and physical reasoning. The first of these by Fucke and Sdunnus(Fucke, 1993) led to the ESA Reference Model for Space Debris and Meteoroids. The physics that went into this model and some validation experiments are well documented in the published report. This report published in 1993 indicated good agreement with the NASA engineering model for the 10 cm flux at 500 km, but estimated a flux that was a factor of 5 lower for the 1 cm flux at this altitude(Fucke, 1993, p.170). The comparison was made with the 1991 NASA model. This analysis and Haystack data indicating lower fluxes prompted the 1994 revisions to the NASA model.

The second effort to independently estimate the fluxes at ISS altitudes has been made by the USAF Science Advisory Board(Canavan, 1996c). The effort developed a set of analytic estimates based on the SSN catalog data and parametric explosion models suitable for analysis with a "spreadsheet" program. They also noted the lack of agreement of the 1991 model with the Haystack data and when the 1994 model was used, achieved reasonable agreement(Canavan, 1996c, Fig. 1). The majority of this effort was directed toward evaluating the possibility of a collisional cascade. Based on the results obtained, a collisional cascade does not appear very likely.

None of the modeling efforts have made a serious attempt at propagating the uncertainty in the data and the model parameters through the models to obtain uncertainty in the final estimates of collision probabilities. As a result all models give an answer to a specific question, but they do not build confidence in that answer. In order to use one of the models for designing a shield for the ISS, factors of safety have to be included to make up for uncertainties in the predicted numbers. When these factors of safety are not clearly identified, as in ORDEM96 with the N parameter(relative debris generation rate), it becomes very difficult to validate the basic model. It is also difficult to estimate the conservatism in the design approach, as it is not clear how conservatism in a model parameter affects the final answer.

I.4: Policy Documents

Four major policy documents have been published in the US since 1995 recommending public action to deal with the space debris problem. These are Orbital Debris, A Technical Assessment (NRC,1995), Interagency Report on Orbital Debris 1995 (OSTP, 1995), Comparison Of Space Debris Estimates (Canavan, 1996), and Protecting the Space Station from Meteroids and Orbital Debris (NRC, 1997). All of these reports present some analysis of part of the space debris problem and go on to recommend specific actions be taken. The focus here will be on the recommended actions.

Orbital Debris, A Technical Assessment

This report written by a panel of space debris researchers goes into a significant amount of depth on most of the problems presented by space debris and has been referenced by all of the others. It makes a total of 22 recommendations for action. They address four areas, Characterizing the Debris Environment, The Hazard to Space Operations from Debris, Designing for the Debris Environment, and Reducing the Future Debris Hazard. Of particular interest to this effort are the eight recommendations on Characterizing the Debris Environment and the seven on Reducing the Future Debris Hazard. These are,

Characterizing the Debris Environment

1.1) *"an international group be formed (1) to advise the space community about areas in the orbital field needing further investigation and (2) to suggest potential investigation methods."*

1.2) *"models of the future debris environment should be further improved,"*

1.3) *"uncatalogued debris in LEO should be carefully studied,"*

1.4) *"further studies should be conducted to better understand the GEO debris environment,"*

1.5) *"a strategy should be developed to gain an understanding of the sources and evolution of the small debris population,"*

1.6) *"the data acquired from this research should be compiled into a standard population characterization model."*

1.7) *"exploring the creation of an international system for collecting, storing, and distributing data on orbital debris."*

1.8) *"the orbital debris community exercise more peer review over its research."* (NRC 1995, p3)

Reducing the Future Debris Hazard

4.1) *"the spacefaring nations develop and implement debris reduction methods on a multilateral basis."*

4.2) *"Space system developers should adopt design requirements to dissipate on-board energy sources to ensure that spacecraft or rocket bodies do not explode after their functional lifetimes."*

4.3) *"The release of mission-related objects during spacecraft deployment and operations should be avoided whenever possible."*

4.4) *"Spacecraft and rocket bodies should be designed to minimize the unintentional release of surface materials, including paint and other thermal control materials, both during and after their functional lifetimes."*

4.5) *"Intentional breakups in orbit(especially those expected to produce a large amount of debris) should be avoided if at all possible. No intentional breakups expected to produce numerous debris with orbital lifetimes longer than a few years should be conducted in Earth orbit."*

4.6) *"Spacecraft and rocket bodies in LEO and in highly elliptical orbits passing through LEO should either be removed from LEO or have their orbital lifetime reduced at the end of their functional lifetime."*

4.7) *"the use of GEO disposal orbits should be studied further. Until such studies produce a verifiably superior long-term strategy for dealing with the GEO debris hazard, operators of GEO spacecraft and rocket bodies should be encouraged to reorbit their spacecraft at the end of their functional lifetimes if they are capable of safely performing a reorbiting maneuver to a disposal orbit at least 300 km from GEO."*(NRC 1995, p8-9).

Recommendations 1.8 and 4.6 have produced the most controversy. The recommendation for additional peer review seems to imply a distrust of some published data by the NRC committee. The recommendation to deorbit or reduce orbital lifetime can have severe penalties for some missions. If additional propellant has to be carried on board to execute an end of lifetime maneuver, the added weight that must be carried to orbit can approach 20% of the satellite weight.(NRC 1995, p146)

This research effort is an attempt to address parts of recommendations 1.2, 1.3, 1.5, and 1.8. Uncertainty analysis of current predictions identifies the major contributors and suggests appropriate areas of further research.

Interagency Report on Orbital Debris 1995

This report published by the Office of Science and Technology Policy and authored by the National Science and Technology Council Committee on Transportation Research and Development updates the US government's *1989 Interagency Report on Orbital Debris* and uses Orbital Debris, A Technical Assessment for most of its data. It makes five specific recommendations. They are,

1. *"Continue and enhance debris measurement, modeling and monitoring capabilities;*

2. *Conduct a focused study on debris and emerging LEO systems;*

3. Develop government/industry design guidelines on orbital debris;

4. Develop a strategy for international discussions;

and

5. Review and update US policy on debris." (OSTP 1995, p56-57).

These recommendations are likely to carry more weight as they are directive for NASA and the DoD.

However the report does contain the following disclaimer,

> *"This report is intended for internal agency and interagency planning purposes only. New programs or activities aimed at modifying existing systems or constructing new ones recommended in this report do not reflect Administration approval and must compete for funding in the budget process."* (OSTP 1995, p3).

Truly these are recommendations and not directives. This research is directed at recommendation (1) and in support of recommendations (2) and (3). The focused study on LEO systems will have to deal with uncertainty and guidelines are only useful if they are likely to produce the desired effects.

Comparison Of Space Debris Estimates

This report, published as a Los Alamos National Laboratory Report, is a summary of a US Air Force Science Advisory Board investigation of current practice on modeling space debris and recommendations for action within DoD based on its findings. Its major conclusion is stated as,

> *"The current environment is assessed as not threatening to defense systems. Projected reductions in launch rates to LEO should delay concerns for centuries. There is agreement between AFSPC and NASA analyses on catalogs and collision rates, but not on fragmentation rates. Experiments in the laboratory, field, and space are consistent with AFSPC estimates of the number of fragments per collision. A more careful treatment of growth rates greatly reduces long-term stability issues.*

Space debris has been shown not to be an issue in the coming centuries; thus it does not appear necessary for the Air Force to take additional steps to mitigate it." (Canavan 1996, p1)

This report reanalyzes the data presented in the NRC and OSTP reports and additional data derived from the US Space Command Catalog and focuses on discounting Kessler's cascade hypothesis. It so doing, it seems to question the need for immediate policy action with regard to the deorbiting issue.

In all three reports, debris growth projections are made into the future for centuries. Given the quality of current data this seems a little risky. However, the lifetimes of some LEO satellites are projected to be on the order of centuries, so the issue is worth considering. This is one of the areas where uncertainty analysis can add to our understanding. By propagating uncertainties in the models used for these predictions, it should be possible to estimate how far into the future it makes sense to predict. That is not a subject for this effort and will be left to a later study.

Protecting the Space Station from Meteoroids and Orbital Debris

This report is an update of the previous NRC report dealing with issues specific to the ISS (NRC 1997). It points out that space debris, particularly those particles with effective diameters in the range between 1 and 10 cm, are a significant risk for the ISS. The estimate of this risk has decreased by a factor of two since 1991 due to improved measurements and better analysis techniques. However, there still appears to be a 35% chance of the ISS being impacted by a particle with an effective diameter of 1 cm or greater over a 10 year lifespan (NRC 1997, p23). It is assumed that the ISS is shielded well enough to withstand impacts by smaller particles. However, the Russian components do not at this time appear to meet the shielding standards being used by the US and other participants. This could significantly increase the risk of penetration of a pressurized volume during operation.

It comes up with seven findings and twenty recommendations, most of which deal with internal management of risk for the ISS by the international team. The importance of the report is not the findings or recommendations, but rather the programmatic concern with the risk from space debris. The ISS is significant because it is the largest structure to be exposed to the LEO debris hazard and a catastrophic failure could result in loss of life for inhabitants and possibly loss of mission for NASA. Therefore, it seems a useful subject for this uncertainty estimation effort. This makes the study very specific, and the consequences for estimating risk inadequately could have programmatic impact.

I.5: Proposed Methodology

The specific problem to be addressed here is estimating the uncertainty in the predicted risk to the International Space Station of an impact by a space debris object with an equivalent diameter between 1 and 10 cm over the life of the Station. Predicting the risk to the ISS is a difficult problem by itself, so it seems that predicting the uncertainty in this risk may not be worth the effort. However, that is simply not true. By trying to predict the uncertainty in the risk, we are led to a much deeper understanding of the adequacies and inadequacies of our estimating procedure. In many cases this can improve the estimation procedure itself and certainly will build confidence in the risk estimate produced.

The formal methodology for doing this will be the Latin Hyper-Square Sampling procedure. This procedure assumes a risk prediction model that can be as simple as an analytic equation to as complicated as a computer code with tens of thousand lines of code. All that is required is a defined calculation sequence for producing the risk estimate given a set of input data. Any such calculation must depend upon the input data provided that describes the physical system. Typically actual computer models also depend on model parameters that have been developed experimentally or analytically to predict the behavior of the system. The result of any estimating procedure, then depends on a set of values for these input data and parameters that describe the physical system. If all of the input data and parameters are known precisely, then the model will predict a precise answer for the risk. In general, and in the space debris case in particular, the input data and parameters are not known precisely. They have some uncertainty associated with them. The object of the Latin Hyper-Square Sampling procedure then is to translate this uncertainty in the input data and parameters into an uncertainty in the calculated answer produced by the model.

One way of doing this would be to take each of the values possible for the input data and parameters and combine it with every one of the values for each of the other input data and parameters. This is known as a factorial design. For a simple problem with ten input data and parameters that could take three values each, this would require 3^{10} (59,049) distinct calculations. That large of a number of separate calculations is very difficult to track. A better approach would be to do a smaller number of calculations and randomly select the value for each of the variables(input data and parameters) for each calculation. This is essentially a Monte Carlo calculation. The Latin Hyper-Square Sampling(LSS) approach is a mix of the two.

The LSS methodology proceeds by defining the number of variables required by the model, for the above example, ten. Then a desired number of calculations is chosen, usually 1.4 times the number of variables or greater. For this case it would be appropriate to choose fourteen or fifteen calculations. For large codes with tens of variables, this procedure has been shown to work very well.(Iman 1985) For a small number of variables, a better final distribution of risk will be obtained if the number of calculations is increased to two or three times the number of variables. (This is discussed in more detail in Appendix A.)

Once the variables have been defined, and the number of calculations specified, the values for each of the variables for each calculation must be chosen. Typically the input data and code parameters are uncertain, but a best estimate and a range of uncertainty can be specified. In some cases a mean value can be specified for a variable and its uncertainty is understood well enough to characterize it with a normal distribution. In other cases only a range of possible values is known, and any value within that range is equally likely. There are many other distributions for uncertainty in a variable that are possible and most can be handled with available software.

Once the distribution of uncertainty in a variable is specified, it is possible to break the spread of the variable up into equal probability ranges totaling the number of calculations to be performed. For instance if a variable is known to take on values between 0.0 and 3.0 with equal probability and we have decided to perform 15 calculations, this range would be broken up into 15 intervals of 0.2 each. The most common LSS procedure is then to select a value for this variable randomly within each of these intervals for each calculation. (Selecting the mid-point of the interval would probably work better, but this makes the process deterministic and one can no longer sprinkle Monte Carlo holy water on it.) At this point the same process is followed for each of the variables. The value of each variable for a particular calculation is then chosen at random from the set of values available. Each interval for each variable is used only once and all intervals are used once. After this selection process is completed, there will be input data and parameter sets for each planned calculation. The calculations are then run in a production operation to obtain a distribution of output values(risk for the study here). Each of these values is equally likely. The output values are sorted from low to high. A distribution function for probability of less than a given value of the output parameter can be obtained. This plot can be fit with an error function, or some other probability function, to obtain an estimate of the distribution of risk.

Then if one wanted to be 97.5% certain that the actual risk was less than some value, that value could be chosen two standard deviations above the estimated mean value. For instance if the mean value of risk estimated is 10 % over the lifetime of ISS, and the estimated standard deviation in this answer is 3%, we could be 97.5% confident that the risk of impact would be less than 16%. Using confidence estimates for risk estimates seems like a procedure thought up to keep statisticians employed. However, we often speak of a conservative design, or a conservative operation. By that we usually mean that we have estimated what is required to meet the design load or complete the design operation, and we add in a little extra of a resource to feel confident that our design will work. The process outlined here is a way of quantifying this conservatism. For very costly or very uncertain activities, the extra analysis is usually very worthwhile.

II: ANALYSIS

II.1: Space Debris Generation

Man-made objects in near Earth space can be categorized into 4 groupings. The first group is active satellites that are currently functioning and being commanded from the ground. The second group is non-functioning satellites that have outlived their mission duration. The third group is spent rocket bodies. These are the last or intermediate stages that go into orbit with the satellite they launch. The fourth group is debris fragments. Of the space objects large enough to track with the SSN radars, approximately 200 are active satellites, 2100 are non-functioning satellites, 1500 are rocket bodies, and 4200 are debris fragments. The SSN can track objects with an equivalent diameter down to approximately 10 cm. At this size, the SSN is between 15% and 50% efficient at detecting objects in orbit. (NRC 1997,p10) It is assumed that there are significantly more objects at smaller sizes, that are for the most part unobserved.

Debris comes from a number of sources, but at large sizes, it is dominated by the fragments from the 125 plus explosions that have occurred in space. (NRC 1995, p61) There have also been three collisions that contributed significant debris clouds. A minor source is the hardware that in the past has been released when systems are deployed from their launch configuration. Also at very small sizes there are large numbers of aluminum oxide particles that have condensed from solid rocket motor exhausts, paint flakes from older satellites that are deteriorating, and pieces of insulation that has flaked off. This study will only be concerned about the first two categories above, debris from explosions and collisions. The other fragments are not a significant threat in the size range of interest..

The current ISS operation plan is to maneuver the ISS if it will intercept an object with an equivalent diameter greater than 10 cm, that is being tracked. It will be shielded against particles less than 1 cm in size, and the risk accepted for particles in the 1 to 10 cm range.(NRC 1997) Estimating the population of 1 to 10 cm particles is therefore a very important problem for ISS risk management.

II.2: EVOLVE Code

The most sophisticated tool that exists for modeling the multiple objects in Low Earth Orbit is the EVOLVE code developed by R. C. Reynolds under NASA sponsorship.(Reynolds, 1991) It numerically simulates the dynamic state of the LEO debris environment. It does so in a year by year approach by adding intact objects and debris from fragmentation events into the environment. It also decays orbital objects until they re-enter the atmosphere and are removed from consideration. It has a number of specific numerical models for fragmentation events and includes sun, moon, and atmosphere effects in decaying the orbits. Its results are calculated in the form of spatial densities or cross-sectional impact flux on an orbiting surface. It is intended to model the debris population on long term or annual basis and does not model transient effects following a collision or explosion. It can forecast future launch scenarios either deterministically or in a statistical sense. Specific models will be described as they pertain to the uncertainties considered in this study.

In order to estimate the uncertainty in the risk due to small untrackable debris particles to the ISS, a number of input and parameter uncertainties must be analyzed. These include,

1) Past and Future Launch Rates,

2) Explosion Frequencies,

3) Fragmentation Models for Explosions,

4) Collision Frequency,

5) Fragment Models for Collisions,

6) and Ballistic Coefficients and Atmospheric Lifetimes.

There are other inputs and parameters that can affect the collision frequency estimate, but these are the major ones and are likely to swamp any uncertainty in other models or data.

II.3: Past and Future Launch Rates

The EVOLVE code reads the exact history of launch rates back to 1957. There is very little uncertainty in what was launched. The user has to project the future. For this study the future has to be projected until 2015. The only objects of interest for this projection are those that are placed in LEO or Geosynchronous Transfer Orbit(GEO). GEO satellites can not directly contribute to debris at LEO.

To realistically estimate future launch rates, at least four components have to be considered. These four components are the total Russian launch rate, the US military and civil launch rate, the rest of world national system launch rate, and the commercial launch rate. This level of structure is required to model the actual component trends that will affect the overall launch rate. The Russian launch rate has dropped to half of what it was during the Soviet Union days. The US military and civil launch rate is fairly stable. The rest of world launch rate is also fairly stable. The commercial launch rate is expected to grow dramatically over the period the ISS will be up. The number of launches by year in the first three categories for the years 1990 to 1995 are shown in Figure No. II.1.

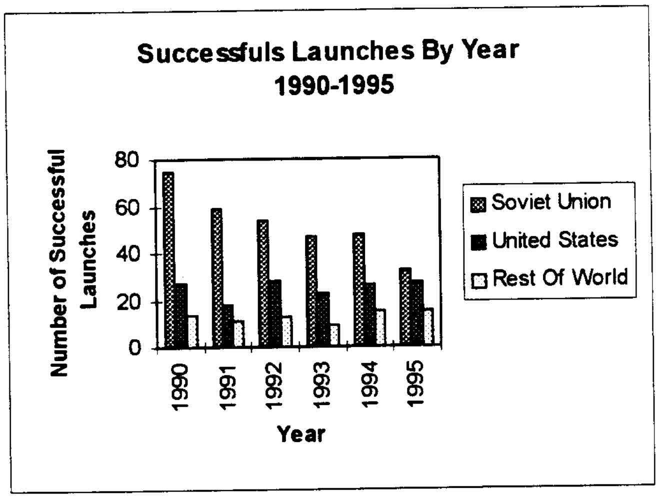


Figure No. II.1: Successful Launches By Year 1990-1995

The average number of launches per year over this period was 90.167, with a standard deviation of 14.716. This rate was used to project a constant launch rate into the future over the period 1996-2015. The Russian launch rate was 58% of the total with 72.1% of their launches going to LEO. The United States and the rest of the world made up the the other 42% with 51.5% of their launches going to LEO. For this study, this base launch rate was projected into the future with an expected value of the mean(90.167) observed during these five years and a standard deviation of 14.176. This gave the probability distribution function(pdf) plotted in Figure No. II.2. Basically for the cases considered here, the base launch rate was assumed constant from 1996 to 2015 with a value randomly selected from the distribution function in Figure No. II.2. Since near-Earth space above

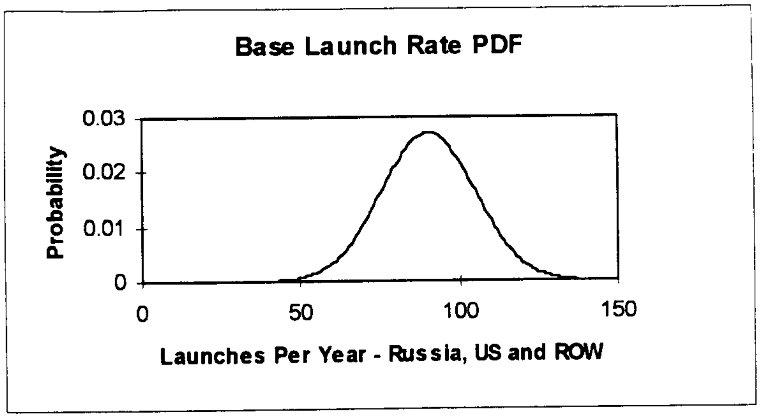


Figure No. II.2: Base Launch Rate

the atmosphere serves as a holding tank for space debris, year to year fluctuations in the launch rate are not as important as the average rate over this time period.

The major increase over this time period will be the launch of new commercial communication constellations. The Office of Commercial Space Transportation(OCST) has developed two scenarios for the new LEO systems. (DOT, 1996) The "modest growth" scenario predicts three Big LEO(including MEO) and two Little LEO systems will be deployed over this period. The "high growth" scenario projects that four Big LEO and three of the larger Little LEO cnstellationswill be deployed. Neither scenario considers the 640 satellite constellation proposed by Teledesic Corporation. An average of 51.8 satellites per year will be required for system deployment, and 7.4 satellites per year will be required for failure replacements for the "modest growth" scenario. For the "high growth" sceanrio an average of 61.4 satellites per year will be required for deployment, and 8.2 per year will be required for replacements. In all cases the plan is to launch multiple satellites per launch vehicle with medium vehicles used for deployment and light vehicles used for some deployments and all replacements. The average is 6 satellites per medium launch and 3 satellites per light launch vehicle.

The pdf for the annual number of satellites launched for the commercial market is based on an average of the "modest" and "high" growth scenarios with the standard deviation taken as half the difference between the two. This gives an expected launch rate of 64.4 satellites per year and a standard deviation in the estimate of 5.2 satellites per year. The pdf for this variable is plotted in Figure No. II.3

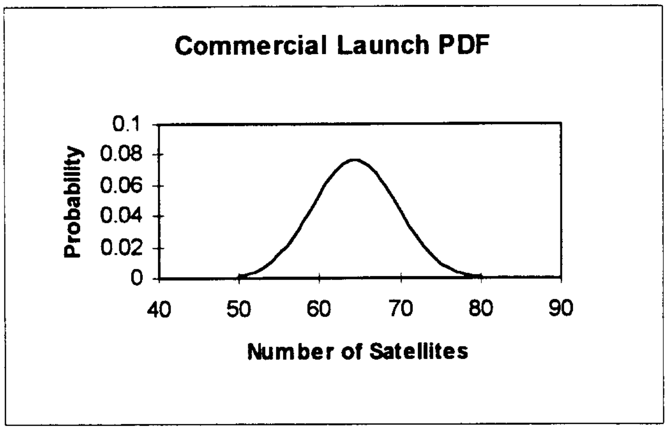


Figure No. II.3: LEO Commercial Communication Satellites Launched Per Year

The EVOLVE code requires the satellite launches to be input as discrete quantities with the appropriate description of the launch vehicle and its upper stages. For the analysis considered here this was accomplished by selecting a value for the number of base launches per year and rounding it to a discrete number. Then the number of new satellite launches per year were selected. This was rounded to a discrete number. Medium and light launch vehicles were selected in a ratio of approximately 2.5 lights to every medium to cover as much of this requirement as possible. Then the remaining satellites were placed on an additional light launch vehicle. The launches during 1994 were selected as the basic launch cycle for this study and augmented or decremented to meet the selected yearly rates. The Delta launch vehicle was selected as typical of a light vehicle and an Atlas was selected as typical of a medium launch vehicle.

II.4: Explosion Frequency

EVOLVE models the explosion frequency by considering four types of objects that can produce an explosion. They are,

1) low-intensity Russian rocket bodies, explosion probability = 0.014/year,

2) low-intensity US/Other rocket bodies, explosion probability = 0.21/year,

3) high intensity Russian photo-recon satellites, explosion probability = 0.252/year,

4) and, high intensity Russian EORSATS, explosion probability = 0.46/year.

All explosions are assumed to occur in the first year. All explosions are characterized as low intensity or high intensity. Low intensity explosions are those that occur due to unvented fuel igniting, a pressure buildup that ruptures a tank, or a battery overpressurization event. High intensity explosions are characterized by an active explosive detonating to destroy the spacecraft. Past non-US events are characterized by the velocities imparted to the debris fragments as to their high or low intensity.

The international community is aware of the hazard to space systems in LEO as the result of explosive events and most nations have taken actions to vent unexpended fuel and safe batteries on mission termination. Both the US and Russia have stopped testing ASAT weapons in space. Therefore it is likely that the number of explosions will decrease in the future. How much, or how rapidly, are difficult questions. A reasonable approach seems to be to model the uncertainty here as a triangular distribution that has zero probability for the current rate with a peak value at a zero rate. A factor will be chosen that simply multiplies the current rates by its value to estimate future rates. The pdf for this factor is given in Figure II.4. The most probable rate is

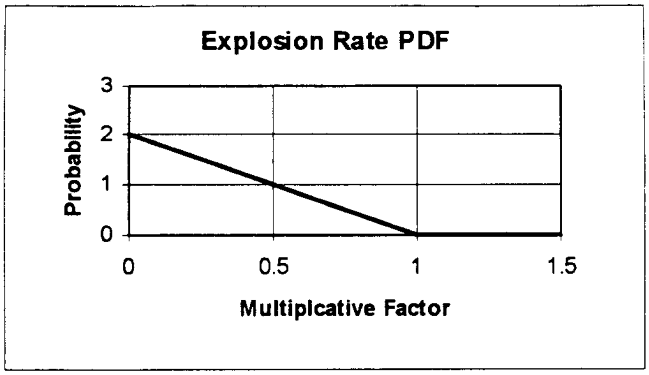


Figure No. II.4: Explosion Rate PDF

the zero rate where the mutiplicative factor is equal to 1.0 and the pdf is 2.0. The least probable rate is a multiplicative factor of 1.0 where the pdf is 0.0. All four rates are raised or lowered the same amount. Of course with the slow down in Russian launches, the rate of explosions will decrease more than can be predicted by this factor alone.

II.5 Fragments Produced In an Explosion

The fragments produced in an explosion are modeled separately for high intensity and low intensity explosions. The low intensity model will be discussed first as it is also used in the high intensity model.

Low Intensity Model

The number of fragments produced in a low intensity explosion are modeled as a cumulative distribution function that depends on the mass of a fragment. That is, for a given fragment mass, the model predicts how many fragments have this mass or a greater mass. The model is implemented in the code by the following equations,

$$f_m = \mathbf{m}_{Ref} / \mathbf{m}_{Sat}$$

$$\nu = (\mathbf{m} * f_m)^{0.5}$$

$$\mathbf{N}(>\mathbf{m}) = 0.171 * \mathbf{m}_{Sat} * e^{-0.6514*\nu}, \qquad \mathbf{m} > 1.936 \text{ kg} / f_m$$

$$\mathbf{N}(>\mathbf{m}) = 0.869*\mathbf{m}_{Sat}*e^{-1.8215*\nu}, \qquad \mathbf{m} < 1.936 \text{ kg} / f_m$$

where,

$\mathbf{f_m}$ = the ratio of the satellite mass to a standard reference satellite mass,

$\mathbf{m}_{Ref}$ = the mass of a reference satellite, currently 1,540 kgm,

$\mathbf{m}_{Sat}$ = the mass of the satellite that explodes in kgm,

m = the mass of the fragment under consideration in kgm,

$\mathbf{N}(>\mathbf{m})$ = the number of fragments that have a mass greater than **m**.

There have been two sets of experiments that actually exploded a piece of space hardware and collected the debris to develop a fragment distribution model. The first of these was an Atlas rocket tank explosion conducted in 1963 as part of a safety study on the ICBM. (Edwards, 1963) The second set was three experiments conducted by Fucke et al. attempting to model hydrogen-oxygen tank explosions in space. (Fucke, 1993) All four tests were found to fit a curve of the form,

$$\mathbf{N}(> \mathbf{m}) = N_o*\exp[-\mathbf{B}*\mathbf{m}^{0.5}/(1+0.5*\mathbf{m}^{0.5})]$$

where,

No = the total number of fragments, and

B = a free parameter that depends on the explosion intensity.

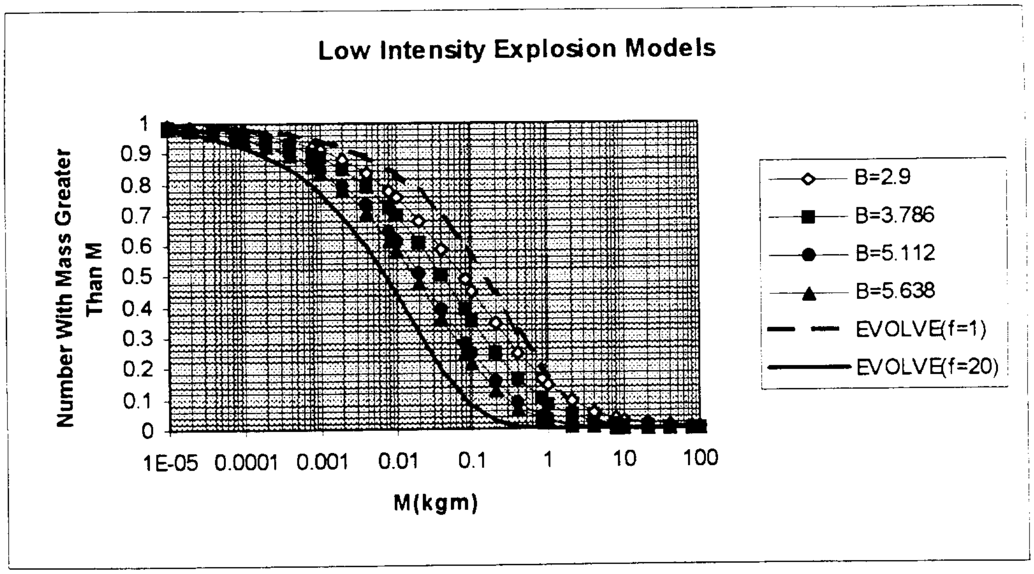


Figure No. II.5: Cumulative Distribution Functions For Low Intensity Explosions

The Atlas explosion fit this form with a value of B = 2.9, and Fucke's three explosions fit this form with B values of 3.785, 5.112, and 5.638. All four curves are plotted in Figure II.5. Also plotted are two bounding curves in the form of the equation used in the EVOLVE code. These two curves are obtained by choosing different values for the reference mass in the EVOLVE equations. The easiest approach to parameterizing the uncertainty in the distribution of explosion fragments would be to go to the form used by Fucke, but his would require reprogramming. So the values of the reference mass have been adjusted to give the two bounding curves of Figure No. II.5. For this case the value of the reference masses are 1,540 kgm and 3,540 kgm. Since the distribution for the explosion will depend on the explosive yield relative to the mass of the satellite, and in general neither will be known, the probability distribution function was assumed to be a constant over the interval from 1,540 kgm to 3,540 kgm. This pdf is plotted in Figure II.6. A value from this distribution for the reference mass was selected for each EVOLVE

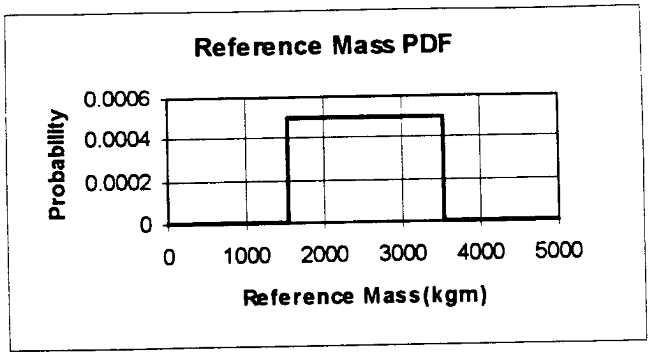


Figure No. II.3: Explosion Reference Mass PDF

calculation, and it was held constant for the complete run.

High Intensity Model

The high intensity fragmentation model is 90% the low intensity fragmentation model and 10% a distribution that varies as $1/\mathbf{m}$. The mass of the satellite is split into two parts. Ninety percent of the mass of the satellite is assumed to undergo a low intensity explosion and the equations above are evaluated based on this satellite mass. The other ten percent of the mass of the satellite is distributed into particles that have a range of equivalent diameters from 1 millimeter to 10 centimeters. This seems to be a rather ad hoc approach to producing more small particles and is not quantitatively justified in any reference. Given this uncertainty, it seems reasonable that the percent of mass going into this $1/\mathbf{m}$ distribution should be varied at least a factor of two. Therefore the probability distribution function for the fraction of mass going into the $1/\mathbf{m}$ distribution is constant from 0.0 to 0.2. It is plotted in Figure II.7.

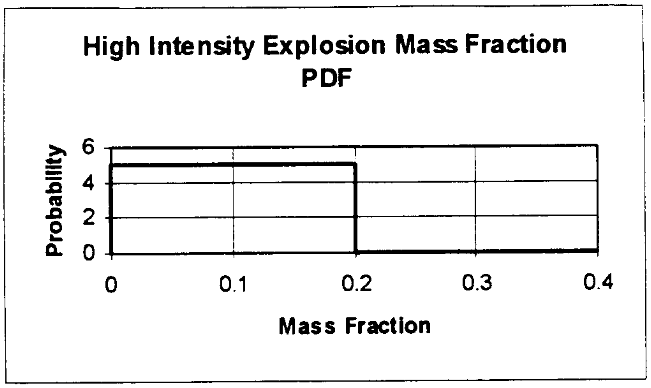


Figure No. II.7: High Intensity Explosion 1/m Mass Fraction PDF

II.6: Collision Frequency

The collision frequency between space objects is calculated by the EVOLVE code dependent on the number of objects present and their size. There are no parameters in this calculation that are uncertain or variable. It may not be a totally correct model, but the uncertainty in this calculation is very small compared to some of the others. Therefore no parameterization was attempted and the deterministic approach of the code was used as is.

II.7: Fragments Produced In a Collision

A number of hypervelocity impact studies have been done to model the impact of projectile moving at several kilometer per second speeds with a satellite. (McKnight, 1994, 1995, and Fucke, 1993) All of these seem to fit a power law distribution fairly well. This distribution is given by,

$$\mathbf{N(> m) = c/m^{b}}$$

where once again,

$\mathbf{N(> m)}$ = the cumulative distribution function of number of particles generated greater than mass **m**, and

c,b = constants that determine the distribution.

Note that to conserve mass, c must depend on b. The EVOLVE model uses a value of 0.7496 for b and calculates c to conserve mass. Other codes and experiments give different values. (Fucke, 1993) A reasonable range seems to be from about 0.5 to 1.0. For this case a normal distribution makes sense and the mean should be the EVOLVE value of ~0.75 and a standard deviation of 0.075. This distribution is plotted in Figure No. II.8.

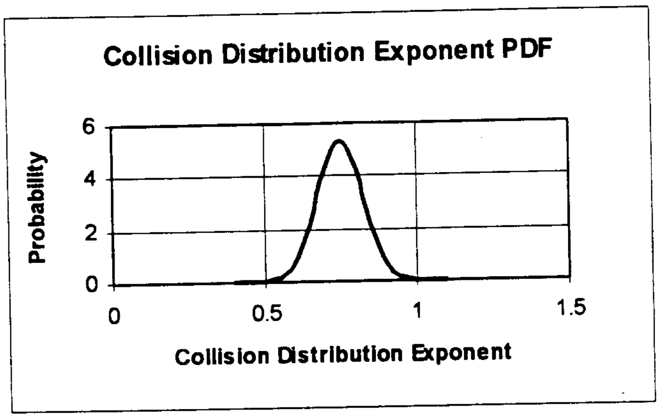


Figure No. II.8: Collision Fragmentation Distribution Exponent PDF

II.8: Ballistic Coefficient Distributions and Atmospheric Lifetimes

Once an explosion occurs and the fragments are released each becomes its own uncontrolled satellite of the Earth. Some will aquire enough of a change in relative velocity that they will enter orbits with perigees in the atmosphere and they will deorbit very quickly. Usually the majority simply expand into orbits near their initial orbit and float there until atmospheric drag or perturbations introduced by solar pressure and the gravitational effects of the Sun and Moon cause them to enter the atmosphere and deorbit. The major parameter that affects how fast this occurs is a variable called the ballistic coefficient. It is a ratio of the mass of the object to its coefficient of drag times its frontal area. (Chobotov, 1996) If an object has a lot of mass and a small frontal area, it will have a large ballistic coefficient and atmospheric drag will have little effect on it. In this case it will stay in orbit for a relatively long time. If it has a lot of frontal area and a small amount of mass, it will slow down much faster and re-enter sooner. (Nominal coefficients of drag are about 2.0 plus or minus 10 percent. Given the other uncertainties in this problem, the coefficient of drag is a minor one and it will be set to 2.0, the value for a sphere at hypersonic speeds.)

Predicting exactly how fast this slowdown will occur for objects of known shape and size is a fairly difficult task. The density of the atmosphere changes exponentially with height and varies over the same spot on the Earth with day or night conditions. (Jacchia, 1993) The atmosphere also expands during periods of increased solar activity and satellites lose altitude much faster at the peak of the solar cycle. A useful variable to correlate the expanded atmosphere with is the solar radiation flux incident on the Earth in the 10.7 micron band. The solar flux index in the 10.7 micron band varies from a value of 75 at minimum solar activity to a value of 250 at maximum solar activity. The average value is about 160. (Chobotov, 1996)

It is interesting to consider some ballistic coefficients for typical objects at LEO altitudes and their effect on decay times and loiter or dwell times. In Figure No. II.9, the time required for an object, inserted into a circular orbit at 1000 km, to decay to a 550 km circular orbit is plotted as a function of ballistic coefficient and solar activity.

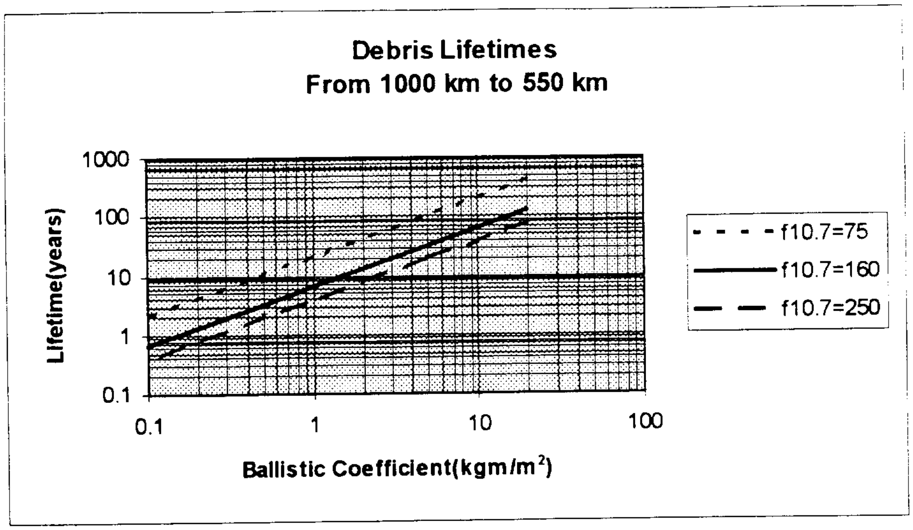


Figure No. II.9 Lifetime from 1000 km to 550 km

It takes an object with a ballistic coefficient of 2.0 about 15 years to descend from 1000 km to 550 km for the average solar flux case. However, after it reaches 550 km, it descends through the next 200 km much more rapidly due to the exponential increase in air density with decreasing altitude. An estimate of the time required to do this is presented in Figure No. II.10. For the object with a ballistic coefficient of 2.0, it only takes a little ove 0.15 years to pass through this band for the average solar flux value of 160.

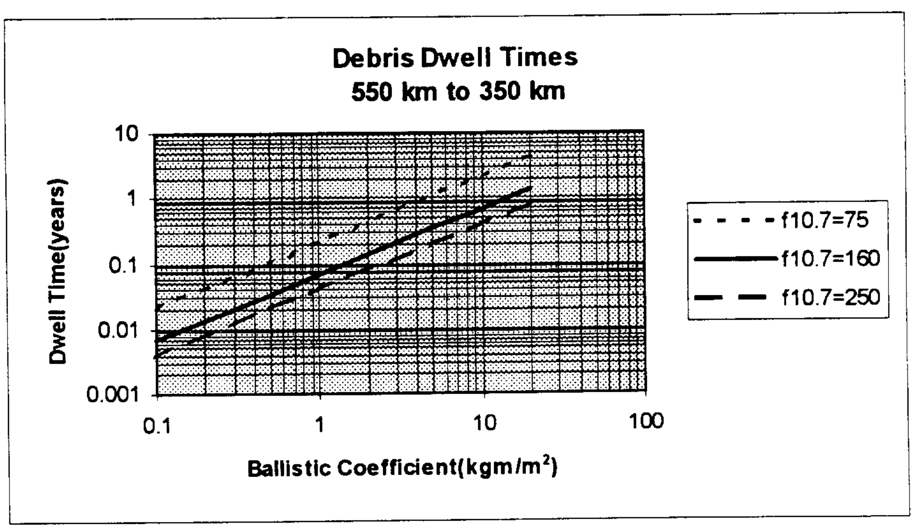


Figure No. II.10 Dwell Time Between 550 and 350 km

Thus it becomes important to estimate ballistic coefficients for debris particles as this parameter determines how long it takes for a particle to reach Space Station altitudes from its initial injection altitude, and how long the particle remains a hazard once it has reached the correct altitude band.

In order to model debris fragments, EVOLVE uses a spherical particle model with a varying density. Below about 1 gram size particles, the density of Aluminum, 2699.0 kgm/m^3, is used. Particles with a mass greater than 1 gram are assumed to have a varying density equal to 90.14 $D^{-0.74}$ kgm/m^3. Unfortunately most experiments that have been done for to model explosions or collisions do not produce spherical particles. Particles tend to have random shapes and in many cases a dominant axis. In order to characterize the average area of a particle, the equivalent diameter concept has been developed. The equivalent diameter is defined as the average of three length dimensions taken in mutually perpendicular directions. The first measurement is made across the longest dimension of the object. A second measurement is made perpendicular to the first at a position that maximizes its value. The third measurement is made perpendicular to the other two at a position that maximizes its value. The average of these three measurements becomes the equivalent diameter. This is probably a reasonable approach as most particles are likely to be tumbling randomly and they will interact with the atmosphere in a random sense. They will also be observed by radar with a random orientation, so an effective size can be computed from the area associated with the equivalent diameter.

Two sets of experiments on particles that have resulted from breakups have been well documented in the recent literature. The first of these were a set of explosions of scaled propellant tanks conducted by Batelle-Institut e.V.(BF) for the European Space Agency. (Fucke, 1993) The propellant tanks were exploded by filling them with a hydrogen-oxygen mixture and igniting it. The tanks were surrounded by soft catch material and over 97% of the tank structure was recovered, weighed, and measured. The results of these experiments are plotted in Figure No. II.11. Also plotted in Figure No. II.11 are a fit to the data, and the D_{eq}^2 vs. mass model that is used in the EVOLVE code.

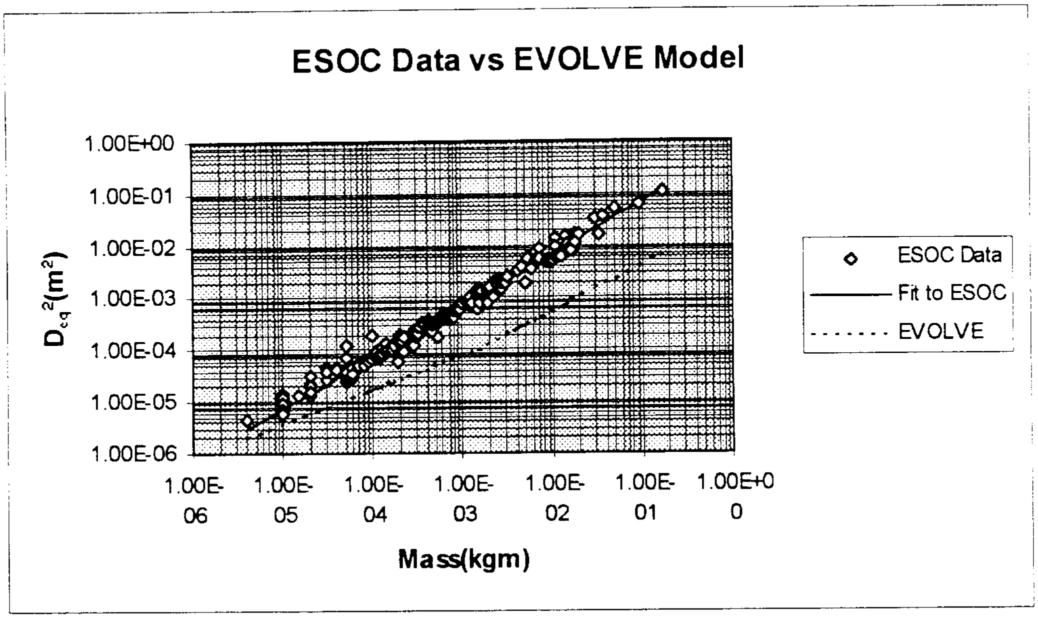


Figure No. II.11: ESOC Data and EVOLVE Model

It should be readily apparent that for a given mass, the EVOLVE model significantly underestimates the value of D_{eq}^2. The fitted curve that passes through the data quite nicely and seems to match the functional behavior of the data trend is given by,

$$D_{eq}^2 = 1.39 \text{ m}.$$

This is a particularly convenient form as it will yield constant ballistic coefficients regardless of the size of the particles.

The second experiment that is of interest was performed at Arnold Engineering Development Center(AEDC). It is a collection of objects that were recovered after hypervelocity impact shots 6470 and 6472 in the AEDC test chamber. Shot 6470 was the impact of an 85 gram projectile traveling at 5.5 km/sec on two water filled 15.2 cm diameter aluminum spheres surrounded by a cylindrical steel cylinder with open ends. Shot 6472 also involved an 85 gram projectile traveling at 5.5 km/sec and impacting a scale model of an interceptor rocket. These experiments are not necessarily prototypic of current space debris, but they should have the spread of densities, sizes, and shapes that could be part of the current space debris population. (Bohannon, 1994, p1)

The data from these two experiments are plotted in Figure No. II.12 along with a number of other curves. The thin solid line is a fit to the data using the form $D_{eq}^2 = 6m$.

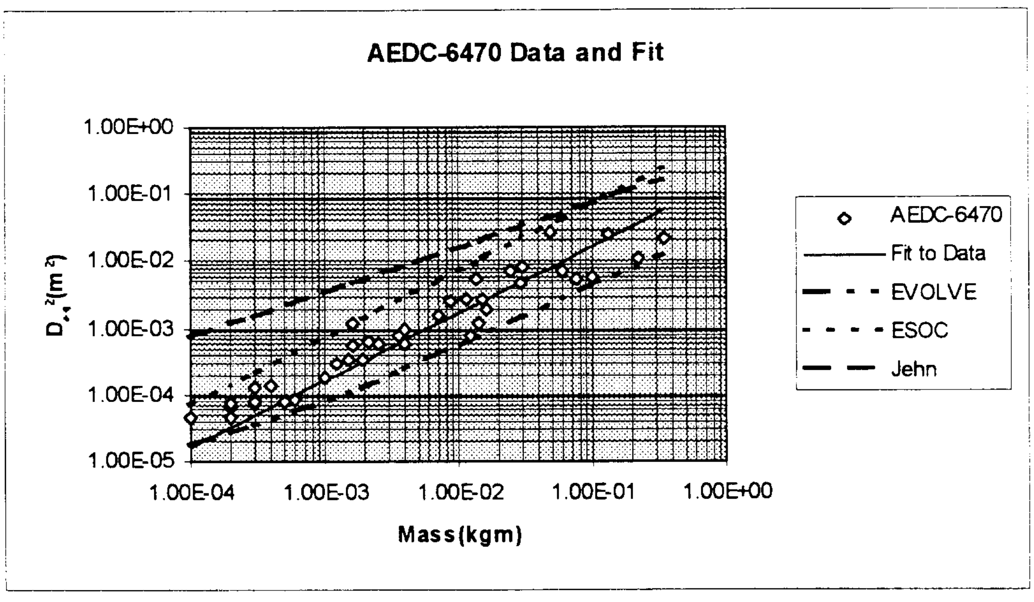


Figure No. II.12: AEDC-6470 Data and Curves from ESOC, EVOLVE, and Jehn

The dotted line is the fit to the data of Fucke plotted above. The lower dashed line is the model used in EVOLVE. The upper dashed line is a relation proposed by Jehn to fit debris with an effective area less than 0.01 m^2. It is given by $D_{eq}^3 = 0.2$ m.

With this much variation, a reasonable compromise seems to be to use the convenient form that produces a constant ballistic coefficient and choose the value given by the ESOC experiments as the most likely value. This gives a most likely value of 1.4 and a range from 0.333 to 15 for K in the equation $D_{eq}^2 = Km$. The probability distribution for K is plotted in Figure No. II.13.

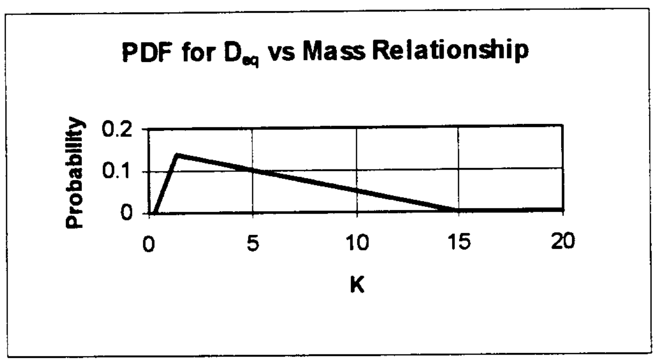


Figure No. II.13: PDF for K in D_{eq} vs. K Mass

III: COMPUTATIONS

III.1: The Latin Hyper-Square Model

Based on the analysis of Section II there have been seven variables identified that affect the uncertainty in the predictions made by the EVOLVE code of the debris environment. These are,

1) The projected basic launch rate of Russia, the Us, and the Rest of the World,

2) the projected launch rate for new commercial communications satellite constellations,

3) the explosion frequency per year relative to historical rates,

4) the reference mass used for predicting fragmentation sizes from low intensity explosions,

5) the fraction of the mass in a high energy explosion that goes into the 1/m distribution for small particles,

6) the exponent in the collision fragment distribution, and

7) the coefficient that relates the square of a fragment's equivalent diameter to its mass.

By applying the standard rule that the minimum number of cases studied should be 1.4 to 2.0 times the number of parameters, a selection of 12 cases for calculation was made. Of course more would be better, but this number should give a reasonable estimate of the uncertainty. With this number, and the pdf's described in Section II for selecting the values for the variables within their range of uncertainty, the LHS code was run. (Iman, 1984c) The LHS code gave the following values for each parameter for the twelve EVOLVE calculations.

Table No. III.1 : Parameter Summary For The 12 EVOLVE Calculations

Case	Basic Launch Rate Launch/Yr	Comm Satellite Rate Sats/Yr	Explosion Frequency Exp/Yr	Reference Mass LIE kgm	Mass Fraction HIE	Collision Fragment Distrib Exponent	Diameter To Mass Coefficient
1	53	52	0.09789	2834.7	0.0551	0.70583	5.0915
2	91	70	0.27541	3270.9	0.0445	0.81144	10.1831
3	113	60	0.95395	2185.1	0.0126	0.78732	4.5372
4	98	75	0.18016	2263.4	0.1479	0.65085	2.5465
5	79	66	0.65459	3040.9	0.1062	0.68252	2.9841
6	82	68	0.20153	2885.4	0.0193	0.74408	7.3711
7	94	63	0.39684	3423.1	0.1956	0.82458	3.6309
8	87	64	0.52714	1611.9	0.1762	0.73066	6.2217
9	71	68	0.47298	1944.4	0.0818	0.75135	1.6559
10	108	59	0.33041	2690.6	0.1242	0.58284	8.2476
11	101	61	0.01933	2467.8	0.0874	0.76795	0.8297
12	88	63	0.07728	1720.4	0.1559	0.90369	11.7202

As a check on the validity of the results, the LHS code prints out the average of the values chosen for the study and this average or mean value can be compared with its expected

Table No. III.2:Comparison of Mean with Expected Values For LHS Problem

	LHS Mean	**Expected Value**
Basic Launch Rate	88.586	90.167
Commercial Satellite Launch Rate	64.162	64.4
Explosion Frequency	0.3489	0.3333
Reference Mass For LIE	2528.2	2540.0
Mass Fraction For HIE	0.1006	0.10
Collision Fragment Exponent	0.7453	0.75
Mass To Diameter Coefficient	5.4183	5.500

value. A summary of this comparison is presented in Table No. III.2. The mean values compare very well with the expected values. The difference is due to the random sampling within each probability range for the individual cases.

The last five variables were read into the code by adding a read statement and establishing a labeled COMMON statement to forward them to the correct sub-programs. This procedure worked very well, primarily due to the excellent discipline with which the code is written. (Since EVOLVE has no labeled COMMON statements, at this point I must beg forgiveness of the code's author for using such a poor programming practice. Obviously I removed them after I completed this effort.) The first two variables were a little more complicated.

EVOLVE reads a set of files containing a description of every satellite and piece of debris that has been launched into space since the beginning of the space age. These files are organized on an annual basis. Each file contains all of the successful space launches for a given calendar year. It includes each spacecraft and all of its associated debris that goes into orbit. It also has the pertinent characteristics of the satellites and rocket bodies. In order to enter a future year, this information has to be made up. The easiest way to make it up is to select a past year that looks like the data that is needed and change the year on it. For this study, the data for 1994 closely approximated the average case. The total number of launches that year was 89 and Russia launched 54% of the total. To match the data required in Table No. III.1, the average year of 1994 was adjusted by deleting or adding base case launches so as to match the total desired number of launches and the appropriate Russian fraction and the appropriate GEO/LEO mix. Then the new commercial launches were added to the table as appropriate, with the correct number of satellites per launch and one rocket body per launch remaining in orbit. All of the satellites were placed in elliptical orbits with a perigee of 600 km and an apogee of 1200 km. An Atlas-Centaur model was used for the medium vehicle launches, and a Delta model was used for the light vehicle launches. The changes to the 1994 year are summarized in Table No. III.3.

Table No. III.3: Changes To 1994 Launch Rates To Meet LHS Values

Case	Basic Launch Rate Lnch/Yr	Add To 1994 Launch Rate	Russia GEO	Russia LEO	US GEO	US LEO	Comm Satellite Rate Sats/Yr	Medium Launch Vehicles (6 Sats)	Light Launch Vehicles (3 Sats)	Ex Light Launch Vehicle (?Sats)	Total Lnches Per Year	Net Launch Increase Per Year
1	53	-36	-6	-14	-8	-8	52	4	9	1	67	-23
2	91	2	0	1	0	1	70	5	13	1	110	20
3	113	24	4	9	5	6	60	4	12	0	129	39
4	98	9	2	3	2	2	75	6	13	0	117	27
5	79	-10	-2	-4	-2	-2	66	5	12	0	96	6
6	82	-7	-1	-3	-1	-2	68	5	12	2	101	11
7	94	5	1	2	1	1	63	5	11	0	110	20
8	87	-2	0	-1	0	-1	64	5	11	1	104	14
9	71	-18	-3	-7	-4	-4	68	5	12	2	90	0
10	108	19	4	7	4	4	59	4	11	2	125	35
11	101	12	2	5	2	3	61	5	10	1	117	27
12	88	-1	0	-1	0	0	63	5	11	0	104	14

III.2: Modifications To EVOLVE

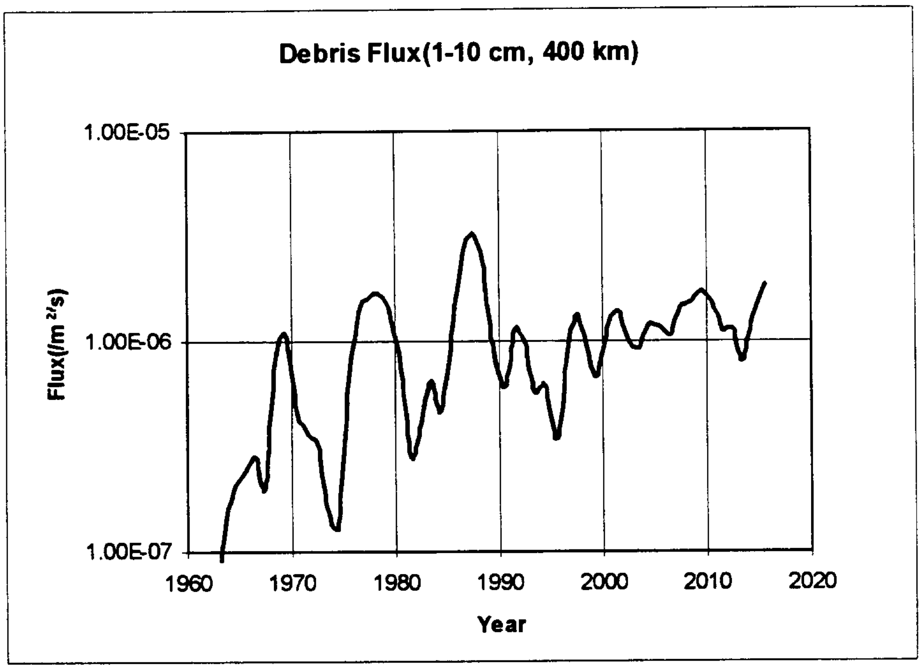
Other than the labeled COMMON added to get the model parameter variations indicated above, the EVOLVE code was not significantly modified. A machine independent random number generator was substituted for the VAX specific generator that came with the version used for this study. The generator has a repeat cycle greater than 2^{30} numbers.(Press, 1992, p266) A modification was made to SUBROUTINE AMR and FUNCTION RM to implement the relationship for the equivalent diameter as a function of mass and the mass as a function of equivalent diameter. The area of a debris particle was made directly proportional to its mass and the constant of proportionality was the seventh parameter varied in the analysis.

Each calculation took approximately 1 hour on a 133 MHz Pentium PC with 64 Megabytes of memory. An ensemble of 10 Monte Carlo cases was run to estimate future environments. The average output from the code required a little over 40 Megabytes of disk storage.

IV: RESULTS

IV.1: Estimated Risk To The ISS

The twelve calculations identified by the LHS model were completed and compiled. The spatial densities and fluxes were computed from 300 to 1500 km above the surface of the Earth. Since the region of interest for the ISS is from 350 to 550 km, two altitudes will be identified as representative of this range - 400 and 500 km. Each case looks a little different, but a typical case, case 3, can provide some insight to the time dependent behavior of the debris flux, before discussing risk. Figure No. IV.1 is a plot of



<u>**Figure No. IV.1: Space Debris Flux, 1 - 10 cm, 400 km, 1957-2015**</u>

the predicted debris flux in the range from 1 to 10 cm at 400 km from 1957 to 2015. The most apparent feature of the flux estimate is its oscillation over time. This is caused by two primary fluctuations. The launch rate fluctuates, reaching 127 successful launches in

1967, 128 in 1976, and 129 in 1984. (US Space Command, 1996). The solar cycle also fluctuates in its heating of the atmosphere. More debris rains down through 400 km during peaks in the solar cycle than during valleys in the cycle. The major and minor peaks up to the current year are all real and best estimates based on the best data available. The future is an estimated flux, based on an ensemble of Monte Carlo calculations. The damping of the fluctuations is a real projection however. Note that the average growth rate levels off somewhat, but remains high. This is partially because the reservoir of space above 400 km contains significantly more debris that dribbles out at a fairly continuous rate, and the methodology used to run the model kept the number of launches per year constant from 1996 to 2015 for each case.

At 500 km the flux looks very similar. Some of the early fluctuations are not as

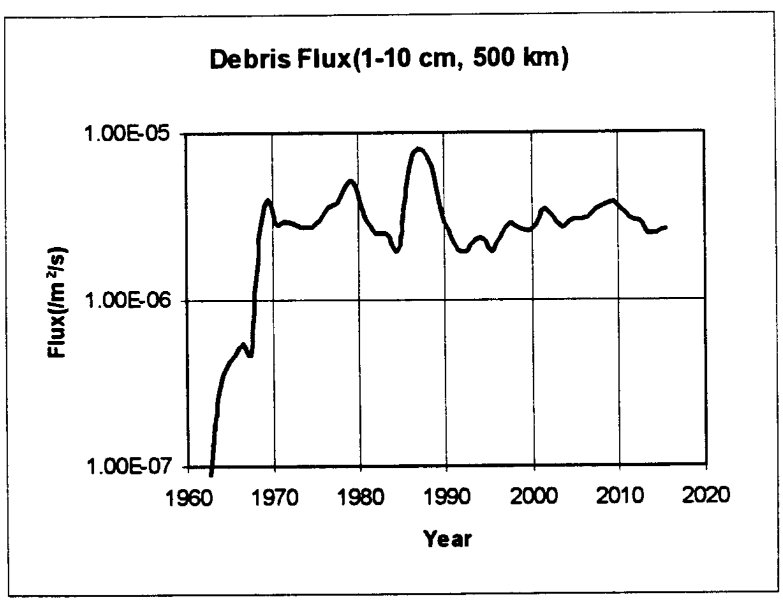


Figure No. IV.2: Debris Flux, 1 - 10 cm, 500 km, 1957-2015

severe, as more of the earlier launches were to lower altitudes. However, the overall flux level is higher. This occurs because the residence time for debris at a particular altitude is longer at higher altitudes.

Using the flux profiles for each of the twelve cases and evaluating the collision rate based on an effective area for the ISS of 2,230 sq. meters(NRC, 1997, p12) over the period of time from 2000 to 2015, the cumulative distribution function for the probability of impact(Impact Risk) by a debris particle in the size range from 1 to 10 cm at 400 km is presented in Figure No. IV.3. It is worth reiterating that this is the size range of most concern as smaller debris particles can be shielded against, and larger debris particles can be tracked and avoided.

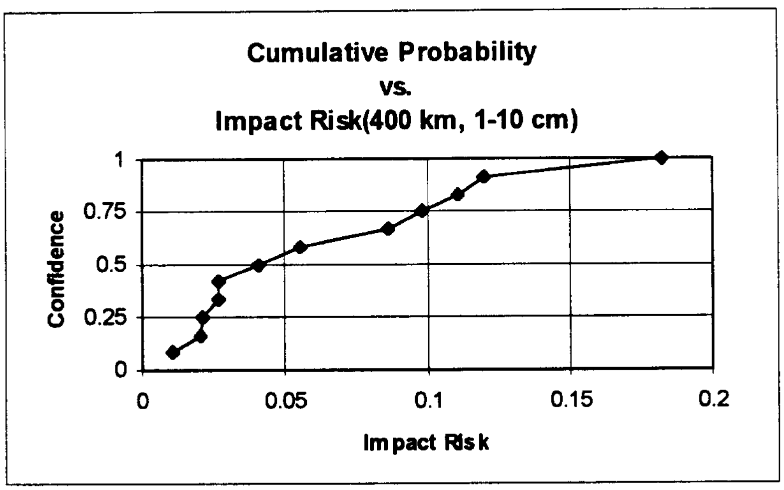


Figure No. IV.3: Impact Risk at 400 km, 1- 10 cm particles, 2000-2015

The median case at the 0.5 probability point corresponds to a probability of impact of 0.04. The lowest probability of impact is about 2% and the highest probability of impact is approximately 18%. The design goal for the ISS is a Probability of Non-Penetration(PNP) of 0.81.(NRC, 1997, p12) All of these cases satisfy this criteria as the probability of impact is given by, $P_{impact} = 1\text{-PNP}$.

At 500 km the situation is slightly different. The Impact Risk at 500 km is plotted in Figure No. IV.4. The distribution is different from that at 400 km for a number of

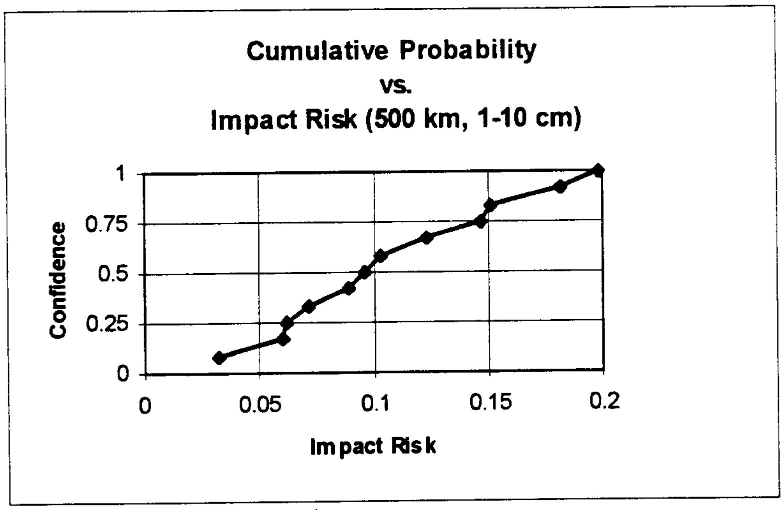


Figure No. IV.4: Impact Risk at 500 km, 1- 10 cm particles, 2000-2015

reasons, as the fluxes were different. The most obvious change, though, is the shift in probability of impact to higher values. The median case here corresponds to a probability of impact of 0.095(9.5%). The lowest calculated risk is a probability of impact of 0.035, and the highest is 0.198. The 0.198 just barely misses the design requirement to have a PNP of 0.81. Of course none of these numbers are accurate enough say that this difference matters.

Perhaps the most interesting conclusion that can be drawn though is that the risk is higher at higher altitude. The ISS operation plan is to "ride" the atmosphere. When the atmosphere is compressed, the ISS will move to a lower altitude. When it is expanded due to solar heating, the ISS will move to a higher altitude. The original driver for this strategy was to minimize radiation dose to the crew. The Van Allen Belts extend to lower altitudes when the atmosphere is compressed.(NRC, 1995) This strategy appears to also be advantageous to avoid some of the risk of small space debris impacts.

IV.2: Fit to Results With Normal Distribution for Conservative Extrapolation

Obviously Figure No. IV.3 and IV.4 are not accurate enough to allow us to say with 95% confidence that a given risk would not be exceeded. Since an equal probability must be assigned to each case in the LHS model, we would need to calculate enough cases such that one case would fall in the interval between 0.95 and 1.0. This would require a minimum of 21 calculations. Of course if we wanted to be 99% confident that the calculated risk would not be exceeded, then we would have to calculate 101 cases. This becomes very difficult, very quickly. A simple approach around this problem is to fit the distributions calculated with a normal curve and extrapolate from it. For example, with the distributions calculated we could choose the 16.7% and 83.3% points and assume that these were the two central standard deviations for the normal curve. This would give the following table for confidence levels of not exceeding a particular risk.

Table IV.1: Approximate Confidence Levels Based On Fit To Calculated Data

	400 km	500 km
16% value	0.0204	0.0606
83% value	0.1112	0.1512
Calculated Mean	0.0658	0.1059
Standard Deviation	0.0454	0.0453
95% Confidence(1.65 sd)	0.1407	0.1807
99% Confidence(2.33 sd)	0.1716	0.2115
99.9% Confidence(3.10 sd)	0.2065	0.2463
99.99% Confidence(3.80 sd)	0.2383	0.2780

The interpretation for Table No. IV.1 is that the probability of impact values listed in the last four rows represent the risk that can be accepted with the confidence specified in the first column. For example, we would be 99.9% confident that the actual risk to the ISS of an impact while operating at 500 km would be less than 0.2463. We could also have a 95% confidence level that the design PNP of 0.81 will not be exceeded at 500 km as the probability of impact is 0.1807, giving PNP = 0.819.

IV.3: Comparison With Published Documents - NRC, OSTP, and AF SAB

Comparing the results developed here with those documented in other studies is somewhat complicated. No one calculates exactly the same scenario. In fact even for studies performed as recently as 1995, it is usually difficult to obtain the exact data that was used. It is also probably irrelevant to make that detailed of a comparison, other than to validate that some piece of software gave the same wrong answer then, as it does now. This is not to disparage EVOLVE, as most pieces of software that are trying analyze as large of a problem as space debris simply can not deterministically track every piece of information that is relevant to the final answer. What is important is in an approximate, or statistical, sense to understand the differences in the calculations and understand the physical phenomena that caused these differences.

Having said that, Figures No. IV.1 and IV.2 can be compared with the growth curves presented in Orbital Debris. (NRC,1995, p20) The curves developed here tend to level off after 1995, but exhibit the same growth up to that point, that was described in Orbital Debris. Basically the two sets of curves are consistent. The curves generated here do not exponentially grow after 1990 as an exponential growth factor was not entered as input for the scenario analyzed. The projected launches were input on a yearly basis. This seems a much more reasonable approach. The slow down in the Russian launch rate was also taken into account. In fact the maximum launch rate considered in any of the 12 LHS cases analyzed was 129 successful launches per year. This is comparable to the peaks that have been achieved in the past and seems to be a reasonable prediction based on the data available.

A comparison with the Interagency Report on Orbital Debris 1995(OSTP ,1995) comes to basically the same conclusions. For many scenarios this report predicts an exponential growth in debris. This occurs because the calculations on which it is based does use an exponential growth in the launch rate as an input parameter. The decrease in the Russian launch rate, the increased number of launches going to GEO, and the increased longevity of currently designed satellites mitigate against an exponential growth rate in LEO launches. Also in this study, the desirability of safing old rocket stages and dead satellites was taken into account by selecting a factor for each case that determined how effective this recommended policy would be. A policy of 100% safing is demonstrated as very effective in the Interagency Report(OSTP, 1995, p18). This study chose to allow this variable as a somewhat uncertain parameter with a bias toward a reduced rate. The resulting debris fluxes are very comparable to the referenced fluxes presented in the Interagency Report.

The Interagency Report does discuss the ISS to a limited extent. It indicates that the probability of impact of a 1-10 cm particle with a 5,000 sqm ISS at 400 km gives an expected value of 1 impact in 71 years. This corresponds to a probability of impact of 0.0346 for the current ISS design, well within the range calculated here.

Comparing the analysis performed here with <u>Protecting the Space Station from Meteoroids and Orbital Debris</u> (NRC, 1997), leads to the conclusion that the mean numbers reported here are moderately smaller than those reported in that document. For instance, the non-Russian part of the ISS is claimed to have met its design goal of a PNP of 0.9 for operation at 400 km.. This corresponds to a probability of impact of 0.1. The reported analysis was based on a 10 year lifetime, so this has to be upped to 0.15 to compare with the numbers calculated here. Since this portion represents only 58.8% of the exposed area of the ISS, this has to be further increased to a value of 0.255 for the whole station. A value of 0.255 is within the range reported here, but it corresponds to a 99.998% confidence level. Since this is a manned system, this may be the appropriate confidence level. However, *that is the whole point of this research. Degrees of conservatism can be quantified.* The confidence level approach developed here is one way of doing that. When lives and dollars are at stake, the additional analysis can help avoid overly conservative designs for one component or sub-system, at the risk of underfunding another less conservative one. Since the conservatism in the analysis reported was not stated, the 0.255 has to be compared with the 0.0658 reported here. There is a significant difference if they are both meant to represent the same risk. It is likely that this calculation would be lower due to the reduction in explosion frequency, but how much is difficult to say.

Finally, comparing the results developed here with "Comparison of Space Debris Estimates" (Canavan, 1996c), leads to the conclusion that the two documents are consistent. A comparison of Figures IV.1 and IV.2 with Figure 13 of that report indicates trend agreement. The main thrust of that report was to demonstrate the weakness of the cascade theory under detailed quantitative analysis. No cascades were observed in this work, and collisions, while they did occur, did not dominate the debris field. Based on this observation for the twenty year time period analyzed, this effort is consistent with "Comparison of Space Debris Estimates".

V: CONCLUSIONS

V.1: Discussion

The objective of this research has been accomplished. A significant environmental problem was analyzed from an uncertainty standpoint and the uncertainties quantified. The problem was limited to the impact of LEO space debris on the International Space Station. This problem was well enough defined that a quantitative approach could be taken. The major uncertainties were explored and the Latin Hyper-Square technique was used to investigate the effect of these uncertainties on the estimates of the risk to the ISS from small untrackable debris.

These risks and their associated uncertainties appear to be within the guidelines currently being used for the design of the ISS if the mean or expected values are used. If a more conservative approach is desired, then some additional action is probably required. The most obvious action that should be taken is to increase the pressure on all space faring nations to safe their upper stages by venting remaining fuel at the end of their useful operations. Satellites should also be safed by purging remaining fuel supplies and venting any batteries that have an explosion potential. The operational cost of these measures should be insignificant if they are planned for in advance.

Deorbiting of dead satellites and rocket bodies is another possible action that has been suggested.(OSTP, 1995) It is not clear whether this is required at this time, or is truly a reasonable approach. Specifically, the requirement to deorbit at end of life could have a significant weight penalty associated with it. Up to 20% of the initial satellite weight might have to be dedicated to the propellant reserve required to accomplish this maneuver if very stable propellants are used. This opens the question of how stable the propellants would have to be, and the explosion potential that they will bring with them during the time they are on orbit. A better approach might be to develop a tug system that could capture dead satellites and deorbit them into the ocean. (OSTP, 1995) This would not work of course, if there were not enough dead satellites in space to achieve some kind of economy of scale. The dead satellite population has to grow enough to make this a reasonable solution.

V.2: Suggestions for further work

Any reasonable research effort generates more questions than it answers. Some important ones raised here that should be investigated further are,

1) a study of how risk is quantified in various space activities, and a quantification of the uncertainty in other risk estimates,

2) a better understanding of the fragmentation process as it occurs on orbit,

3) a better understanding of the risk to the ISS from debris at different inclinations,

4) and, what are the details of the space debris population as it evolves under more specific scenarios.

The approach outlined here estimated the risk to the ISS of impact by 1-10 cm particles during the period 2000-2015 under the assumptions of a stable civil and military launch program and a fairly aggressive commercial launch program. Other detailed scenarios need to be investigated and this one needs to be expanded. The ISS is a major financial and psychological undertaking for the major space faring nations of the world. A better understanding of what is at risk will be important in the future as problems develop. Space debris can not be ignored, but it is also not going to stop all space operations anytime soon.

It would appear that the most uncertain process that produces debris in the size range of interest for this problem is the explosion fragmentation event. There have only been four real experiments (the Atlas test and Fucke's tests) that can provide data for this problem. Additional experiments would be useful. It is also possible that numerical modeling on the computer could be useful. Based on the work of Fucke (Fucke, 1993), the size distribution of particles generated in an explosion peaks in a range that could be modeled on current computer platforms. The problem of numerically modeling explosions has always been one of getting a small enough mesh to track all of the particles. The development of smooth particle hydrodynamics and very large memory machines may make this a solvable problem. (Allahdadi, 1994) If numerical techniques could be demonstrated, they could also be applied to investigating fragmentation events observed on orbit. This would be a very useful diagnostic tool. Further work is indicated.

The last two recommendations have really to do with better predicting the discrete flux on a spacecraft as it orbits the Earth. The current methodology is based on one that was developed by Kessler (Kessler, 1991a) with reference to Jupiter's moons. It smoothes particle distributions over inclinations and eccentricities. This is a relatively gross approximation but good enough for preliminary estimates. It can be improved as we become more interested in debris belts and have larger computers at our disposal.

However, we will also need a laboratory for validating our results. Once again we can turn to the scientific space exploration that NASA has pursued from its inception. Currently the Galileo probe is in orbit about Jupiter and the Cassini probe to Saturn will be launched in the fall of 1997. These two planets are really our laboratory for studying multiple satellites about a central massive body. Newton solved the two body problem, but the three body problem including the Moon into the Earth-Sun system gave him real headaches. He eventually solved it because he had a lot of data. Jupiter and Saturn are our data for the long term evolution of debris fields. The rings of Saturn are the best known debris field in the solar system. Certainly we can learn more about long term behavior of space debris near the Earth by studying the makeup of Saturn's rings. The data will allow us to test our models and develop new ones. We will never be able to control everything that is released in near Earth space, so we better understand what happens to it. Future investigations are warranted.

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APPENDIX A: LATIN HYPER-SQUARE SAMPLING

Latin Hyper-Square sampling is an improved method for tracking uncertainty and variability through a mathematical model. It is very general and particularly applicable to analyzing large scale computer models. The object of applying Latin Hyper-Square (LHS) sampling to predict uncertainty or variability in a particular case is to be able to estimate the uncertainty or variability in a predicted value given the uncertainty or variability in the parameters and inputs that are used in the model. (To simplify terminology slightly, it is best to explain the difference between uncertainty and variability. Variability is a property of a phenomena that is random in nature. An example would be the value of a future weather parameter such as the direction of the wind. Uncertainty is a lack of knowledge of a quantity that could be very precisely specified, but measurement difficulties preclude knowing it exactly. An example would be the early measurements of the speed of light in vacuum. Both phenomena will be lumped under the concept of uncertainty in what follows.) Computers have allowed us to deal with great masses of data and draw many detailed relationships. We are able to analyze better, but when we finish our analysis, it is often difficult to tell how sensitive the final answer is to the inputs and parameters chosen along the way. Often it seems that we need a whole new analysis, or program, to understand the basic analysis. The major advantage of LHS is that it allows us to estimate uncertainty with the same tools that we use to make first order predictions without a great deal of new programming. It is also relatively fast and conserves computing and programming resources.

Before the age of large scale computer modeling, it was relatively easy to estimate the uncertainty in a calculated or derived value. One simply took the equation that predicted a derived value and took partial derivatives with respect to any of the uncertain inputs or parameters in the equation. The uncertainty in the final value could be computed by multiplying the partial derivatives times the uncertainties in the parameter values, squaring the result, adding up all such "sensitivities", and taking the square root of the final sum. Consider the equation for Ohm's law.

$$E=IR$$

This equation can be used to predict the voltage, E, at the output terminals of a resistor, R, by measuring the current, I, flowing through the resistor. As a concrete example consider a resistor of 10k ohms and a measured current of 0.5 milliamps. This would give a nominal output voltage of 5 volts. Now if the exact value of the resistor varies as a normal distribution about 10k ohms with a 5% standard deviation for its variability, and we are only able to measure the current to 0.1 milliamps accuracy, we would like to know how well we can specify the voltage across the resistor. The partial derivative of E with respect to I is R and the partial derivative of E with respect to R is I, so the following equation would express the variance in E based on the variability in its measured parameters,

$$\mathrm{Var}(E) = [(I)(s_R)]^2 + [(R)(s_I)]^2 = [(0.5)(1.0)]^2 + [(10)(0.1)]^2$$

$$\text{Uncertainty In } E = [\mathrm{Var}(E)]^{0.5} = 1.12 \text{ volts}$$

Or the uncertainty in E is about 1.12 volts out of 5.0 volts, roughly a 20% effect. This a simple example of uncertainty propagation from the input, I, and the parameter, R, to the final estimated quantity, E. This is exactly what LHS allows us to do for much more complicated and sophisticated mathematical models.

To apply the LHS method to a specific computer model, we begin by identifying the parameters and inputs on which the model depends. Typically an input will be a value that the computer takes from an input stream that is specified at the time of execution. A parameter is a value that the code uses in its calculations that may have been determined empirically. The uncertainty in the final answer depends on the uncertainty in both types of values. (For the purpose of LHS there is very little difference between parameters and inputs, so the term inputs will be used from here on.) For each defined input, a probability distribution is developed that specifies the likeliness of particular values for the input. This distribution can come from measured data, or it can be developed by consulting with experts in the phenomenology of interest. The current version of the LHS code can handle a variety of distributions from normal, beta, or log-normal to constant or triangular. The LHS code itself simply keeps track of probabilities in a consistent manner.

Once the important inputs have been specified, and their distributions determined, the total number of sample cases to be analyzed is established. The number of sample cases analyzed should be at least 1.4 times the number of inputs identified as uncertain. The number 1.4 is a good rule of thumb developed over the years. It is probably low if there are few inputs to vary, and it is conservative if there are a lot of inputs to vary. If the number of predicted sample cases is in the range of 20 to 30, reasonable results can be expected. As an example consider a case with 15 uncertain inputs. The minimum number of cases, or problems, that would have to be run to get some estimate of the uncertainty in the answer, would be 21. The LHS code is the used to define the values of the inputs to be chosen for the 21 cases to be calculated. Each probability distribution, for an input of interest, is divided into 21 intervals of equal probability, or likelihood. A value is assigned for each of these 21 intervals. It could simply be the equal probability mid-point of each interval, or it could be randomly chosen somewhere in the interval. Using a mid-point value is probably more accurate, but the current LHS code chooses a random point within the interval. This allows the code to keep the aura of a semi-Monte Carlo analysis. The 21 input cases are assembled by choosing one of the 21 values for each of the 15 inputs. Each value for an input is chosen once and only once. The are combined in a random or uncorrelated fashion.

Once the 21 cases have been developed, the calculations are run. This means that to get an estimate of the uncertainty in the final answer produced by a computer model with 15 uncertain inputs, it will be necessary to run 21 similar calculations. This could require a significant amount of labor. However, this labor is fairly repetitive and uses the same code or model that is used for the base analysis. The alternatives are to run either a truly random Monte Carlo analysis or some sort of a factorial design. Both approaches have been shown to require significantly more effort to achieve comparable accuracy. For example, a factorial design would require combining each of the values of the input variables with a value of each of the other input variables. If the probability range of each input variable were divided in half and a value from each half chosen to combine with each of the other variables, 2^{15} (32,768)calculations would be required to perform the full factorial design. A partial factorial design might be possible, but selecting which cases to throw out can be very difficult and always biases the answer. The Monte Carlo approach converges so slowly that it does not generally compete with a more direct LHS approach.

The other alternative is to perform some additional calculations with a modified code. The problem here is that there are no general approaches to modifying a code to get an uncertainty estimate. If all of the models are linear in the code, adjoint or Green's function methods can work. Fourier analysis can also be applied or linear ranges of performance for some models. However, for highly non-linear models, there is no rigorous basis for applying these methods. In general, the uncertainties depend on the base case path chosen for analysis. The requirement to program for each case also probably introduces more uncertainty than desired with any of these methods. Thus, the LHS approach does require more work to get an uncertainty estimate, but the work is rather straight forward, and the LHS computer program performs the book keeping problem associated with setting up the calculations quite easily. The code itself runs on nearly any version of the IBM PC with a FORTRAN compiler and requires an insignificant amount of time to setup and run.

After the required number of calculations have been run, the results are analyzed and can be presented as a cumulative distribution function for the output variables of interest. There are a large number of other ways that the results of the calculations can be analyzed, but this approach is the one of most use here. The resulting cumulative distribution function allows the analyst to put a known amount of conservatism in the risk levels chosen for design. It also can be used to suggest areas for research investment to reduce uncertainty and improve risk estimates.

Before providing a simple example, it should be pointed out that the LHS method was developed at Sandia National Laboratories for understanding uncertainties in physical phenomena that could not be measured experimentally. It has been successfully applied to nuclear reactor accident modeling and to radioactive waste migration in underground reservoirs. Phillips Laboratory is currently using it to analyze the uncertainties associated with high energy laser-material interactions. It is a tool with a growing number of applications. It allows us to use very sophisticated computer models to predict physical phenomena, and to understand the accuracy of the prediction when the calculation is complete. Numerous applications are discussed in the report literature.

Consider now a very simple case. Let us toss 15 coins and count the number of heads that occur in each toss. The exact answer for the number of heads is given by the binomial distribution. To exhaustively enumerate all cases would require 32,768 cases. However, let's try to estimate the cumulative distribution function for the fraction of time that a specified number of heads, or less, are obtained. The cumulative distribution function is the integral of the binomial distribution function and is normally the form that LHS out puts will be used.

To approximate this problem with the LHS method, we will chose 21 calculations or experiments. Since there are only 2 outputs possible from a given coin toss, we can create a continuous distribution by choosing the interval from 0 to 1.0 and sampling randomly. If the value obtained is greater than 0.5, it will be considered a "heads", if it is less, it will be considered a "tails". So for each coin the interval 0 to 1.0 is divided up into

21 sub-intervals. Each sub-interval is chosen once for one of the 21 sample cases. The sub-intervals are randomly mixed for each coin. This gives 21 tosses of 15 coins.

The results of one trial of this LHS experiment are presented in Figure A-1.

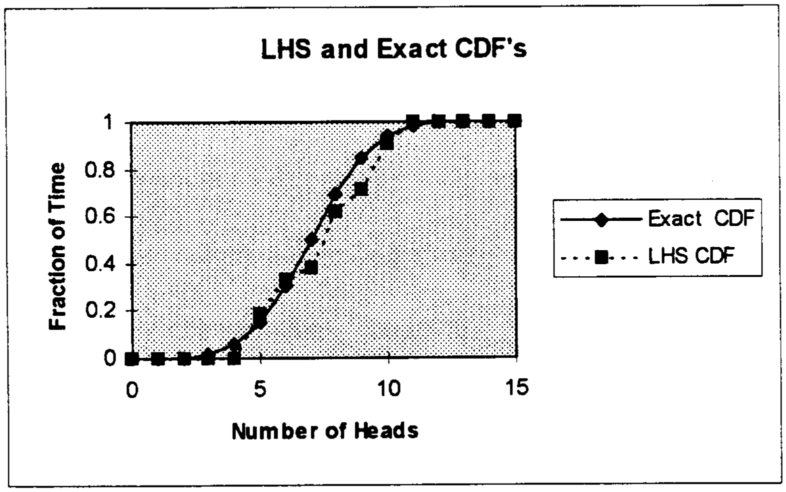

Figure A-1: LHS and Exact CDF's

The cumulative distribution functions plotted in Figure A-1 are for the number of heads in the flipping of 15 coins. That is, the probability plotted on the vertical axis represents the probability that N or less coins are obtained in 15 tosses. Another way of saying this is that no more than N heads are obtained in 15 tosses. It is obvious from the plot that the LHS distribution function tracks the exact distribution function very closely. In fact if the chi square test is applied to the two distributions, a value of 0.154 is obtained for the chi square variable with 15 degrees of freedom. There is a probability of less than 1 part in 10^4 of obtaining a fit this good. If the probability distribution functions are compared, rather than the cumulative distribution functions, a value of chi square of 0.503 is obtained. This is also an excellent fit.

This example demonstrates that the LHS methodology can obtain a very good approximation to the actual cumulative distribution function for this case with a small number of calculations or experiments. It is only one example and doesn't prove a thing. But this type of result has been obtained over and over again in the many areas that LHS sampling has been applied. Quite simply, this is the justification for applying it here. (Of course if you suspect that the classic law of large numbers is operating here, you are probably correct. Unfortunately it is difficult to develop a general proof that quantifies how accurately the LHS cumulative distribution functions match the real world.)