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**A STOCHASTIC METHOD FOR CALCULATING SPACECRAFT
VULNERABILITY TO LOW EARTH ORBIT DEBRIS**

by

Michael Edward Elvidge

B.Eng. (Aerospace Engineering)

A thesis submitted to the Faculty of Graduate
Studies and Research in partial fulfillment
of the requirements for the degree of
Master of Engineering

Department of Mechanical and Aerospace Engineering
Ottawa-Carleton Institute for
Mechanical and Aerospace Engineering
Carleton University
Ottawa, Ontario
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A handwritten signature in black ink, appearing to read "K. Goheen", written over a dotted line.

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Dr. K. Goheen

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ABSTRACT

Beginning in 1990, the Canadian Space Agency conducted a series of studies in order to determine the probability of survival of the RADARSAT spacecraft, due to be launched in 1995. It was found that the artificial debris environment predicted would pose an unacceptable risk to the vehicle. Therefore, a review was conducted of current methods of estimating the survival of spacecraft in a debris environment. This revealed that the current methods used to calculate the result of hypervelocity impacts are very conservative. The present study was conducted in order to develop a more accurate method for determining shielding requirements and component vulnerabilities.

Many of the previous estimates of the probability of critical satellite damage had relied upon unnecessarily conservative assumptions. Therefore, a method which applied solid modelling was used. Spacecraft components and shielding were modelled and then a series of simulated impacts were generated to determine component and overall vulnerability. The impacting particle and the resultant debris was modelled using cones centred around the particles path. The estimated vulnerability was significantly less when solid modelling was used, than determined previously, since this allowed for the elimination of some of the heretofore standard assumptions.

Component vulnerabilities were determined and used to identify the most vulnerable components and to suggest some changes that could be made to the current

configuration of RADARSAT. The software developed is applicable to any kind of orbiting vehicle.

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Chapter 1 : Introduction & Literature Review

1.1 Introduction

The survivability of a spacecraft depends both on the reliability of the various components and the environment to which the spacecraft is exposed. One of the primary environmental considerations in early spacecraft was the presence of meteoroids. This led to the use of shielding to protect components from incidental collisions. The probabilities of encounters with meteoroids of a significant size in earth orbit is extremely small, however, and therefore, any damage caused was only surface erosion from very small particles.

Over the last thirty years the amount of space activity has led to the creation of a significant debris environment in orbit around the earth. In low earth orbit (LEO), the danger of the artificial debris environment has far surpassed that of the natural meteoroid environment. Therefore, it has become necessary to develop methods of estimating this small particle environment, since only objects of size 10 cm or greater are currently being tracked. The danger of artificial debris has also required the development of advanced shielding techniques to protect critical components.

Estimating the particle density of debris in various orbits for small untrackable debris has been a difficult task. Most current estimates are only reliable to within a factor of two or three, due to the almost entirely stochastic analysis involved. Efforts are currently being made to enable tracking of smaller particles, especially in LEO in order to reduce this uncertainty.

As the probability of a long duration spacecraft colliding with space debris of the magnitude of 0.1 millimetre diameter or greater increases, simple single shields become less and less suitable. Shielding an entire spacecraft with a thick enough material to stop penetration by any remotely possible particle size leads to unacceptable weight increases. Therefore it has been necessary to examine more advanced shielding concepts. This has led to the development of the Whipple shield and multi-bumper shielding concepts, which are described in detail in the subsequent sub-section on shielding. These allow for adequate protection at greatly reduced weight cost but with obvious increased complexity.

1.2 Literature Review

1.2.1 Environment

The debris environment in earth orbit consists of two components which can be superimposed. The natural meteoroid environment consists of interplanetary debris which passes through earth orbital space at an average speed of 20 km/s. Observational data indicates that at any one time there is approximately 200 kg of meteoroid mass within 2000 km of the earth's surface. Most of this mass is made up of 0.01 cm meteoroids with equal amounts of larger and smaller particles. The exact amount of meteoroid mass varies as the earth orbits the sun [US Intragency 1989, Kessler 1989].

Artificial debris differs from meteoroids in that it is not transient but remains in earth orbit until its orbit decays enough for reentry or burning in the upper

atmosphere. It is estimated that there is more than 3 000 000 kg of artificial orbiting objects within 2000 km of the earth's surface. Most of this mass is contained in more than 3000 spent rocket stages and in both active and inactive satellites. About 40 000 kg is contained in another approximately 4000 objects of 10 cm or greater diameter [US Intragency 1989].

Most of the smaller trackable objects are due to over 130 recorded on-orbit breakups, primarily due to explosion of spent rocket stages. The rate of on-orbit breakups has been significantly reduced in recent years by using up all rocket stage fuel to reduce the likelihood of explosion. These on-orbit breakups also produced a great number of particles under 10 cm in diameter. These particles are untrackable, so a great deal of estimation is involved in defining this portion of the artificial environment. Ground telescope measurements and analysis of hypervelocity impact pits on returned surfaces of satellites have indicated an approximate mass of 1000 kg for orbital debris sizes 1 cm and smaller and approximately 300 kg at sizes less than 0.1 cm. This orbital debris is mostly at high inclination angles and passes most operating LEO satellites at between 10 and 15 km/s [US Intragency 1989, Kessler 1989]. It is readily apparent therefore that the artificial debris environment poses a much greater threat than the meteoroid environment at altitudes of less than 2000 km.

Another difference between the natural and artificial environment is that the meteoroid environment tends to have a more even distribution while there are concentrations of artificial debris in certain orbits. This is due to the popularity of these orbits and altitudes. Considering only the trackable debris flux, one can find

peak debris concentrations at altitudes of 800 km, 1000 km and 1500 km [Kessler 1990].

Mathematical models have been used in an attempt to predict the uncatalogued population [Kessler 1990]. Two types of breakup mass distributions were examined and compared to an upper limit which assumes that all of the fragment mass goes into some preferred size. Both the Atlas missile explosion and a hypervelocity test show most of the mass going into particles just over 10 cm in size. The Atlas missile explosion showed very little mass going into 1 mm to 1 cm fragments. However, the hypervelocity impact test showed a significant fraction of the mass also went into 1 mm to 1 cm fragments. By fitting these breakup patterns to known satellite breakups due to explosion or collision, the uncatalogued population can be predicted. This method of prediction indicates, however, that the actual 10 cm population is twice the current tracked population.

In order to reduce the uncertainties in the debris population, NASA began sponsoring a program of telescopic observations of orbital debris in 1984. These observations to date have indicated a population of 5 cm debris five times the tracked population. They have also indicated that there are twice as many 10 cm objects in orbit as are currently tracked, and that some objects as large as 1 m are not tracked. The potential error with these figures is that objects often appear brighter as they pass through the telescopic view causing them to be recorded as a larger object. By taking the measured brightness of satellites with known radar cross sections, the probability of an object appearing optically larger was determined. It was found that 50% of

objects will appear at least as large as they actually are with up to 2% appearing as much as 5 times larger [Kessler 1990].

Another method of reducing uncertainty, which is currently used, is to analyze the pitting observed on returned spacecraft surfaces. To date the best data has been from the recovered Solar-Max surfaces [Zook 1990] and from the LDEF [Kinard 1990]. Information from the Solar-Max satellite was provided by the 1984 return of approximately three square meters of surfaces which were exposed to space for 4.15 years. The analysis of holes found in the thermal blankets and aluminum louvers of the returned Solar-Max has contributed to estimates of the current environment. This analysis also indicated that the debris flux dominated the total particle flux at sizes below 0.01 mm due to aluminum oxides derived as exhaust effluents from solid rocket motors [Zook 1990]. Meteoroids dominated the 0.03 mm to 0.2 mm particle impacts by about a factor of four. An extrapolation of the data would seem to indicate that debris dominates the particle flux for sizes larger than 1 mm [Kessler 1990].

A second contributor to current collision rate data is the LDEF experiment. The LDEF is a 12 sided, 15 foot diameter, 30 foot long aluminum frame designed to transport experiments to and from space via the Space Shuttle. Eighty-six trays, each approximately 4 feet long and 3 feet wide and anywhere from 3 to 12 inches deep were attached externally to the 12 sides and two ends of the frame to record impacts. One end of the LDEF always pointed towards the centre of the earth while in orbit, while at any given time one of the twelve sides always pointed in the direction of flight. The LDEF was deployed in an orbit of 260 nautical miles at an inclination of

32 degrees on April 7, 1984 with the initial intention of retrieving it in one year. However, due to problems with the Space Shuttle program including the Challenger accident, the retrieval was delayed by almost 6 years. At this time the orbit had decayed to an altitude of 180 nautical miles. Upon examination, more than 5000 visible impact craters were documented in sizes ranging from about 0.5 mm to 5 mm. There were also tens of thousands of smaller craters which will be studied at a later date. The active Interplanetary Dust Experiment on LDEF recorded the direction and precise time of thousands of impact events [Kinard 1990]. This information will be very significant in establishing more accurate estimates of the present debris environment and will also provide information on interplanetary meteoroids.

Estimates of the current debris flux in the 1 mm to 10 cm range were obtained by a combination of modelling and an extrapolation of Solar-Max and ground telescope data [Kessler 1990]. This is the size range about which the least is known and yet, it is the most significant. Smaller debris sizes produce mostly surface erosion although 0.1 mm to 1 mm particles can cause pitting or more serious impact damage. The 1 mm to 10 cm size range, however, will cause serious impact damage or even catastrophic damage [US Intragency 1989].

The environment given by Kessler in NASA Technical Memorandum 100 471 [Kessler 1989] was based on an extrapolation of current Solar-Max and telescope data. Tests run to measure the flux between 0.2 cm and 2 cm agreed with this proposed environment within the errors of measurement [Kessler 1990]. An estimate of the cumulative flux of orbital debris of size d and larger on a given spacecraft may be

made using the following formula [Kessler 1989]:

$$F(d,h,i,t,S) = k \cdot \Phi(h,S) \cdot \Psi(i) \cdot [F_1(d) \cdot g_1(t) + F_2(d) \cdot g_2(t)] \quad (1-1)$$

where

F - flux in impacts per square meter of surface area per year

k - a factor which depends on spacecraft orientation: it is 1.0 for a randomly tumbling surface

d - orbital debris diameter (cm)

t - year (e.g 1995)

h - altitude (km): $h \leq 2000$ km

S - solar activity for the previous year: 13-month smoothed 10.7 cm-wavelength solar flux (10^4 Jy)

i - spacecraft orbital inclination (degrees)

and

$$\Phi(h,S) = \Phi_1(h,S) / (\Phi_1(h,S) + 1)$$

$$\Phi_1(h,S) = 10^{(h/200 \cdot S/140 - 1.5)}$$

$$F_1(d) = 1.05 \times 10^{-5} \cdot d^{-2.5}$$

$$F_2(d) = 7.0 \times 10^{10} \cdot (d + 700)^{-6}$$

p - the assumed annual growth rate of mass in orbit

$$g_1(t) = (1 + 2p)^{(t-1985)}$$

$$g_2(t) = (1 + p)^{(t-1985)}$$

The function Ψ , which is inclination-dependent, is a ratio of the flux on a spacecraft with an inclination of i to the flux on a spacecraft with an inclination of 60 degrees. 60 degrees is used because it is the current population's average inclination. An average solar cycle lasts 11 years and has values of S which range from 70 to 150.

The above flux is defined such that the average number of collisions N which occur between orbital debris and a spacecraft surface area exposed to the environment for a given duration is given by the following formula [Kessler 1989]:

$$N = \int_{t_i}^{t_f} F \cdot A \cdot dt \quad (1-2)$$

where A - is the surface area exposed

F - is the flux

t - is the time (year)

Kessler's environment, and tests run to measure the flux between 0.2 cm and 2 cm, suggest uncertainties of a factor of 3 on 2 cm flux, and a factor of 2 on 0.05 cm flux at an altitude of 500 km. Other sizes and altitudes are based on interpolation between these "known" values and mathematical modelling of known breakups. There are, however, no data which precludes the flux of particle sizes between 0.05 cm and 2 cm from being as high as the 0.05 cm flux, or as low as the 2 cm flux or anywhere in between. This allows for the flux in these size ranges to vary by as much as several orders of magnitude [Kessler 1989].

Additional uncertainties arise because there are no measurements of debris of sizes 2 cm or smaller anywhere other than at the 500 km altitude. The large number of breakups at altitudes between 700 km and 1000 km and at 1500 km, together with the long orbital lives at these altitudes, make predictions sensitive to the nature of these breakups. These uncertainties also lead to a model which gives flux at the 800 km and 1000 km altitudes as half that provided by U.S. Space Command data [Kessler

1989]. In the 1000 km to 2000 km altitude range the model overpredicts flux as provided by U.S. Space Command data from objects tracked. However, it may be that the collisions at the 1500 km altitude have spread many smaller fragments over this region [Kessler 1989].

In order to estimate the future environment, necessary for the design of any spacecraft with a long duration future mission period, many factors must be considered. These factors include future traffic, satellite fragmentation rate, and solar activity. Even if these were known, there may be some unmodeled sources of debris which are important. Based on past accumulation rates of tracked debris and an average solar cycle and plans by the US, European Space Agency(ESA) and China to increase their launch rates, a 5% to 10% per year increase in mass in LEO is expected [Kessler 1990]. Mathematical modelling suggests that the amount of mass in the 1 cm and smaller sizes will increase at twice the rate as the accumulation of total mass in Earth orbit [Kessler 1989].

In defining the debris environment in LEO, two other important pieces of information which are required are the velocity and directional distribution of the debris particles. The impact velocity and direction distribution of collisions are primarily functions of the orbital debris inclination distribution. This in turn is a function of time and altitude, and can change substantially as the result of a single breakup at any particular altitude. Since future breakups and their orbits are unpredictable the most important variable in determining the velocity and direction distributions of collisions with a given spacecraft is its orbital inclination. However,

the velocity distribution will still change with time and position in space affecting the average velocity from the distribution by several km/s [Kessler 1989].

Orbital debris is assumed to travel in circular orbits though this is not exactly true. However, the small eccentricity of these orbits only causes uncertainties of the order of 1 degree in direction and is virtually negligible with respect to velocity distributions. For low velocities (under 2 km/s), the uncertainty in direction can be as high as 20 degrees. This error in direction can be in the local horizontal plane or above or below this plane. High velocity impacts nearly always occur in or near the local horizontal plane and from the downrange direction. Low speed collisions may occur at any angle in the horizontal plane as well as at sizeable angles out of that plane.

The Johnson Space Centre(JSC)/NASA has developed a program, EVOLVE, to simulate the evolution over time of the debris environment in LEO, from the beginning of the space age in 1957, to an arbitrary point in the future, typically the year 2010 [Ojakangas 1990]. This date is commonly chosen since it covers the mission life of any earth orbiting vessel currently in use or being designed. The program uses historical space traffic and specific mission models of future traffic as input in order to model the future environment. The model treats intact objects and debris clouds as separate components of the environment. Intact objects are introduced using historical and mission model data. Debris clouds are created deterministically by historical or projected traffic data or stochastically by explosions or collisions [Reynolds 1990]. The program operates in discrete time steps,

organizing altitudes and particle sizes into discrete units called 'bins' [Ojakangas 1990]. A Monte Carlo method is used to determine the characteristics of future environments. (The Monte Carlo method is a way of solving a mathematical problem by constructing a random process such that the parameters of the process are equal to the required quantities of the problem. These quantities are found approximately by observing the random process and computing its statistical characteristics which are approximately equal to the required parameters [Schreider 1966]. For example, the Monte Carlo method of determining the probability of rolling a two numbers which sum to seven with a pair of dice would be to roll the dice repeatedly keeping track of the number of sevens rolled. After a fixed number of rolls the number of sevens rolled would be divided by the total number of rolls. If enough rolls are made a very accurate result may be obtained.)

Since the EVOLVE program begins using historical traffic from 1957, a check on the model is possible by comparing EVOLVE's predictions of the current environment to observed characteristics [Reynolds 1990]. This also gives an estimate of smaller unobserved particle bins for the current environment.

The EVOLVE program was run for the period from 1957 to 1989, with known historical traffic and on-orbit explosions as input. Projections of the future environment were then made for the period of 1990 through 2010 assuming that traffic launch rates were comparable to the 1980s. This was done for three different cases. The first case assumed that on-orbit explosions would continue at the observed historical rate. The second and third cases assumed a reduction in explosions by a

factor of three and an elimination of explosions respectively. The debris flux projections produced clearly show that, with the historical explosion rate, mass will continue to accumulate in the 1 mm to 10 cm size range at a significant rate. It is also clear that reducing the number of on-orbit explosions will greatly reduce the rate of accumulation leading to a safer future environment [Ojakangas 1990].

The reduction of on-orbit explosions is a significant factor in controlling the future environment but it is also necessary to consider the effect of incidental collisions. A single catastrophic collision between an orbiting debris particle and a large satellite may produce hundreds of 10 cm particles [Eichler 1991]. Mathematical modelling suggests that in the near future, random collisions could become an important cause of satellite fragmentations. Under these conditions the small debris population would increase at twice the percentage rate of the large population, until a 'critical density' is reached. Once the critical density is reached the number of small particles will increase very rapidly. It is thought that the critical density of large objects is between 10 and 100 times the 1985 population [Kessler 1989]. It is conceivable that if the critical density is reached the accumulation of debris in the 1 mm to 10 cm size range will be such that a debris belt could be formed such that spaceflight activities could become impossible for several centuries - at least in the near earth environment [Eichler 1991].

The circumstances which may lead to the formation of such a belt are as follows. As the population of 10 cm particles increases the probability of these particles colliding with one another or catastrophically with smaller particles increases

significantly. This eventually could lead to a chain reaction of collisions. To examine this possibility a program, CHAIN, was developed at the Institute for Space Technology and Nuclear Reactor Technology of the Technical University of Braunschweig [Eichler 1991]

The CHAIN program divides the current population and collision risk into six mass ranges, 21 collision types and four altitude regions. Using a step size of one year the program consists of an analytical part and a stochastic part. The analytical part calculates the collision risk of the respective population using analytical formulae. The stochastic part simulates fragment generation by triggering collisions using a Monte Carlo method corresponding to the respective collision risks.

The important results achieved through the use of this program show that a chain reaction of collisions may not be far in the future and that this chain reaction may be 'invisible'. Due to the limitations on what can be and is being tracked by the U.S. Space Command, collisions will mostly produce a large amount of small untrackable debris. Also, in some cases one or even both of the colliding objects may not be large enough to be among the tracked population. This could hide the chain reaction of collisions which will lead to an exponential increase of the number of fragments. At some high risk orbits (e.g. 800 km) the critical population for a chain reaction of collisions may be very near the current population. If spaceflight activities are continued as in the past the critical population at these orbital altitudes will certainly be reached in 20 to 50 years [Eichler 1991].

The threat of a chain reaction indicates a need to reduce the accumulation of

debris, especially in high traffic orbits, and even to clean up some of these orbits. To reduce the accumulation of debris many simple steps can be taken. Items such as lens covers which are traditionally discarded may be retained so they do not become independent hazards. Pin pullers can be used instead of cable cutters again eliminating a traditionally discarded item. Circuit protection can be provided to protect batteries from short circuits which may cause them to rupture. Upper stages can be vented as is done for the Centaur and Ariane stages. The Delta second stage is burned to depletion after placement of payload and execution of the collision avoidance manoeuvre. Some Japanese upper stages provide an idle mode for depletion of propellants after payload separation. Using up excess propellants reduces the risk of on-orbit explosions. Controlling the time of launch of geosynchronous satellites will allow for reduced perigees and therefore reduced lifetime of upper stages used for geosynchronous transfer [Loftus 1991].

Active measures to remove current debris which could be applied include active or passive debris sweepers. A large foam ball could be placed into orbit and could act as a passive sweeper while a laser mounted on a satellite could actively shoot down debris. Large objects could be collected and removed by the Space Shuttle. In future, satellites could be designed with methods of de-orbiting after completing their useful life. This could include the use of tethers or solar sails or propulsion de-orbit motors [Eichler 1991, Loftus 1991].

As efforts are continued to reduce the accumulation of debris, and to catalogue in greater detail the nature of the current and future debris environments, confidence

in the survivability of spacecraft will grow. Currently spacecraft are designed to survive collisions with only very small particles under the belief that even a strike by a 1 mm particle for most missions is highly unlikely. This appears presently to be the case, however, this may quickly change if the problem of increasing debris is not addressed before it becomes worse.

1.2.2 Spacecraft Shielding Techniques Against Natural and Artificial Space Debris

At the start of the Space Age, the only consideration in the design of spacecraft protection was the natural meteoroid environment. This environment consisted mostly of very small particles in the range of 0.1 mm diameter [US Intragency 1989]. This size of particle primarily causes surface erosion which at low altitudes can reach a rate of 20 nm/year. In order to protect early spacecraft from this environment, only simple single wall coverings were required. It was not long before dual wall or Whipple shields came into use, with this method of protection being used and evolving throughout the Apollo Program [Cour-Palais 1969]. The most modern concepts now proposed include multi-shock shielding, and are often designed using geometric programming and optimization [Mog 1990].

The single wall is usually simply the unprotected outer skin of the spacecraft. The double wall has become the classic method of protection while the triple or multi-shock walls are more modern concepts. The single wall is the heaviest but it is the

simplest to apply and the best understood concept. As the number of walls increases not only does the complexity of wall design increase but our understanding decreases dramatically because of the number of parameters which need to be investigated.

There is a certain limit on the understanding of all of the concepts given the limitation on velocity of current test facilities [Reimerdes 1991]. Currently hypervelocity tests use gas guns, and are limited to a velocity of 7 km/s [Crews 1992].

For single wall protection, many formulae have been developed based on particle mass, density and velocity to predict the crater depth caused by a hypervelocity impact. The most commonly used formula for spacecraft design is:

$$p_{\infty} = K_{\infty} m_p^{0.352} \rho_p^{1/6} v^{2/3} \quad (1-3)$$

where:

p_{∞} - crater depth in a semi-infinite plate [cm]

m_p - particle mass [g]

ρ_p - particle density [g/cm³]

v - velocity [km/s]

K_{∞} - a constant developed from testing

K_{∞} is dependent on the target material. For aluminum alloy it is taken to be 0.42 [Reimerdes 1991].

For a thin plate, the modified formula for target thickness is:

$$t = k p_{\infty} \quad (1-4)$$

If k , the ratio of target thickness to crater depth, is greater than 3 there should be no spallation on the rear side. Above $k = 2.2$ the spall should not detach and above $k = 1.8$ spallation will occur but not perforation. These formulae are based entirely on

test data, and due to size and velocity limitations on test equipment extrapolation of these formulae for debris collisions at higher velocities and masses may result in incorrect results [Reimerdes 1991].

The efficiency of the Whipple dual wall concept arises from the fact that the incoming particle is destroyed upon impact with the shield, or first wall. The fragments heat up and may even melt or vaporize. The resulting debris cloud of particles, droplets or vapour expands and therefore hits the second wall over a greater area. In this manner the load can be defeated without serious damage to the second wall, less damage than might be caused by a solid particle. The Whipple shield is most effective against high velocity impacts since the higher velocity leads to higher impact energy leading to particle melting or vaporization. Against slow moving particles little breakup of the initial particle will occur upon contact with the shield. The dual wall concept is most efficient when average particle impact velocities are of the 7 to 9 km/s range. At these velocities the total wall thickness of the double wall concept can be reduced to about 20% of that of a single wall design [Reimerdes 1991].

If the same material is used for both wall and shield then the main parameters influencing the efficiency of this sort of design are the particle velocity and the ratio of shield thickness to particle length. Another important factor is the distance between the wall and shield. In order for a particle to be destroyed, a certain pressure must be achieved which occurs during collisions above a certain velocity. For aluminum this occurs at about 3 km/s and below this velocity the first wall(bumper) is almost

completely ineffective. Efficiency drops off rapidly if the shield thickness to particle diameter becomes too small because part of the particle will remain solid and intact if the shield is too thin [Reimerdes 1991].

Once again many equations have been developed from test data for this type of shield design. The double wall shield must differentiate between three regimes and treat each separately. First is the ballistic region, below 3 km/s, followed by the shatter region, followed in turn by the hypervelocity region of greater than 7 km/s.

The double wall is treated as a single wall in the ballistic region except that the crater depth in the second wall of the double wall is taken to be reduced by the thickness of the shield from the crater depth that would have occurred in a single wall.

$$p_{-1} = p_{-2} + t_s \quad (1-5)$$

If the relationship between crater depth in semi-infinite, that is very thick, targets and the required thickness in thin targets to achieve certain results (Eq. 1-4) are considered one gets the following expression for the second wall thickness:

$$t_w = p_{-2}k = (p_{-1} - t_s) k \quad (1-6)$$

where different values of k will again provide results similar to those stated for a single wall [Reimerdes 1991].

There exist no design formula for the shatter region but several governing formulae have been derived for the hypervelocity region. A formula developed originally for small particles was modified according to suggestions made by Cour-Palais [Reimerdes 1991] in order to also apply it to larger particles:

$$t_w = (0.045 + 0.084 d)(\rho_p \rho_s)^{1/6} m_p^{1/3} v \sqrt{\frac{482}{S \sigma_y}} \quad (1-7)$$

where:

- d - particle diameter [cm]
- ρ_s - shield density [g/cm³]
- ρ_p - particle density [g/cm³]
- σ_y - yield strength - back up wall [N/mm²]
- S - distance between shield and bumper [cm]

A further modification is recommended for cases when the shield thickness is a factor of 5 or more smaller than the particle diameter. At this shield thickness to diameter ratio the shield is not thick enough to completely destroy the particle and therefore a thicker bumper is required than predicted by Eq. 1-7. Therefore the bumper thickness should be multiplied by a factor F^* which is given by the following expression:

$$F^* = 5 - 40(t_s/d) + 100(t_s/d)^2 ; (t_s/d) \leq 0.2 \quad (1-8)$$

Another more recent set of equations used for the hypervelocity regime are suggested by Christiansen [Christiansen 1992]. These equations replace the "non-optimum" Cour-Palais Whipple equations and are as follows:

$$t_s = c_s m_p / \rho_s = c_s d \rho_p / \rho_s \quad (1-9)$$

$$t_w = c_w d^{0.5} (\rho_p \rho_s)^{1/6} M^{1/3} V_a / S^{0.5} (70/\sigma)^{0.5} \quad (1-10)$$

Where: $c_s = 0.25$ for $S/d < 30$, $c_s = 0.20$ for $S/d \geq 30$

$$c_w = 0.16 \text{ cm}^2 \text{sec/g}^{2/3} \text{km.}$$

m_p - projectile area density [g/cm²]

M - projectile mass [g]

V_n - normal component of projectile velocity [km/s]

σ_y - rear wall allowable yield stress [ksi]

These wall thicknesses are defined so that there will be no perforation or detached spall of the rear wall. These equations potentially underpredict rear wall thickness for S/d ratios less than 15, and t/d ratios of less than 0.18. Impact angles greater than 70 degrees should be assumed to be 70 degrees [Christiansen 1992].

As stated earlier there currently exists no independent formula for the shatter region so commonly interpolation between the ballistic and hypervelocity regions is done. This seems to be a very conservative way of estimating the required bumper thicknesses [Reimerdes 1991].

The multi-shock shielding concept is similar in concept to the dual shield concept except that instead of shocking the incoming particle once, as the Whipple shield does, it is shocked a number of times by a series of thin shields before reaching the final wall. It is felt that this type of shielding, though more complex, may allow for another 21% to 37% weight savings over the double wall shield [Cour-Palais 1990]. A further advantage to the multi-shock shield is that it saves even more weight and produces excellent results using Nextel fabric. The advantage of Nextel over aluminum is that it is a flexible fabric which produces non damaging ejecta. Nextel showed no weight savings when used as the first wall in a double wall shield [Cour-Palais 1990].

One of the difficulties of the application of this design is the lack of understanding and the complexity of testing. There are many more variables involved

in this sort of design than for the previous designs discussed. The variables involved include: the first sheet thickness, the intermediate sheet thicknesses, the number of sheets required to produce a total melt of the projectile, the thickness of the final wall, the spacing between each shield and the materials involved. Testing done to date indicates that the total distance between the first shield and final wall as well as separation between individual shields is critical. As well, the mass per unit area of shielding is important but is also affected by the number of shocks. That is, four shields half as thick produce better results than two thicker shields. This is likely because if the shield is too thick the debris cloud gains additional mass from the shield itself [Cour-Palais 1990].

Empirical formulae have been developed from the initial multi-shock tests. The testing was all done in the 6 to 8 km/s velocity range but it is felt that the formulae are applicable up to the maximum orbital object collision velocity of 15 m/s. These formulae do not apply below 6 km/s where the multi-shock shield does not cause complete melting. The formulae as developed by Cour-Palais and Crews [Cour Palais 1990] are as follows:

$$\{\sum_1^n t_s + t_w\} = \frac{C_1 M_p V_p}{(\sum_1^n \Delta S)^2} \left[\frac{2.76 \times 10^8}{Y_t} \right]^{1/2} \quad (1-11)$$

$$t_w = \frac{C_2 M_p V_p}{(\sum_1^n \Delta S)^2} \left[\frac{2.76 \times 10^8}{Y_t} \right]^{1/2} \quad (1-12)$$

where:

- t - thickness [cm]
- C - coefficient
- M_p - projectile mass [g]

V_p - projectile velocity [km/s]

ΔS - inter-shield spacing [cm]

Y_t - tensile yield stress [N/m²]

Using the test data the values of C_1 and C_2 were determined to be 73 and 44.4 cm³ x s/km x g respectively for the aluminum alloy 6061-T6. Similar equations were derived from the test results in terms of total mass per unit area penetrated.

$$\left\{ \sum_1^n m_s + t_w \right\} = \frac{C_1 M_p V_p}{\left(\sum_1^n \Delta S \right)^2} \left[\frac{2.76 \times 10^8}{Y_t} \right]^{1/2} \quad (1-13)$$

$$m_w = \frac{C_2 M_p V_p}{\left(\sum_1^n \Delta S \right)^2} \left[\frac{2.76 \times 10^8}{Y_t} \right]^{1/2} \quad (1-14)$$

These equations though similar were empirically derived and therefore stand alone.

The coefficients C_3 and C_4 for Nextel with an area density of 0.043 g/cm² were found to be 131 and 73.4 s/km respectively [Cour-Palais 1990].

Christiansen also suggests slightly modified versions of the Cour-Palais and Crews [Cour-Palais 1990] equations for the multi-shock shield design [Christiansen 1992]. In these equations normal velocity replaces velocity in the mass per unit area equations:

$$m_w = \frac{C_4 M_p V_n}{\left(\sum_1^n \Delta S \right)^2} \left[\frac{2.76 \times 10^8}{Y_t} \right]^{1/2} \quad (1-15)$$

The values of C_4 used to calculate the mass per unit area of the wall are 43.1 for four equally spaced Nextel shields followed by an aluminum wall, and 43.6 for similar shields followed by a Nextel wall. The individual shields mass per unit area are

predicted to be 0.19 times the areal density of the incoming particle. These versions apply to velocities whose normal component exceeds 6 km/s and for S/d ratios of greater than 15. They are valid for all impact angles since Nextel fabric does not produce damaging ejecta [Christiansen 1992].

A final method of spacecraft shielding is the Mesh Double-Bumper (MDB) shield. This shield is an advanced form of the Whipple shield which has a layer of mesh a short distance in front of the shield and a high-strength fabric layer between the Whipple shield and the rear wall. The areal densities of the mesh can be predicted by:

$$m_1 = c_m d \rho_p \quad (1-16)$$

where: c_m - coefficient ranging from 0.035 to 0.057

The mesh is composed of wires in a square pattern with a wire diameter of from 0.07 to 0.10. The separation between the shield and the mesh should be about 4 times the particle diameter.

The areal density of the aluminum shield is:

$$m_2 = 0.093 d \rho_p \quad (1-17)$$

The intermediate high strength fabric is placed 4 times the particle diameter in front of the rear wall. For Spectra or Kevlar, the sizing equation is:

$$m_f = 0.064 d \rho_p \quad (1-18)$$

while for Nextel the coefficient becomes 0.095. The rear wall sizing equation is the same as for the multi-shock rear wall (Eq. 1-15) with the C_4 being 34.8 [Christiansen 1992]

As the weight of shielding required to assure the safety of new and future space missions becomes more prohibitive, not only is the type of shielding selected important, but it becomes important to optimize the shielding for minimum weight given a mission and an acceptable risk. Recently it has been found that along with many other physical phenomena spacecraft protective structures may be attributed to a geometric model using posynomial (polynomials with positive coefficients) predictors. This allows for the use of Geometric Programming as a non-linear optimization technique [Mog 1990]. This technique allows for the solving for an optimum weight distribution without having to establish the geometry of the shields. That is, rather than establishing the optimum geometry of the shields and using this solution to find optimum weight one begins by first finding the optimum weight distribution first. The most generalized form of the geometric program is as follows:

Minimize

$$y_o(x) = \sum_{i=1}^{T_o} \sigma_{oi} c_{oi} \prod_{n=1}^N x_n^{a_{oin}} \quad (1-19)$$

subject to

$$y_m(x) = \sum_{i=1}^{T_m} \sigma_{mi} c_{mi} \prod_{n=1}^N x_n^{a_{min}} \leq \sigma_m; \quad m = 1, 2, \dots, M \quad (1-20)$$

where

$$\sigma_{mi} = \pm 1, \quad \sigma_{oi} = \pm 1 \quad \text{and} \quad \sigma_m = \pm 1$$

$$c_{mi} > 0, \quad c_{oi} > 0$$

$$a_{min}, \quad a_{oin} \quad \text{are unrestricted in sign}$$

$$T_m \text{ is the number of terms in the } m\text{th constraint} (m = 1, \dots, M)$$

$$T_o \text{ is the number of terms in the objective function}$$

In this case the problem is posynomial in nature so all of the σ are positive. For engineering design formulations, the c_{mi} are appropriate coefficients, the x_i are design decision variables and the a_{mi} are the technological exponents of the decision variables [Beightler 1976].

For analysis of the Space Station Freedom a meteoroid and debris impact analysis program called BUMPER was written. This program has been used to make an indepth analysis of spacecraft penetration risks to reveal weak areas of the design which allows for optimal distribution of shielding. Certain directions and sides of any spacecraft are at different risk levels and the amount of shielding on each side should reflect these differences. It is suggested that risk of penetration should be distributed equally among all sides of a spacecraft [Christiansen 1992].

It is readily apparent that the design of protective structures for spacecraft is a very complex and not well understood task. The development of hydrocodes and higher velocity gas guns will aid in understanding the physical phenomena of hypervelocity collisions. Similarly, methods of optimization such as Geometric Programming will aid in the reduction of shielding weight for given risks and missions. However, a great deal of research still needs to be done in order to determine whether still better approaches exist and if the current approaches to shielding are being fully optimized.

1.3 SCOPE OF WORK

The project is an attempt to make survivability calculations less tedious and

more accurate. This is accomplished through the application of solid modelling as a tool. A model of the vulnerable components, their structure and their shielding is created. A control program is used to generate a series of possible lifetimes of the modelled spacecraft and to analyze the results of any dangerous collisions which occur within each lifetime. These results can then be used to generate the overall probability of the spacecraft surviving the expected environment.

The use of solid modelling to generate models of the spacecraft structure as well as the incoming particle and the resulting debris cloud allows for the consideration of several factors which were previously ignored. Shadowing of some components by others due to their location with respect to each other cannot be accounted for accurately using older methods. This can be dealt with simply and extremely accurately using solid modelling. Furthermore, all hits were previously assumed to be complete. That is, all of the debris generated by a collision is assumed to hit the component when a check is being made to see if penetration occurs. Due to shadowing and the large spread of debris after a hypervelocity collision with shielding this is an unlikely occurrence. Again, solid modelling allows for this quite simply and accurately.

The control program will depend on other factors which must be determined separately and then input so that the program may make the survivability determination. First and foremost is an accurate model of the satellite geometry using the appropriate solid modelling software and meeting certain requirements in terms of definition. The control software will also require the following: probability of various

sized particles colliding with the spacecraft during its mission life; material properties of the bumpers and shields; and the velocity and angle distributions of the colliding particles. Redundant components will need to be identified.

The survivability of the RADARSAT Bus Module was found using this method as an example of its utility. The program developed for this project is somewhat simplified with the RADARSAT project in mind. This test should be enough, however, to demonstrate that this method of survivability analysis could be an excellent tool in the shielding design of any spacecraft. This will test the effectiveness of this approach as well as produce results which will be used to determine whether upgraded shielding will be required for the RADARSAT project or if the present configuration is adequate. The results will be presented along with recommendations not only for the RADARSAT shielding design but also for the developed software.

CHAPTER 2 : Physical Problem Description

2.1 Statement of Problem

The problem addressed in this study will be: can RADARSAT survive the projected debris environment through its intended lifetime? In order to answer this problem, the probability of damage being incurred on any specific component due to collision with orbital debris will be determined. This data will then be used to find the overall probability that RADARSAT will survive, given a launch date of Jan 1, 1995 with the end of useful life projected to be Dec 31, 1999.

2.2 RADARSAT Orbit and Encountered Environment

The Radarsat spacecraft is a sun synchronous satellite. In order to maintain its constant position in relation to the sun it will require an unusually high orbital inclination. This inclination and the altitude required, which is one of the most debris dense, create a very risky environment for this spacecraft. Figure 2.1 contains a full layout of the RADARSAT spacecraft [Yelle 1994].

The Radarsat spacecraft will orbit at a mean altitude of 800 km at an inclination of 98.5 degrees. It will be assumed that it will maintain a circular orbit. Given the debris peak at 800 km, as well as those at 1000 and 1500 km, this is a dangerous orbital altitude [Kessler 1989]. Additionally, most orbital debris are in nearly circular orbits with eccentricities of 0.01 or less and also have high angles of inclination, which leads to higher collision speeds and a higher frequency of collisions since

Figure 2.1 : The RADARSAT Satellite

RADARSAT will spend a great deal of time within areas of high debris concentration and will be exposed to many near head on collisions. Many other satellites at lower angles of inclination only pass through the areas of high debris concentration twice per orbit and are moving virtually normal to the debris.

The orbital debris flux which will be used in this survivability analysis was gathered from EnviroNET on May 1, 1990 [Lauriente 1990]. The flux gathered is based on cross-sectional area, as opposed to surface area. EnviroNET was provided with the following input conditions for its flux function calculation:

Table 2.1: Input parameters used to gather orbital debris flux data for RADARSAT from EnviroNET [Warren 1990]

Debris diameter (cm)	0.01 - 1.0
Satellite altitude (km)	794.5
Orbital inclination (degrees)	98.5
Growth Rate	5%
*Small Growth Rate	10%
Time (year)	1995-1999
Solar F10.7 flux (Input/Calculated)	calculated
**Spacecraft attitude (Random/Oriented)	oriented
**Yaw angle (deg.)	0

* - indicates included in 1994 software only

** - indicates included in 1990 software only

The growth rate of 5 percent given to the EnviroNET software is the anticipated rate of increase in launches per annum. The Small Growth Rate is the anticipated rate of growth of the number of particles with a diameter of less than 10 cm. The results obtained from the EnviroNET software on May 1, 1990 can be found

in Table 2.2. More recently, a set of flux data was gathered from the EnviroNET system on May 3, 1994. The second set of flux data can be found in Table 2.3.

It must be noted that the flux data gathered in 1990 is much higher than that gathered in 1994. It is believed that this difference is due to a change in the information requested by and the operation of the EnvironNET system. Flux is dependent in part on satellite orientation which was a part of the earlier software but which has apparently been removed from the current version.

For a randomly tumbling spacecraft the constant k , the factor used within the flux equation (equation 1-1) takes on the value 1.0. However, for a surface area which is facing in the same direction as the spacecraft velocity vector, and which has a near polar orbital inclination like RADARSAT's, k approaches its maximum value of approximately 3.5 [Kessler 1989]. A cursory examination of the two sets of results reveals that the fluxes for the same years and particle diameters differ by a range of 3 to 5. The average variation between the two sets of data within the relevant 3.0 mm to 10.0 mm range used in the simulation is 3.62. It is believed that this is mainly because the k value was set to 1.0 in the 1994 version while it was about 3.5 during 1990. The other differences can be explained by updates in the estimates of debris populations due to improved data collected in the past four years.

The 1990 flux data is used in this study since it is more conservative and since it is believed that this data more accurately applies to RADARSAT which is a three axis stabilized spacecraft. The lower k values for the sides of RADARSAT, whose normals lie at 90 degrees to the spacecraft's velocity vector, are accounted for

through the visible cross-sectional area system for determining the average number of hits which is explained in Chapter 3.

**Table 2.2: Orbital debris flux gathered from EnviroNET.
May 1, 1990.**

SIZE (cm)	YEAR				
	1995	1996	1997	1998	1999
1.0E-02	1.568E+01	1.724E+01	1.897E+01	2.086E+01	2.295E+01
2.0E-02	2.771E+00	3.048E+00	3.353E+00	3.688E+00	4.057E+00
3.0E-02	1.006E+00	1.106E+00	1.217E+00	1.338E+00	1.472E+00
4.0E-02	4.899E-01	5.388E-01	5.927E-01	6.520E-01	7.172E-01
5.0E-02	2.804E-01	3.085E-01	3.393E-01	3.732E-01	4.106E-01
6.0E-02	1.778E-01	1.955E-01	2.151E-01	2.366E-01	2.603E-01
7.0E-02	1.209E-01	1.330E-01	1.463E-01	1.609E-01	1.770E-01
8.0E-02	8.660E-02	9.526E-02	1.048E-01	1.153E-01	1.268E-01
9.0E-02	6.451E-02	7.096E-02	7.806E-02	8.587E-02	9.445E-02
1.0E-01	4.958E-02	5.453E-02	5.999E-02	6.598E-02	7.258E-02
2.0E-01	8.768E-03	9.645E-03	1.061E-02	1.167E-02	1.284E-02
3.0E-01	4.023E-03	4.425E-03	4.867E-03	5.354E-03	5.889E-03
4.0E-01	1.555E-03	1.710E-03	1.881E-03	2.069E-03	2.276E-03
5.0E-01	8.923E-04	9.815E-04	1.080E-03	1.188E-03	1.306E-03
6.0E-01	5.677E-04	6.244E-04	6.869E-04	7.556E-04	8.311E-04
7.0E-01	3.879E-04	4.267E-04	4.694E-04	5.163E-04	5.679E-04
8.0E-01	2.794E-04	3.073E-04	3.380E-04	3.719E-04	4.090E-04
9.0E-01	2.095E-04	2.305E-04	2.535E-04	2.789E-04	3.068E-04
1.0E+00	1.623E-04	1.785E-04	1.964E-04	2.160E-04	2.376E-04

The EnviroNET software was designed using Kessler's theories and all key assumptions and conclusions concerning data sources are as per NASA TM 100-471 [Kessler 1989]. The orbital debris flux given in Table 2.2 is centred around a zero degree angle which is parallel to but in the opposite direction of the +X axis. As will be explained later, the probability of a hit occurring and with what faces it may occur are determined by the angle of trajectory of the incoming particle. By the nature of this distribution it can be concluded that the +X face will be hit most often, followed by the +Y and -Y faces and with a very small chance of strikes occurring on the -Z face. The +X axis for the co-ordinate system used points down range along the space craft velocity vector. The +Y axis points along the negative orbit angular momentum

vector leaving the +Z axis to point toward the local nadir as per the right-hand rule.

The XY plane forms the local horizontal plane [Warren 1990, Terillon 1991].

**Table 2.3: Orbital debris flux gathered from EnviroNET.
May 3, 1994.**

SIZE (cm)	YEAR				
	1995	1996	1997	1998	1999
1.0E-02	3.8338E+00	4.3035E+00	4.8068E+00	5.3400E+00	5.9048E+00
2.0E-02	6.7773E-01	7.6076E-01	8.4973E-01	9.4399E-01	1.0438E+00
3.0E-02	2.4594E-01	2.7607E-01	3.0836E-01	3.4256E-01	3.7879E-01
4.0E-02	1.1981E-01	1.3449E-01	1.5021E-01	1.6688E-01	1.8453E-01
5.0E-02	6.8585E-02	7.6987E-02	8.5990E-02	9.5529E-02	1.0563E-01
6.0E-02	4.3481E-02	4.8807E-02	5.4515E-02	6.0562E-02	6.6967E-02
7.0E-02	2.9577E-02	3.3201E-02	3.7083E-02	4.1197E-02	4.5554E-02
8.0E-02	2.1185E-02	2.3780E-02	2.6561E-02	2.9507E-02	3.2628E-02
9.0E-02	1.5784E-02	1.7717E-02	1.9789E-02	2.1984E-02	2.4309E-02
1.0E-01	1.2131E-02	1.3617E-02	1.5209E-02	1.6896E-02	1.8683E-02
2.0E-01	2.1560E-03	2.4200E-03	2.7029E-03	3.0026E-03	3.3201E-03
3.0E-01	7.9303E-04	8.9008E-04	9.9406E-04	1.1402E-03	1.2209E-03
4.0E-01	3.9496E-04	4.4325E-04	4.9498E-04	5.4977E-04	6.0780E-04
5.0E-01	2.3295E-04	2.6138E-04	2.9184E-04	3.2409E-04	3.5825E-04
6.0E-01	1.5314E-04	1.7179E-04	1.9177E-04	2.1292E-04	2.3531E-04
7.0E-01	1.0858E-04	1.2178E-04	1.3590E-04	1.5085E-04	1.6667E-04
8.0E-01	8.1397E-05	9.1255E-05	1.0180E-04	1.1297E-04	1.2478E-04
9.0E-01	6.3669E-05	7.1351E-05	7.9567E-05	8.8258E-05	9.7449E-05
1.0E+00	5.1497E-05	5.7683E-05	6.4295E-05	7.0585E-05	7.7496E-05

Impacting debris particles will be assumed to consist of aluminum 2024 [Warren 1990]. The target material or back plate material will also be aluminum: 6061-T6, since this is the material used for component boxes and for the honeycomb sandwich plates (q.v. 2.2 Radarsat Bus Module). The shield, or initial material which the impacting particles will hit is a thermal insulating blanket. The impacting particles are assumed to be spheres. Both RADARSAT and the debris particles will be assumed to have exactly circular orbits.

It is necessary to find the probabilities of a given collision or series of collisions occurring during the RADARSAT's lifetime from the flux data. Poisson

statistics provide the following formulae [Kessler 1989, Warren 1990]:

$$P = 1 - e^{-N} \quad (2-1)$$

where P - cumulative hit probability, or the chance of being hit once or more by a particle of a given diameter.

N - the average number of hits on the spacecraft during a given time period. This is found by multiplying the average flux over that time period by the spacecraft's cross-sectional area. This makes use of the fluxes found in Table 2.2 and equation 1-2.

$$P_n = \frac{N^n}{n!} e^{-N} \quad (2-2)$$

where P_n - probability of exactly n impacts, or the chance of being hit exactly n times by a given diameter particle.

The formulae above cannot simply be applied. For this study the assumption that all hits are normal to the impacted surface and that the spacecraft cross-sectional area is constant has been eliminated. Since area is no longer a constant but depends on the incoming particle's angle, probability calculations are significantly more complicated. The above problem will be examined in detail in Chapter 4 (q.v.).

The equation used to determine the collision velocity between RADARSAT and any colliding orbital debris will be taken from NASA TM 100471 [Kessler 1989]. This velocity distribution, given below, is non-normalized and is specific to a given

Figure 2.2 : Velocity Distribution of impacting Particles

orbital inclination but is averaged over all altitudes.

$$f(v) = [(2vv_0 - v^2)G * \exp(-(v-Av_0/Bv_0)^2)] + HC(4vv_0 - v^2) \quad (2-3)$$

The constants (A,B,G,H,C) are empirically derived and are functions of the satellite orbital inclination. RADARSAT's inclination of 98.5 degrees results in the following set of values:

$$\begin{aligned} A &= 2.5 \\ B &= 0.3 \\ C &= 0.0125 \\ G &= 250.0 \\ H &= 1.0 - 0.0000757*(i-60)^2 \\ &= 0.8878 \\ v_0 &= 7.7 \end{aligned}$$

For a graph of this distribution see Figure 2.2. The velocity distribution can then be numerically normalized so that $f'(v)$ over any 1 km/s interval becomes the fraction of debris impacts which occur within that velocity interval. This is done in NASA TM 100471 [Kessler 1989].

Once the velocity distribution is established, it can be used to find the debris impact angle distribution. The impact angle is defined as the angle between the velocity vectors of the satellite and the impacting debris particle, where 0 degrees represents a hit 5 degrees above the normal to the +X surface due to the 5 degree pitch of the spacecraft [Warren 1990]. Since the assumption has been made that both the satellite and the debris are in circular orbits, their speeds must be equal. The relative velocity of impact can be written as [Kessler 1989]:

$$\mathbf{V} = \mathbf{V}_D - \mathbf{V}_S \quad (2-4)$$

where $\mathbf{V}$ is the relative velocity of impact,

V_D is the orbital debris velocity and

V_S is the satellite velocity.

Knowing the complete velocity (vector) relationship and the fact that the speed (magnitude) of the satellite and the debris particle must be the same gives the following [Kessler 1989]:

$$\cos A = V_D / V_S \quad (2-5)$$

where A is the angle of impact.

There is a further complication specific to RADARSAT because the spacecraft orbits with a 30 degree roll and a 5 degree pitch down which will change the angles of impact that the bus module will see.

The angle of impact of the incoming particle with respect to the face being hit also determines several variables which control the direction and spread of the debris cloud formed after bumper shield penetration. When an oblique particle impact occurs with a bumper, a variety of events may occur which can be determined by the angle of the impact from normal. If penetration of the bumper occurs, two debris clouds will be formed. The first debris cloud is made up of the debris of the shattered or otherwise broken-down incoming particle. The second cloud contains the debris from the bumper where it has been penetrated. In some cases a third type of debris cloud, a ricochet type, may occur. This type usually occurs when there is little or no penetration and at very high angles of impact [Oblique]. A complete diagram of the possible results of an oblique impact is shown in Figure 2.3.

The debris cloud type of principal interest here is the debris cloud formed by

a1 - impact angle
b1 - bumper debris angle
b2 - particle debris angle
s1 - bumper spread angle
s2 - particle spread angle
rc - mass center of ricochet
r99 - 99% of ricochet

Figure 2.3 : Oblique Impact Diagram

Figure 2.4a : Path Angle of Debris with respect to Angle of Impact

Debris Angle of Spread (degrees)

Angle of Impact (degrees)

Figure 2.4b : Debris Spread Angle with respect to Angle of Impact

penetrating particle material. To determine the path and spread of this type of cloud, the incoming path of the debris and data from Technical Memorandum Oblique Hypervelocity Impact Response of Dual-Sheet Structures were used [Oblique]. From the data within the above report two graphs were derived. These graphs show the relationship between the incoming particle angle and the path angle of the centre of mass of the debris cloud and its angle of spread. The solid lines show the relationships used in subsequent calculations. These graphs appear as Figures 2.4a and 2.4b.

The debris cloud formed by the bumper material can be neglected in this case because of the very light material used for the bumper. The RADARSAT's effective bumpers are the thermal insulation blankets which cover the entire bus module. The debris from this blanket torn loose by a penetrating collision would have far too little mass to be a danger to the spacecraft. Ricochet material is also neglected since any material which ricochets will be thrown away from vulnerable components if the ricochet occurs off the bumper. Ricochets off component walls can be neglected since by virtue of the fact that the debris has ricocheted once it will not be able to penetrate another component's outer wall. This debris would be at too high an angle with respect to the component faces in question to be dangerous.

2.3 Radarsat Bus Module

The bus module's primary structure consists of four corner posts set at 45

degrees to normal on each corner. These four posts are attached to the payload module beneath. Each corner post has a sheath which acts as a bracket to support four honeycomb sandwich plates which run corner to corner and top to bottom of the payload module. These plates support all of the bus module components which are mounted externally onto them. The three sandwich plates of this type which are of interest in this thesis can be seen in Figures 2.5 a-c.

There are also four flat plates which are mounted to the external face of each of the four corner posts and which run from top to bottom of the bus module and to the outside edges of the space deck. The space deck is the top platform which encloses the bus module. It is also a honeycomb plate (see Figure 2.6).

The four honeycomb plates are 42.5" wide and 42.0" high. Each is 1.0" thick, consisting of two face plates 0.032" thick mounted on the aluminum honeycomb. The plates are made of Al 6061-T6. The space deck is of similar construction except that it is 63.5" long, 71.0" wide and 2" thick. The four flat plates consist of 0.25" thick Al 6061-T6.

Mounted externally on the honeycomb plates are the majority of the bus module's components. Most of these components are contained within boxes which have 0.15" thick walls on all sides. Some of the components which were deemed to be at higher risk by initial debris damage analysis have had their leading edge thickened to 0.30" thick. These boxes are made entirely of Al 6061-T6. These components are only protected by the boxes in which they are contained and by the thermal insulating blanket which fits on top of them. These components consist of sun

Figure 2.5a : Positive X Face of RADARSAT Bus Module

Figure 2.5b : Negative Y Face of RADARSAT Bus Module

Figure 2.5c : Positive Y Face of RADARSAT Bus Module

Figure 2.6 : Bus Module Layout

sensors, horizon scanners and other such components and are often redundant.

Internal to the four sandwich plates is a limited internal structure designed to support the fuel tank and momentum wheels. In addition there is a large spherical titanium fuel tank and six momentum wheels set at a variety of angles. As well as these large components, all the wiring and fuel lines run through the inside of the bus module. There are several thrusters mounted on the bus module which are supplied from the fuel tank.

2.3.1 Component Types and Descriptions

In this section a brief description of each component and its operation will be included. Unless otherwise stated, each component is contained within a box of 0.15 inch thick Al 6061-T6 and is attached to its respective honeycomb wall. Note that all dimensions are in inches and given width by height by depth with respect to their compartment face. The depth dimension always refers to the component length along the normal to the face against which it rests.

POSITIVE X-FACE

1) Terminal Board (6.50 x 9.00 x 5.50): This component has a double thickness 0.30 inch cover plate. This is simply an electrical board for incoming and outgoing circuitry.

2) Solar Array Switching Unit (22.50 x 2.25 x 6.07): This component also has a 0.30 inch cover plate. This controls the amount of power generated by the solar array by switching on and off different panels on the array. This is used when power

generation requirements are reduced.

3-4) Control Electronics Unit 1-2 (3.66 x 5.34 x 6.48): These units control the orientation of the solar arrays by sending signals to the solar array drive when reorientation of the arrays is necessary.

5) Pyro Firing Unit(5.99 x 9.10 x 6.34): This unit controls the firing of pyrotechnics used to explode fasteners which hold down certain components, such as the solar arrays, during launch and placement. This unit need only operate for only the first several days of the mission.

6-7) Magnetometer Electronics 1-2 (5.67 x 5.67 x 2.16): These units control instruments which measure magnetic field strength.

8-10) Sun Sensor Electronics 1-3 (5.94 x 4.86 x 2.29): These components have the double thickness 0.30 inch cover plates. Components 1 and 2 control a sun sensor on the front of the satellite while component 3 controls one on the back of the satellite for the infrequent occasions on which the satellite is flying backwards. Sun sensors measure the position of the sun which is used to help orient the spacecraft.

11-12) Horizon Scanner Electronics 1-2 (11.76 x 5.94 x 2.56): These units control scanners which locate the positions of the horizons of the earth for use in orienting the spacecraft.

13-14) Frequency Standard Unit 1-2 (2.43 x 6.75 x 3.24): These units are part of the satellite's internal clock.

15-16) PB3 (Parallel Binary) Timer 1-2 (7.38 x 3.63 x 7.00): These units are the satellite's internal clock.

NEGATIVE Y-FACE

1) Heat Controller (7.53 x 6.45 x 6.18): This component is mounted away from the negative y-face compartment back wall and instead is mounted to the underside of the space deck. As its name indicates, this unit controls the heating and cooling of the satellite.

2) Power Management Unit (17.74 x 8.60 x 9.14): This component is also mounted to the spacedeck's underside and away from the rear wall. This unit controls the distribution of power throughout the spacecraft.

3) Terminal Board (8.60 x 6.45 x 5.49): This unit is similar to the one on the +X face.

4) Power Control Unit (36.55 x 15.05 x 7.64): This component has had all its wall thicknesses doubled to 0.30 inches. This unit is similar to the Power Management Unit.

POSITIVE Y-FACE

1) Telemetry Distribution Unit (12.35 x 8.51 x 10.21): This component has a double thickness front cover plate. This unit gathers and distributes as necessary information on telemetry gathered by sun sensors and other similar components.

2-3) Attitude Control Electronics 1-2 (12.35 x 8.51 x 10.21): These units control the satellite's thrusters, momentum wheels, and torque bars as required.

4-5) Data Storage Unit 1-2 (6.45 x 7.53 x 4.57): These units store data gathered by the satellite's instruments.

6-7) Digital Telemetry Unit 1-2 (15.05 x 3.23 x 5.37): These two components are

mounted slightly away from the rear wall using brackets which extend from the rear wall.

8) Attitude Control Processor (11.29 x 15.10 x 7.25): This unit is the computer which calculates the control signals required to keep and or place RADARSAT in its proper position.

CHAPTER 3 : The Computer Model and Simulation Program

In this chapter, the method used by the developed software to simulate RADARSAT's lifetime in order to estimate its probability of survival will be described. This description will include the program's operational requirements and limitations as well as the necessary layout of the satellite model.

3.1 Solid Model

The program is designed such that the model must consist of a series of bumper shields and components named and defined in a specific way. This is done so that the program can easily recognize each object and identify its purpose. The model must lie in the positive x, positive y and negative z octant.

Each component must be identified by two surfaces. These surfaces are the outer and inner surfaces of the component. If the component is a tilted block it must also have a single point located to one side. This point must be located to the left of the block if the lower angle of tilt occurs at the bottom left while it should be on the right if the lower angle occurs at the bottom right. This assumes that the block is viewed in its local co-ordinates such that the Z axis is the axis about which the block is rotated and is positive pointing into the block, the X axis is the local horizontal and is positive right while the Y axis is the local vertical and positive up.

Each individual component must be named as block "b*" where the *

represents an integer identifying the component's object number. This means that if there are 20 components, they will have block names ranging from b1 to b20. The two surfaces must be named "outer2" for the outer surface and "outer1" for the inner surface. The point used to further identify rotated blocks must be named "vertex".

The bumpers are represented by a plate the appropriate distance from the components. There may be up to three such bumpers for each of three directions. These directions are for particles approaching downstream along any of the major axes. These bumpers must be given block names of bumper (negative z direction), bumper2 (negative x direction) and bumper3 (negative y direction). Each must have the object name "shield".

This model is transformed by the program into a more easily used model internally. The bumpers are left as originally defined. Block components are redefined so that each has a plate representing the six sides of the block. These are given block names "a*" with object names being determined by their position in the world axis frame. The world axis frame has a +Z axis which points downrange along the velocity vector and an +X axis which is parallel to but in the opposite direction of the orbit angular momentum vector which leaves the +Y axis to point toward the local zenith. For instance, the top of component "b1" will become a plate of the appropriate size and thickness and will be known as block "a1", object "top". Spherical components are redefined as two semi-spherical plates known as block "a*", objects "front" and "back". The frontal semi-sphere is the entire portion that may be hit by the current approaching particle. This is due to the division of the sphere into its two

halves lying along a plane created by a normal to the approaching particle and a diameter.

3.2 Software Requirements

The task of analyzing impact damage on a model satellite requires the interaction of a solid modelling package and a program written specifically for the computation and analysis of strike patterns and resultant damage. The two pieces of software need to operate simultaneously and be capable of passing information back and forth.

The solid modelling package therefore has to be designed to operate under the control of an external program. The package chosen and used for this project is Silver Screen V4.0. It was designed and distributed primarily as an educational tool by Schroff Corporation in Kansas. This software has an internal C compiler, SilverC, which was designed specifically to allow for the writing of control programs for the solid modelling package. This compiler contains additional internal functions specific to control and operation of the modelling package. The software loads and contains the spacecraft model, produces solid representations of debris clouds and performs physical operations on the model. The program written for this project controls and manipulates the model using the aforementioned physical operations. This program also records the results of these manipulations.

The principal design requirements of the software to be produced were: to generate a series of simulated particle strikes based on environmental data, to produce

information sufficient for the solid modelling package to produce solid representations of the resulting debris clouds, to likewise provide information for the production of interference solids to simulate shadowing of model components by one another, to retrieve collision angles and areas from the model and use these to determine whether a component has been damaged, and to track the probability of critical model damage based on the probability of individual particle collisions and the damage, or lack thereof, caused by each individual strike.

3.3 Overview of Software Design

In order to meet the above requirements in a realistic time frame it was initially decided to place a series of restrictions on the model. At the same time it was necessary to create a program which would allow for any potential debris cloud and for analyzing damage patterns on a suitably wide variety of potential models. Initially the decision was made to restrict the model to a series of blocks which could be of any dimension but could only be rotated about one of the three world axes. The components were assumed to be protected by a single wall bumper to be represented by a thin semi-infinite sheet. The analysis was divided into three using the direction of particle approach. Principal direction of approach of a particle is determined by which bumper the particle strikes. The model construction on the Silver Screen system also needed to be constrained to a certain configuration to allow for easy recognition of component shape types since each shape would require its own pattern algorithm.

In order to speed up the model construction, the standard configuration used was based on recognizability and dimension accuracy. The program would then translate the model into a more readily usable internal form. Once the internal model is developed the next step would be the development of an algorithm for the creation of solid representatives of the resultant debris clouds of given particle impacts. Initially a single particle size, velocity, and trajectory was used for the purposes of testing. The program was written such that the inclusion of successive particle impacts simply involved placing the entire program in a finite loop. This brute force programming method increased potential run time but greatly simplified program design.

In order to create representations of the debris clouds, their effect and how they interacted with the model, certain solid modelling tools need to be applied. These consist of boolean operations similar to those used in the mathematical manipulation of sets. These operations would include, for example, union, intersection and difference. These operate similar to the corresponding set functions. For example, in solid modelling, if one unions object "a" and object "b" the result is an object "c" which consists of everything in both objects. The function primarily applied in this project is differencing. The result of object "a" difference object "b" is an object "c" which consists of object "a" except that all parts of object "a" which were contained within object "b" have been removed. This is used extensively within this project to remove portions of damage clouds blocked by components in their path and to remove the area of a collision from the component side hit.

In order to create easily analyzed damage patterns on components the debris cloud was represented by a series of concentric cones of varying angles of spread and an equation was developed for the distribution of mass density across each cone as illustrated in Figure 3.1. This resulted in a series of damage patterns on each component about which the angle, area, mass density, and velocity of the collision was known. After each particle impact this information would be known for all components.

However, this information could not be obtained simply by differencing the damage cloud solid from each individual component. Some allowance needed to be made for the shadowing of each component by others potentially in the path of the approaching damage cloud. To make this allowance each component was prioritized according to its proximity to the bumper along the vector of the approaching debris particle. The highest ranked (1st) component could then be simply differenced using the debris cone since the probability of component interference would be zero. The result of this collision would be stored by the program, which would then proceed to the next highest ranked component. The appropriate damage cone is then recreated and the appropriate interference pattern caused by the first component is removed from it. The resulting damage cloud is then simply differenced from the second component. This sequence is repeated for each successive component. Inherent in this methodology is the assumption that debris will not completely pass through a component but will be stopped by the rear wall given front wall penetration. This process is explained further through descriptions of the procedures involved in

Figure 3.1 : Debris Cloud - Concentric Cone Representation

section 3.4.1.

In the next step, data gained from the collision is used to check each component individually for penetration. If penetration of any exterior wall to a component occurs, that component is assumed to have been rendered inoperable. At first, simply examining a fixed number of impacts for all of the appropriate particle sizes was considered. This method led to prohibitive difficulties in the calculation of probabilities and accuracies (q.v Chapter 4). Therefore, the decision was made to examine satellite lifetimes. For each lifetime, collision probabilities for each particle size included are calculated. These can then be used along with a set of random numbers to determine whether one or more hits of that size have occurred. If one or more hits of any size occur these are examined to see if they result in component damage. The probability of each individual component being damaged is found by simply summing the number of lifetimes in which that component is damaged and dividing by the total number of lifetimes examined.

In order to discover the probability of a given collision the area seen by an approaching particle needs to be known. However, this area is dependent on the angle of approach. Therefore, a set of ten possible particle strikes, one for each appropriate particle size, is randomly generated. The information generated on each potential collision includes the particle's velocity and angle. Using the angles generated, the area visible to the particle is found. This, at the same time, allows for a stochastic determination of the face hit using the relative areas of the visible faces. Each face is represented by its own model which can be loaded in the event that that

Figure 3.2 : Model of RADARSAT Bus Face Arrangement

face is hit in order that the hit may be analyzed. The model used to determine cross-sectional area of each face is included as Figure 3.2. The three face models can be found in Chapter 2 Figures 2.4 a-c.

The probability of overall system failure was subsequently determined from manual calculations. To determine overall survival probability of an entire spacecraft, one need only sum the probabilities of individual component failure, applying the condition that, for redundant components, both must be damaged for complete system failure to occur. This is easily determined by examining a list of the lifetimes tested which contain more than one hit and recording every instance in which all of a set of redundant components were damaged in that lifetime. For example, the satellite in question has redundant Horizon Scanners. While Scanner 1 and Scanner 2 may each individually be damaged 5% of the time the incidence of lifetimes in which both are damaged may be only 0.5%. The program will only identify the first fact, while the second must be found by examining the list of multiple hit lifetimes.

3.4 Software Operation

The main program serves primarily as an organizer which collects information using functions and procedures and relays this to other functions and procedures. Many of the critical variables used by this software were defined globally since they are used throughout and they are easily identifiable and singular. Examples of this include angles of approach with respect to the x and y local axes, angle of debris

spread and particle information such as mass and velocity.

The main program initializes the solid modelling package to prepare it for use. It then defines a series of global variables which relate to the model of the satellite and the particles. All probabilities of component failure are initialized to zero. The next step involves the numerical integration of the velocity distribution curve so that later analyses could use the uniformly distributed random numbers in conjunction with the velocity distribution in order to stochastically select particle collision velocities.

Once these initial preparations are complete the program enters the main loop. Each complete run through this loop represents a possible lifetime of the satellite. If enough lifetimes are simulated a fairly accurate estimate of the probability of the satellite surviving a lifetime is obtained.

Within the life-loop the procedure 'attack' is called. This procedure returns to the main program the number of hits which have occurred in this lifetime and all the necessary information on these hits. This information includes the particle size, velocity, angle of approach and the location on the face where initial contact is made. If no hits have occurred the life-loop repeats until the number of required life simulations have occurred. Otherwise the program enters the hits-loop.

Each hit-loop contains the entire determination of damage by a colliding particle and repeats until each hit within a given lifetime has occurred. In order to do this, the basic information is expanded to find such necessary facts as particle mass and the face which has been struck. The appropriate model is loaded of the face in question in order that the damage analysis may take place. The procedure

'define_blocks' then takes the external solid model and changes it into an internal model that the program will use. It also identifies the types of components involved and assigns each component's basic information to a global storage variable. Once this is completed the procedure 'blast' is called which creates an appropriate damage pattern and determines which components, if any, are damaged. If any are damaged, this information is stored, via a global variable which stores the probability of each component being damaged, and is also written to an external file.

This completes the hits-loop which will repeat until all the hits which have been determined to occur within the current lifetime have been analyzed. Once the life-loop is complete the program's run is effectively complete. The final step consists of outputting the final probabilities of a given component surviving a lifetime to an external file for examination. A flow chart of the above operation is included as Figure 3.3.

There are a series of assumptions which are made throughout the course of the program which simplify its operation:

- 1) Ricocheting of debris on high angle of impact collisions is not modelled.

This should not seriously affect results since any ricocheting should take debris away from danger areas in cases where it is hitting a component's front face. In cases where the particle is hitting a side face and ricocheting it should not be a danger to other components since it has already ricocheted off a side face. Due to the planar arrangement of components and component spacing it is unlikely that such a ricocheting particle will then hit

Figure 3.3 : Main Program Operation

a front face which would result in a much lower impact angle.

- 2) On individual debris damage cones the mass is equally distributed across the frontal area.
 - 3) Each concentric cone represents an equivalent angular distance. That is, if the first concentric cone represents zero to ten degrees of debris spread then the second will represent ten to twenty degrees of spread. The assumption is made that each of these concentric cones represents an equivalent portion of the total mass of debris. In the example above where these two cones represent the entire debris cloud each cone will represent 50% of the debris mass even though the outer cone has three times the area. This was done because the debris is more concentrated in the centre and the higher the concentration, the greater the chance of penetration.
 - 4) Christiansen's equations are applicable to partial debris cloud strikes, given the adjustment for the colliding mass.
 - 5) The normal velocity is calculated using the debris cloud's central axis.
- Previous studies have not considered partial strikes of debris clouds so these kinds of assumptions have not been necessary and hence little information is available on some of these variables.

3.4.1 Procedures and Functions

This section contains a list of the various procedures and functions in the software and a brief description of the function and operation of each. These are

given in the order in which they would occur during program operation. A more complete flow chart which includes the calling of all of these functions and procedures can be found in Appendix A.

FORMULA : This is a function which receives as data a velocity and uses the velocity distribution function to return the relative number of hits which occur at that velocity. It is used by the main program to integrate numerically the velocity distribution function and is later used to determine stochastically possible particle impact velocities.

ATTACK : This procedure produces for the main program the information on the hits, whether zero or more, which could possibly occur in a given lifetime. Using the functions 'unirand' and 'formula' it produces a set of ten potential collision velocities. These are used in turn to find the corresponding ten angles and, using the function 'get_area', the areas. Each of these ten velocities, angles and areas correspond to the ten distinct sizes of particles being considered such that they are used to find if a hit has occurred at that size, and then later if a hit has occurred, to determine if damage has been done. Using these areas and flux data, which must be entered into the software prior to operation, the probabilities of different sized particles colliding with the satellite can be determined. These probabilities are compared to uniformly distributed random numbers generated using 'unirand' to discover whether or not hits have occurred and if they have occurred, at what sizes.

Figure 3.4a : Ranking Components by Position along the Particle Path

Side View

Top View

Figure 3.4b : Debris Cone and Vulnerable Components

Side View

Top View

Figure 3.4c : Shadowing Pattern Example

Figure 3.4d : Resulting Damage Pattern after Shadowing of Front Block Removed

Finally, the dimensions of the faces which may be struck are used to determine randomly a set of initial collision co-ordinates for the hits which have occurred. This is also done using 'unirand'.

GET_AREA : This function uses as input the angle of approach of the potential impacting particle and returns through simply searching a data base the corresponding total visible x-section area. This data base was generated using an external program based on the procedure 'areas'.

UNIRAND : This function requires as input the previous integer random number in the sequence and, using this integer, will generate a uniformly distributed random number between zero and one. Initially the integer random number is the seed. The pattern will not repeat until 2^{29} numbers have been generated. The mixed congruential technique is used [Dyck et al 1979].

AREAS : This program receives as input the angle of approach of a colliding particle from the main program. It makes use of a simple overall model of the satellite and some sophisticated techniques in order to determine which face of the satellite has been hit and what the angles which define spread and path of the debris cloud are.

The model is rotated by the angle provided as input. Once in this final position, lines are drawn out from the centre of each face plate directly along the line

of sight. The entire model is then rotated so that its face planes lie along the xyz coordinate system. This may be more complicated than simply rotating back the angle provided since the satellite may be oriented with constant roll, pitch and yaw angles. This completed, the angles of the created lines are measured with respect to the x and y local axes. These lines can now be deleted. The model is now rotated to its position of orientation in space followed by the input rotation. By projecting this on to a two dimensional surface and measuring the resulting areas the area of each face is determined. The probability of hitting a given face is proportional to its area with respect to the projected area of the whole model. Therefore which face is hit is easily selected using 'unirand'. The model used for this operation is found in Figure 3.2.

A final step must be taken to determine the angle of spread and to adjust the angles with respect to the x and y axis which define the debris clouds path. The angle of spread is determined from the angle of approach of the particle. The path angles must be adjusted since the angle defining the path of the debris cloud is less than the angle of approach of the colliding particle by a constant ratio of 50/64 as given by Figure 2.3a.

DEFINE_BLOCKS : This procedure identifies each component in turn and assigns each with a set of variables used for drawing and identifying the component in other areas of the program. It also ranks each component according to distance along a vector defined by the path of the approaching particle.

The first step involves using the dimensions and the volume of the object to

identify its type. The types which can be identified by the current software include: rectangular blocks, which may be rotated along any one of the axes; spheres; and cylinders whose central axis lies along one of the axes. After identifying the type of component, enough co-ordinates to reproduce the component are stored in a global variable. A number identifying the object type and wall thicknesses and angles of edges are stored as necessary within the same global variable.

The next step is to create a new model of the components which the program will use. The reason for using a different system to define the model created by the user and the model created and used by the program is so the user is not required to create such a complex model. The model defined and used by the program is much more complex than the user defined model. These models were described in more detail in section 3.1. The internal model is created using two procedures. The first, called 'assign' uses the globally defined component variables to create a more complete set of locally defined co-ordinates which can be quickly applied to the current need. In this case, the need is to create the software's internal model from the co-ordinates obtained from the user defined model. This is done by the procedure 'draw'. As the components are redrawn in the new form, the old components as they are represented by in the user defined model are deleted.

Once the components have been produced in the form that they are to be used by the program, they must be ranked. This is done by creating an axis along the vector of the approaching particle pointing upstream. Each component's foremost point is then placed on this axis with the shortest distance along this axis leading to

the highest ranking. This ranking is necessary later for determining where shadowing of one component by another may occur.

ASSIGN : This procedure receives the object number of the component of interest and then using stored information on that component, as produced by the procedure 'define_blocks', it produces a complete set of co-ordinates for that component and returns this information.

DRAW : This procedure receives the set of co-ordinates produced by 'assign' along with the component type, its edge angles if necessary and the object number of the component. It uses this information to create a more sophisticated model of the component in question from the original user-defined model. This process involves some geometry but otherwise involves straight forward use of the solid modelling program.

BLAST : This procedure uses particle location and direction of travel and, eventually through the use of a series of procedures, removes the damaged areas from the components struck by the incoming particle. The procedure is called twice by the main program. The first time it is called it simulates the collision of the particle with the external wall or bumper. In the case examined in this project, this consists of a thermal insulating blanket. The main purpose of this call is to locate the point at which debris spread begins to occur.

The second call of this procedure by the main program occurs to simulate the damaging of the components. This procedure call creates the damage cone which originates at the point of exit from the bumper and expands to its largest at the most distant component along its path. A loop is entered so that each component can be considered in turn according to their ranking. A second loop is entered so that up to three contact sides may be considered for each component. A third loop is entered so that a series of concentric cones are created to represent the debris cloud rather than just a single cone. For each component side two identical damage cones are produced. The first will be used for establishing the possible contact area of the damage cone with a given surface and the second will be used for actually damaging that surface.

Once the two cones are created the procedure 'damage' is called. This procedure checks which side is currently being considered, produces shadowing effects, removes the final damage cone from the component side and determines whether penetration has occurred. This is repeated within the two loops until all components and sides possible have been considered or until enough debris has been blocked to render the remainder ineffective. If a component has been hit by some of the debris, but not enough to stop examining this particular debris pattern, then this component's object number is added to a list of components 'needed' by the shadowing procedure 'channel'.

DAMAGE : This procedure uses a series of other procedures to determine what side of the component in question may be hit, what shadowing of the debris

cloud has occurred prior to a possible collision with the current component and whether the collision which finally occurs is sufficient to penetrate the component. This is done by first calling the procedure 'what_side' which returns the object name of the component side to be hit.

Once the above information has been obtained, the area and volume of the current component side, prior to the removal of the collision area, must be found. This allows for its comparison at a later time to data gathered about the damaged component side in order to determine the extent of the collision if any has occurred. The next step calls the procedure 'channel' which will eliminate portions of the debris cloud which have been blocked by previously contacted components.

Now a final debris pattern has been obtained. This is differenced from the component side in question. The second damage cloud which was unadjusted by the channel procedure is differenced from a semi-infinite plate which lies along the plane of the component side. This semi-infinite plate is created by the procedure 'draw_plate'. Data is gathered on the damaged component side and compared to the undamaged side so that the collision area is obtained. This is compared to the damaged semi-infinite plate so that a ratio of actual collision area to possible collision area is obtained. The assumption is made that the debris spreads equally over the area allowing for this ratio to provide the actual mass of debris involved in the collision.

All of this information is now passed into a procedure called 'penetrate' which uses the particle data stored in global variables and the data received from 'damage' on areas and angles to determine whether penetration has occurred. It uses

Figure 3.5 : Collision Area Determination

Christiansen's equations to make this determination. It also determines whether sufficient debris remains unaccounted for to continue examining further components for damage.

WHAT_SIDE : This procedure uses the vector of the approaching particle, information on the location and orientation of the component in question and a predefined order of side priority to select the side to be examined for damage. The side, once selected, is attributed its object name and this is returned to the 'damage' procedure. It is also possible that this procedure will eliminate the possibility of certain sides being hit.

It operates using geometry to eliminate impossible collisions and to indicate what ones must be considered. For example, a debris cloud approaching from the front, right and below a component may not hit the back, left or top sides. It is also possible that some of the three principle sides may be eliminated from consideration.

CHANNEL : This procedure identifies the type of interference due to shadowing that the components in question will create and passes this information on to the appropriate procedure for creation of the damage pattern. It then differences the damage patterns created from the initial debris cone leaving the damage pattern which will be used to damage the current component side.

The 'assign' procedure is used to collect a complete set of defining co-ordinates for the shadowing component. This information is used along with

component type and direction of particle approach to define a set of co-ordinates and angles which can be used to establish the appropriate type of interference pattern.

There are many possible types of interference patterns. For example, for an unrotated rectangular block, there are no less than twenty-five distinct interference patterns which can be created. These are identified by a set of five conditions along the local right - left plane and five conditions along the local up - down plane. These five conditions are displayed for an unrotated block in Figure 3.6a-e. These combine to create a series of possible complex interference patterns. These two identifying conditions, each of which has five possibilities, only represent blocks. Separate conditions may occur with other types of components. In the end only blocks and spheres were accounted for at this level because the other component types did not occur within the test case being examined by this project.

BLOCK : This procedure uses the information obtained in 'channel' about interference types to produce the appropriate interference patterns. It does this primarily by sweeping out a series of objects using component faces as starting points and a calculated shadow as the ending face.

It may be necessary at this stage to rearrange the co-ordinates as defines by the procedure 'assign'. This would become necessary if the block being considered were rotated about an axis by more than forty-five degrees therefore changing which face is actually the front, right or top sides, etc.. This is done by the procedure 'rearrange_blocks'.

The next step calculates the co-ordinates of the four points which are the vertices of the rear face of the shadowed area. These four defining points are all in the same plane, that plane being that created by two of the three primary axes parallel to the bumper plate but at the rear most point of the model. There are four vertices, defining the rear face of the shadow, for each of the three faces which will cast a shadow. The faces which will cast shadows are determined by the type of interference pattern using the same logic as the 'what_side' procedure (i.e the back wall does not cast a shadow on a debris pattern approaching from the front). Establishing the co-ordinates of the shadow cast on the back plane is tedious due to the number of possibilities, as explained previously. It also can be geometrically challenging to establish these co-ordinates especially when a rotated block is being considered.

Once these rear plane defining points have been established it is three objects must be created using the faces of the component which are casting the shadows and the rear plane shadows cast by these faces respectively. This creates in combination an interference pattern which does not allow any of the debris cloud which has hit the component casting the shadow to reach components which are within its shadow.

REARRANGE_BLOCKS : This procedure is used to rearrange the co-ordinate points as defined by the procedure 'assign' into the local co-ordinate system. It is also used when a tilted block has been rotated more than 45 degrees and therefore the initially defined front face may not be the actual front face.

Debris Cone

Figure 3.6a : 2D Shadowing Type 1

Rebri's Cone

Figure 3.6b : 2D Shadowing Type 2

Figure 3.6c : 2D Shadowing Type 3

Debris Cone

Figure 3.6d : 2D Shadowing Type 4

Figure 3.6e : 2D Shadowing Type 5

BLOCK_SPHERE : This procedure serves the same function and operates similar to the 'block' procedure except that it creates the interference patterns for spheres. This procedure is different because the sphere has no definable sides or edges. This procedure only removes the direct shadow of the sphere, or the area directly behind the sphere along the particle trajectory. This is not entirely accurate since the debris spread would lead to a larger shadow in most cases. In order to accurately create a shadow pattern, a series of points calculated from edge points on the sphere and debris trajectory and spread angles would need to be calculated. In theory an infinite number of these defining points would exist. These points could define a sphere, an ellipse, an oblong egg shape or almost anything in between. This would be a very difficult and tedious geometric problem. It was not completed in this way since the sphere involved in the model turned out to be extraneous since it was not in any danger under this satellite's conditions.

DRAW_PLATE : This procedure is used by 'damage' to create a semi-infinite plate on the plane of the component side being damaged. A debris damage cone in its initial form is differenced from this plate. The unadjusted damage cone is used because the purpose of this procedure is to establish what area of plate would be required to stop all of the material from the collision if it were to reach this plane. This area compared to the area of the collision with the component side allows for the simultaneous exclusion of the amount of matter which has either been blocked by previous components or which has simply missed this component side altogether.

2 of/de 2

PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

PRECISIONSM RESOLUTION TARGETS

PENETRATE : This procedure makes use of Christiansen's equations as described in Chapter 2(q.v) to determine whether penetration of a component side has occurred due to its collision with a debris cloud. Adjustments made to his equations include replacing total mass with the colliding mass based on area as found by the 'damage' procedure.

This procedure uses global particle variables as well as the information collected by the procedure 'damage' to make this determination. It also evaluates a number of necessary variables used in Christiansen's equations itself including the constants involved and the distance between the bumper and the component wall. Once this determination is made the procedure checks whether or not there remains enough debris to continue examining remaining components.

FINISH : This procedure collects all the information on total number of hits on each component and, applying the total number of lifetimes examined, determines each component's failure probability. This information is then output to an external text file for examination. It also outputs the total number of hits which have occurred and the final seed for unirand to this file so that the initial seed can be reset for consecutive runs.

ABS : This is the standard absolute value function. It was programmed since one did not already exist in SilverC.

COMBO : This procedure is used to combine two angles which are with respect to the x and y local axes and create an equivalent angle with respect to a different set of co-ordinates axes.

DIVIDE : This procedure uses the total angle of spread of the debris cone and a set value for the maximum size of concentric cone required and calculates the number of separate concentric cones required for the damage analysis.

OBLIQUE : This procedure uses the global variables for angles of particle trajectory with respect to the local x and y axes, along with an input distance of travel along the local z axis, and calculates the difference along the x and y axes between the starting and end point of the path defined.

Chapter 4 : Simulation Determinations - Parameters, Probability and Accuracy

This chapter will examine the usage of the software that was developed. The methods used to determine input parameters are explained and the results of those determinations are given. There is also an explanation of how certain probabilities are determined and how the accuracy of a simulation is found.

4.1 Simulation Strategy

The strategy being employed to determine the probability of the RADARSAT satellite surviving the intended mission is a life simulation type. The entire lifetime of the satellite will be simulated to determine the entire sequence of collision events which may occur in a given lifetime. A given lifetime may have any number of collisions from a variety of different sized particles or may have no collisions whatsoever.

A large series of these possible lifetimes will be simulated to determine how often a critical failure will occur. For example if 200 simulated lifetimes indicate critical component damage while another 9800 indicate survival then it will be assumed that there is a 98% chance that the RADARSAT satellite will survive its mission.

This method is used because of its simplicity in determining the probability of

survival. An alternative method which was considered and rejected, one which considers a set number of hits and determines the probability of a hit doing critical damage, results in a very complex statistical problem.

4.2 Parameter Determination

PARTICLE SIZE:

The first determination which needed to be made was the size of particles to be considered by the simulation. It is obviously unnecessary to simulate very tiny particles which have no chance of damaging the most vulnerable of components. It is equally unnecessary to simulate particles so large that the collision occurrence is negligible. Therefore this parameter can be narrowed to include only those particles with a realistic opportunity to both hit and do damage to the spacecraft.

The decision was made to restrict particle size to a maximum of 1.0 cm in diameter. Particles greater than this in size would have less than a 0.1% chance of hitting the spacecraft during its entire 5 year mission. In order to determine the smallest particle which need be considered, the worst case for a particle strike was examined. This meant determining if a normal hit, at the maximum velocity, with 100 percent of the particle mass hitting the object, would result in internal damage in the form of penetration or rear wall spallation. The Christiansen equations [Christiansen 1992] and the following data were used:

shield and particle density - 0.277 g/cm^3

normal velocity - 15.0 km/s

component wall allowable yield stress - 64.8 ksi

component wall thickness - 0.15" or 0.381 cm

distance between shield and wall - 1.0 cm

It was discovered that the minimum particle size which might lead to rear wall spallation was approximately 2.10 mm. The closest particle bin size being considered which exceeds this size is the 3.0 mm bin size.

Initially it may seem negligent to exclude particles of sizes slightly over 2.1 mm. This, however, is not the case since the 3.0 mm bin represents in actuality all particles within the 2.5 mm to 3.5 mm range. Also, it must be noted that the case examined was a worst case scenario and strikes of this kind are rare. The average collision will have a velocity of approximately 13.4 km/s and therefore an angle of approximately 20 degrees. An analysis of this collision still assuming a complete strike results in a minimum threatening particle size of 2.35 mm. As can be seen a very small region remains and this was assumed to be negligible.

A second consideration had to be made in deciding the smallest particles to consider. Christiansen's equations apply to the hypervelocity regime and not all collisions will occur within this range. Since there are no formulae for the shatter region the formula for the ballistic region is assumed to apply to all collisions of 7.0 km/s or slower. This means that another worst case occurs at 7.0 km/s assuming a normal and complete strike. Using Reimerdes' equations 1.3 through 1.6 it was found that a 0.95 mm particle may penetrate a component [Reimerdes 1991]. The same data was used as for the earlier calculation for the hypervelocity regime. This leads to the

selection of the 1.0 mm size bin as the smallest to consider. Once again since these worst case hits are rare, especially in this case given the high angle associated with slow speeds, and since the 1.0 mm bin is assumed to represent some larger and some smaller particles, this selection is relatively accurate.

Therefore the decision was made to consider ten bin sizes during the simulation which would range in size from 1.0 mm to 10.0 mm at 1.0 mm intervals. The 1.0 mm and 2.0 mm size particles could be neglected from the damage determination stage in all cases where the velocity of their collision exceeded 7.0 km/s. It is felt that this will represent accurately the size range that is dangerous to RADARSAT without resulting in unrealistic run-times.

IMPACT VELOCITY and ANGLE:

This parameter is determined by generating a uniform random number between 0 and 1 and using this in conjunction with the velocity distribution curve found in Figure 2.2. The velocity distribution is divided into 0.1 km/s segments and numerically integrated resulting in the fraction of debris impacts which occur within that velocity band [Warren 1990, Kessler 1989]. Thus, a velocity is readily selected using the random number generator and a set of velocities selected in this manner should accurately represent the true velocity distribution.

The angle of impact is simply determined by using the orientation of RADARSAT and the direct relationship between the debris' path angle within the local horizontal plane and the velocity of impact. This process was described fully in

previous chapters.

LOCATION OF IMPACT:

The first step involved in locating each individual collision is to determine which face is hit. In order to do this, a model of the satellite faces, shown in Figure 3.2, is rotated so that it is viewed along the line of flight of the debris particle in question. The respective visible cross-sectional areas are then measured. Since there is a uniform probability of striking a unit area the respective probabilities of each face being struck is found directly by comparing these areas. Which face is hit can then be stochastically determined using a uniform random number generator.

Once the face which has been hit has been determined the position on that face where the hit occurs must also be found. There is a uniform probability that a given unit area on each individual face will be hit. This is true because each individual face is planar. Therefore, the exact location of a given hit is quickly determined using a uniform random number generator and the extents of the face in question.

4.3 Model Simplification

The model used within the program is not an exact replica of the actual bus module of RADARSAT. The first significant simplification is the neglecting of the angle plates which are attached to the surface of the corner-posts. This assumption is conservative since particle impacts near the edges of the faces will be assumed to impact with the thermal blanket which is much lighter than the corner plates.

A second simplification involves the neglecting of side strikes against the two surfaces whose normals lie along the Y axis. All impacts with the front area of the thermal blanket are assumed to hit the front face. It is possible for an impact to hit this face and have a path which would take it toward a component on one of the side faces. This can be neglected since the particle sizes being considered are not capable of first penetrating the corner plate of 0.25" aluminum on its 45 degree angle and then penetrating a 0.15" aluminum component wall on an angle 45 degrees from the angle of the corner plate.

Finally, only the external faces of RADARSAT have been modelled. The entire interior which consists of a spherical titanium fuel tank, six momentum wheels, an internal aluminum structure and a multitude of wires and fuel lines has been neglected. The reasons for this include: in the worst case a particle need be over 4.6 mm in diameter to penetrate the front honeycomb mounting face or over approximately 9.2 mm to penetrate one of the other three faces; the only occurrences of hits which may enter the interior will be hits on the front face which are not blocked in part by any components; of the lifetimes in which a hit occurs which will enter the interior, even fewer will be capable of damaging the fuel tank which is the component at greatest risk; the wires and fuel lines are kept behind protection as much as possible; the travel of debris clouds through honeycomb sandwich plates is very poorly understood; and the inclusion of a model of the interior would vastly complicate the simulation.

4.4 Probability Analysis

In the past, the cross-sectional area of a spacecraft was assumed to be a function of time only. That is the area could change over time due to re-orientation or, in the case of two axis stabilized spacecraft, constant rotation. The average number of impacts within a given period of time N is defined by the following [Kessler 1989]:

$$N = \int_{t_i}^{t_f} F \cdot A dt \quad (4-1)$$

where F - flux at time t

A - area at time t

This allowed for the use of Poisson statistics to find the probability of impacts occurring on a surface. These equations are found in section 2.2.

This assumption is not accurate for many types of space vehicles. Often the cross-sectional visible area is dependant upon the angle of approach of the incoming particle and the orientation of the vehicle. This was accounted for previously through the use of a constant k which adjusts the flux value of a given surface based on orientation to reflect the different probabilities of impacting with different surfaces. If this assumption is no longer made then the probability of impacts occurring on a surface become a function of the velocity as well as flux, which in turn is size dependant. In this case the flux for a surface facing in the same direction as the spacecraft velocity vector is used.

The probability of a hit which has occurred resulting in critical damage being

done to the satellite is determined by the software simulation. This probability is dependant on velocity as well. This is readily apparent since velocity is a variable within the Christiansen equations [Christiansen 1990] for determining efficacy of shielding.

Realizing that the overall probability of a satellite being critically damaged by orbital debris during its lifetime is the product of two individual probabilities which both depend on velocity a problem is readily apparent. The formula for the probability of critical damage is:

$$P_d = \int_0^{V_{\max}} \int_{d_{\min}}^{d_{\max}} \sum_{n=1}^{n=\infty} P_{\text{nhit}}(V,d) * [1 - \{1 - \prod_{1}^n P_{\text{h-d}}(V,d)\}] \quad (4-2)$$

where: P_d - overall probability of critical damage

P_{nhit} - probability of exactly n impacts occurring as found using
Poisson statistics

$P_{\text{h-d}}$ - probability of critical damage occurring given that a hit
has occurred

V - impact velocity

d - particle diameter.

Since the probability of a hit doing damage is velocity dependant as well as dependant on particle size an entire series of hits would have to be simulated for each velocity at each particle size. This would result in a prohibitively large number of runs which would lead to unrealistic run-times.

For the above reasons the program does not simulate sets of hits at given

velocities and sizes and calculate the probability of critical damage being done but rather follows the lifetime simulation approach described earlier. This leads to the formula:

$$P_d = \frac{\text{\# of lifetimes in which critical damage occurs}}{\text{\# of lifetimes}} \quad (4-3)$$

In order to apply this technique the program must determine whether any collisions have occurred within a given lifetime. This is done using the following formula:

$$P = 1 - e^{-N} \quad (4-4)$$

where P is the probability of being hit one or more times by a particle of a given diameter. Given that the probability of exactly n hits occurring is:

$$P_n = (N^n/n!) e^{-N} \quad (4-5)$$

then it follows that the chance of exactly one hit occurring is:

$$P_1 = Ne^{-N} \quad (4-6)$$

and the fraction of time periods which will contain only one collision is:

$$P_{1hit} = Ne^{-N} / (1 - e^{-N}) \quad (4-7)$$

Evaluating equation 4-7 with the lifetime flux of 3.0 mm particles and a typical area used in this study shows almost a 98% chance that if hits occur at this size or greater during RADARSAT's lifetime, for a given diameter, it will be a single impact. The trend of this equation is that the lower the flux the higher the percentage of hit occurrences which will be singular.

A problem occurs when the 1.0 mm and 2.0 mm sizes are considered. When a hit occurs at the 1.0 mm size there is a nearly 25 percent chance that there will be

multiple hits. The probability drops to about 7.4 percent for the 2.0 mm size.

However, due the knowledge that a small percentage of hits, approximately 7.5 percent, will have velocities of less than 7 km/s the significance of this is reduced.

The method used for determining whether a hit has occurred at a given particle size is as follows:

- 1) Randomly determine the velocity of a potential impacting particle of a given diameter.
- 2) Determine the angle of approach and area seen by the incoming particle.
- 3) Use gathered flux data and the area to determine the probability of one or more hits occurring at that diameter (equation 4-4).
- 4) Find whether or not an impact has occurred by comparing the probability to a uniform random number.
- 5) Assume that all cases where an impact has occurred have only one collision. This is justified above (equation 4-7). For the 1.0 mm and 2.0 mm sizes an estimate of the number of damaging hits which have been neglected will be made.

The reason for neglecting hits beyond the first, for a given particle size, besides the fact that they occur so infrequently is that determining whether a second or third hit occurs presents a paradox. Every collision must have its own independent velocity which is used initially to determine whether one or more hits have occurred.

However, a second collision would necessarily have a different velocity which would have a different chance of occurring. This creates a difficult problem most easily

solved by simply neglecting these occurrences.

4.5 Accuracy

The method used for establishing the accuracy of the simulation is to divide the operation of the program into a series of groups. Each of these groups contain enough life-times to obtain a significant number of occurrences of damage. In this study the number of life-times per group was chosen as 2000. The complete run of the software produces a number of these groups. Important data such as number of lifetimes in which damage is done and number of hits which occur is saved for each group.

The data is combined from each group to obtain final results of the entire run. The groups are then used to conduct a variation study of the results. The degree of variation of the results from group to group should give a good indication of the accuracy of the simulation. An accurate simulation will produce consistent results for different groups.

The standard error S_p is calculated on the overall results using the following formula [Ferguson and Takane 1989, Chen 1994]:

$$S_p = (pq / N)^{0.5} \quad (4-8)$$

where

p - is the probability of the event

q - is $(1 - p)$ or the probability of the event not occurring

N - is the sample size

This formula is only appropriate when the product of the sample size and the smaller of the two probabilities is greater than five. This is not a problem since such a large

sample size is being used for this study.

The standard deviation S_d of the probability can now be estimated simply using the standard error calculated using the above formula [Ferguson and Takane 1989, Chen 1994]:

$$S_d = 1.96 S_p \quad (4-9)$$

Now, results may be quoted as $p \pm 1.96S_p$.

The following formula was used to find the standard deviation in cases where multiple results were being used to calculate a single probability [Wadden 1984]:

$$\text{Given:} \quad P_z = aP_x + bP_y - cP_u + \dots$$

$$S_{dz}^2 = a^2 S_{dx}^2 + b^2 S_{dy}^2 + c^2 S_{du}^2 + \dots \quad (4-10)$$

$$\text{where:} \quad P_z, P_x \text{ etc. are probabilities}$$

$$a, b \text{ etc. are constants}$$

$$S_{dz}, S_{dx} \text{ etc. are standard deviations}$$

In order to calculate the empirical variance between groups the following formula is applied [Ferguson and Takane 1989, Chen 1994]:

$$S_e = \left(\frac{\sum (x - X)^2}{N - 1} \right)^{0.5} \quad (4-11)$$

$$\text{where:} \quad x - \text{number of occurrences in a group}$$

$$X - \text{average number of occurrences}$$

4.6 Software Operation

The software analyzed 20 000 lifetimes in ten groups of 2000. For each group an output file was created to which relevant data on each collision was written as well as a final summary of results. For each hit the following is recorded: the lifetime in which it occurs; the face impacted; the component or components hit; the particle diameter; and whether or not a component hit was damaged. The summary recorded: the number of times each component was hit; the number of times each component was damaged; the total number of hits and how many of those were dangerous; the total number of lifetimes in which a component was damaged; and the total number of lifetimes in which a non-redundant component was damaged. Also recorded was the number of hits, dangerous hits (all hits of 3.0 mm or greater size and hits with smaller particles which have speeds of 7.0 km/s or less), damaging hits, and critical hits according to particle size.

Chapter 5 : Results and Discussions

This Chapter will examine the results of the simulation and compare this information to the results obtained in previous studies. The significance and accuracy of the final results will be presented along with a further justification of some of the assumptions made in Chapter 4 regarding the selection of certain parameters.

5.1 Final Results

5.1.1 Survivability of RADARSAT

The following results are based on 20 000 simulated lifetimes. The probability P_d that the RADARSAT satellite will be critically damaged such that continued operation of the vehicle will be impossible is:

$$P_d = 0.01001 \pm 0.00133$$

The Pyro Firing Unit, component 5 on the positive X surface, is needed only for the first three days of the mission and therefore damage to this unit will likely occur after its usefulness is expended. Therefore this unit was not included when determining the above probability. The probability P_{cd} that at least one component, whether redundant or not, will be damaged due to a collision with orbital debris is:

$$P_{cd} = 0.03228 \pm 0.00237$$

It should be noted that these results include an estimate of the number of occurrences of component and critical damage which was neglected through the exception of

multiple hits within a size bin. The actual simulation which neglected any multiple hits predicted the following:

$$P_d = 0.00895 \pm 0.00131$$

$$\text{and } P_{cd} = 0.02975 \pm 0.00235$$

5.1.2 General Results

The total number of hits that occurred during the 20 000 simulated lifetimes was 12643. This included 122 lifetimes which had two hits occur and two lifetimes in which three occurred. Therefore, the probability P_h that at least one hit will occur during a given lifetime is:

$$P_h = 0.62585 \pm 0.00671$$

If the weighted average area seen by an incoming particle is used the theoretical probability P_{th} of at least one hit within the size range examined occurring can be calculated using Poisson statistics. The weighted average area was found using one degree steps from negative 90 to positive 90 degrees, finding the visible cross-sectional area at each angle and then finding the weighted average based on the probability of a collision occurring at a given angle. The weighted average area was estimated to be:

$$A_{avg} = 1.8123 \text{ m}^2$$

which led to:

$$P_{th} = 0.65124$$

Table 5.1 below compares the theoretical and simulated probabilities and occurrences

of hits in each size bin.

Table 5.1 : Theoretical and Simulated Number and Probability of Hits within each Size Bin

Particle Size(mm)	Theoretical Probability of a Hit	Simulated Probability of a Hit	Theoretical Number of Hits	Simulated Number of Hits
1.0	0.42219	0.40930	8444	8186
2.0	0.14090	0.13850	2818	2770
3.0	0.04353	0.04365	871	873
4.0	0.01705	0.01600	341	320
5.0	0.00982	0.00850	196	170
6.0	0.00626	0.00495	124	99
7.0	0.00428	0.00395	86	79
8.0	0.00309	0.00325	62	65
9.0	0.00232	0.00230	46	46
10.0	0.00179	0.00175	36	35

The total number of hits occurring which resulted in damage was 604. There were 9 incidences in which more than one component was damaged in a single lifetime. This lead to the above simulated result for P_{cd} . Since the conditions under which it is possible for a small particle to damage a component is far more restrictive, requiring impact velocities of less than 7.0 km/s, than for larger particles it is necessary to consider them separately. For these purposes small means 1.0 mm and 2.0 mm sized particles while large refers to any particle greater than that in size. There are 231 incidents of component damage which are caused by collisions with small particles while the remaining 373 are caused by the larger particles. This indicates that the probability P_{h-cd} that given a hit a component will be damaged is:

$$P_{h-cd} = 0.02108 \pm 0.00269 \text{ for small particles,}$$

and $P_{h-cd} = 0.2211 \pm 0.0198$ for large.

The number of hits which resulted in a non-redundant and critical component being damaged, resulting in satellite failure, was 179. Of these critical hits 104 involved small particles while 65 involved large particles. This figure was used to arrive at the simulated P_d stated in the previous section. This information also establishes that the probability P_{h-d} that given a hit a critical component will be damaged is:

$P_{h-d} = 0.009493 \pm 0.001816$ for small particles,

and $P_{h-d} = 0.04445 \pm 0.00984$ for large.

The following Table 5.2 indicates the probability that, given a hit, damage is done, either critical or non-critical, for individual size bins. A critical hit is any hit which damages a non-redundant component and thereby causes satellite failure.

Table 5.2 : Simulated Number and Probability of a Hit Causing Damage within each Size Bin

Particle Size(mm)	Number of Hits Causing Critical Damage	Number of Hits Damaging a Component	Probability of a Hit Doing Critical Damage	Probability of a Hit Doing Damage
1.0	66	156	0.00806	0.01906
2.0	38	75	0.01372	0.02708
3.0	34	153	0.03895	0.17526
4.0	6	72	0.01875	0.10625
5.0	5	36	0.02941	0.21176
6.0	8	29	0.08081	0.29293
7.0	7	31	0.08861	0.39241
8.0	5	19	0.07692	0.29231
9.0	5	17	0.10870	0.36957
10.0	5	16	0.14286	0.45714

The estimation of the relative debris particle flux seen by each face requires the number of the total hits which contacted that face compared to the total number of

hits. This result would be biased if all sizes were considered since the face hit was only determined for dangerous particles which neglects all small particles which would have resulted in hypervelocity collisions. In other words, since 1.0 mm and 2.0 mm particles which had velocities of less than 7.0 km/s were simulated, including these small particles in an analysis of the total flux seen by a face would bias the result. Therefore only particles of 3.0 mm or greater size should be considered in making this determination.

Therefore, a previous simulation of 12 000 lifetimes which considered only large particles was used to calculate the relative flux of each surface. The distribution of the 1041 hits which occurred was as follows: the positive X surface or front face was hit on 620 occasions; the positive Y surface or left face was hit on 119 occasions; the negative Y surface or right face was hit on 104 occasions; and the negative Z surface or top face was hit on 198 occasions. This results in the following fractions F of the flux which will result in hits on the respective faces:

$$F_{+X} = 0.59558$$

$$F_{+Y} = 0.11431$$

$$F_{-Y} = 0.09990$$

$$F_{-Z} = 0.19020$$

Given that it is believed that the k value used in equation 1-1 to obtain the flux values which were implemented in this experiment was 3.5 (see Chapter 2), and using the weighted average areas of the faces, the effective constants k of the RADARSAT's various surfaces can be estimated to be:

$$k_{+x} = 3.280$$

$$k_{+y} = 0.630$$

$$k_{-y} = 0.550$$

$$k_{-z} = 0.415$$

Some of the hits which occurred while hitting one of the faces of RADARSAT did not actually hit a component. These types of hits are insignificant except for those which impact on the front face and are of large sizes and velocities. The only hits of any consequence are 94 hits on the front face which are larger than 4.6 mm in diameter and therefore may penetrate to the interior of the bus module. Of these there are 28 which are greater than 7.4 mm in size which may penetrate the fuel tank. Therefore the maximum probability P_{fmax} that the fuel tank may be ruptured is:

$$P_{fmax} = 0.0014 \pm 0.0005$$

This result could increase the probability that the satellite will be disabled during its lifetime by .14 percent of the predicted result.

The following Table 5.3 contains a summary of the number of hits and the number of times damaged per component.

Table 5.3 : Number of Hits and Times Damaged per Component

Face	Component	Redundant With	Number of Hits	Times Damaged	Probability of Damage
+X	1	N/A	81	31	0.00155
	2	N/A	46	8	0.00040
	3	4	28	15	0.00075
	4	3	19	19	0.00095
	5	N/A	79	53	0.00265
	6	7	44	20	0.00100
	7	6	48	24	0.00120
	8	9	35	7	0.00035
	9	8	29	10	0.00050
	10	N/A	42	20	0.00100
	11	12	63	14	0.00070
	12	11	46	14	0.00070
	13	14	16	8	0.00040
	14	13	22	8	0.00040
	15	16	47	43	0.00172
	16	15	48	43	0.00172
-Y	1	N/A	8	3	0.00015
	2	N/A	43	37	0.00185
	3	N/A	26	5	0.00025
	4	N/A	148	45	0.00225
+Y	1	N/A	44	14	0.00070
	2	3	43	21	0.00105
	3	2	54	37	0.00185
	4	5	36	18	0.00090
	5	4	32	18	0.00090
	6	7	25	13	0.00065
	7	6	30	20	0.00100
	8	N/A	71	36	0.00180

The following information can be found per group in Appendix B: number of hits per component; number of times an individual component is damaged; the vulnerability of each component; the total number of hits; the total number of lifetimes in which a component is damaged; the total number of lifetimes in which critical

damage is done and satellite operation fails; the number of times hit by each size of particle; the number of times a component is damaged by each particle size; and the number of times critical damage is done by each particle size.

5.2 Discussion

The probability that the RADARSAT satellite will complete its mission is very good. There is less than 1 in 100 chance that the satellite's life will be cut short. This indicates that the debris environment expected does not pose a serious threat to RADARSAT under its current configuration. This variability of this result is very good given the inherent uncertainty involved in making these sorts of calculations. A very large inherent uncertainty exists due to the uncertainty of flux values predicted by current models which may be as high as a factor of two to three. Given that the result indicates little threat and due to this inherent uncertainty it was decided that it was unnecessary to conduct a larger run which would have improved the accuracy of the simulation.

If the weight of RADARSAT with its current configuration is within the desired launch limit then it is apparent that no changes need to be made to the current design. However, it would be possible to reduce the shielding on certain components while keeping the survivability of the vehicle quite high. This decision would have to be made based on a required maximum risk level.

A series of studies were done in 1991 in an attempt to predict the survivability of the RADARSAT bus module. These reports are based on the same debris

environment predictions used within this study, however, they rely on an additional series of assumptions. The assumption was made that the multi-layer insulating blanket would have no effect on the incoming particle and therefore all hits were considered as direct strikes on the component boxes. This is conservative since it reduces the minimum size required to penetrate a component box from 2.1 mm to 0.6 mm for hypervelocity collisions. The number of strikes occurring in this range is very large compared to the number of strikes occurring above 2.1 mm in size. Neglecting this effect is inaccurate since the insulating blanket is thick enough at 0.333 mm to cause a break down of the debris especially since the addition of one layer of Nextel to the blanket (this was done specifically to improve shielding). Further assumptions included the following: shadowing of one component by another was neglected; the flux values were assumed to have a full $k = 3.5$ on the front face and to be $2/3$ of this on the side faces; all internal components are protected by the honeycomb sandwich plates; and the pitch and roll of the satellite was neglected [Poley 1991].

The method used involved calculating the area of each component individually and, using the flux data, determining the probability that one or more particles of a size large enough to penetrate that component would impact it. This resulted in the survivabilities of each individual component. The final result was obtained by summing the probabilities of component failures. In cases of redundant components the chance of both being damaged in a single lifetime was assumed to be the product of each individual being damaged and then this was added to the total. The most recent prediction of survivability of the satellite was 0.875 [Poley 1991]. This is much

lower than the 0.990 probability of survival predicted here and is due to many conservative simplifications applied. Some attempt was made at a later date by the RADARSAT group at CSA to account for effective area and angle of approach by calculating the effective area of each individual component box. This resulted in a prediction of 0.87 as the minimum survivability of the spacecraft given the current configuration[Terrillon et al 1991].

The probability that a component, not necessarily a non-redundant one, will be damaged during the satellite's lifetime is considerably larger than the probability of satellite failure. This will occur approximately once every 31 lifetimes. This is likely acceptable given the redundancies built into RADARSAT but a consideration may need to be made as to the probability of a given component failing by means other than through collision of the spacecraft with orbital debris. Since the components used on spacecraft are generally very reliable it is very unlikely however that a redundant pair might have one fail because of a collision and the other fail for other reasons.

The variability of this probability is much less than for critical damage being done. This is quite simply due to the greater number of occurrences of component damage which has allowed the simulation to become quite stable in 20 000 lifetimes.

The number of hits which occur are slightly less than that predicted by theory. In theory, given 20 000 lifetimes approximately 13024 hits should occur while the simulation only predicted 12643. This is a discrepancy of -3.01 percent. There are a number of factors which may be contributing to this difference. This may be due in part to the variability of the estimate of the weighted average area and due to the

variability of the simulated lifetimes. The weighted average area was found using a second program which analyzed the visible area at each angle between positive and negative ninety degrees, multiplied each by a weighting factor based on the angle distribution (developed from the velocity distribution), and then took the average of these results. This discrepancy, though small, is unusual due to the relatively stable nature of the number of hits occurring per group. The standard error, calculated using equation 4-11, of the number of hits using the simulated groups is 0.00502 which accounts for only one sixth of the error. It would be extremely unusual for a uniform random number generator to be this largely biased over this number of executions.

It can be seen from Table 5.1 that this tendency for the simulation to predict less hits than the theory on which it is based is quite consistent. Six of the ten size bins have significantly lower numbers of simulated hits than predicted in theory while the other four are very near predicted levels. This may indicate that the weighted average area calculated may be slightly higher than that effectively created by the simulation and its more than 20 000 hits. Some error here is to be expected since both are simulations.

As displayed in Table 5.2 through the simulation the probability of a hit of a given size damaging a component or causing critical damage has been established. The trend one would expect to find is one in which the larger the particle the greater the chance of causing damage, critical or otherwise. This trend is evident although not all of the particle sizes follow the trend neatly. Specifically, particles in the 4 mm sized bin show lower than expected probability of causing component damage while

particles in the 6 and 7 mm size bin seem overly dangerous. This is not unusual since at the larger sizes even within 20 000 lifetimes only a handful of hits are occurring which leads to high uncertainties. For example, the 7 mm size bin has a very high probability of a collision of this size damaging a component. This probability is 0.39241. However, the variability of this result if estimated using equations 4-8 and 4-9 is very high with the 95 percent confidence interval being ± 0.10768 which is over 27% of the result.

These high variabilities at large particle sizes is not critical for the following reasons. First of all, when the overall situation is considered, the result is quite accurate as indicated by the overall probability of satellite failure presented earlier. Also, these occurrences are extremely rare as indicated by the low number of occurrences in 20 000 lifetimes and therefore, although variable, do not matter a great deal in the practical picture. The large particles which have very high variabilities over this size a run contribute only about 15 percent of the critically damaging cases.

The important individual results are for the small sizes which contribute most of the damage. In this case 3 mm diameter particles will be included within the definition of "small". These individual results are important because they have been used to predict the number of incidences in which a neglected "multiple" hit may have caused damage to the satellite, either critical or otherwise. Due to the high number of occurrences of collisions involving these small particles the accuracy of these results are quite good.

The estimate was accomplished using equation 4-7 to predict the percentage of

occurrences of hits which were singular for a given size. This result then could be used in combination with the number of hits which occurred in the simulation to predict the number of second hits which may have occurred. This was then multiplied by the simulated probability that given a hit of that size, damage or critical damage would be done. Thus the number of damaging and critically damaging hits which were neglected through the assumption of single hits was predicted. This number, when divided by the 20 000 lifetimes over which they were assumed to occur, results in the probabilities of damage caused by multiple hits. It was assumed that multiple hits did not result in multiple damagings which neglects the chance that a consecutive hit may damage the second of a redundant pair. It was not possible to account for this since there were no such occurrences and so no probability could be assigned to this occurrence. The standard error of the result was adjusted using equation 4-10 as the probabilities were combined.

Another interesting fact which can be derived from the individual results by particle size is the more "critical" nature of the small slow moving particles. These particles while contributing only 38.2 percent of the component damage, contribute 62.2 percent of the critical damage. This is easily explained when one considers the requirement that a small particle be moving slowly in order to cause damage. Since angle of approach and velocity are directly related it is known that the slower moving particles will be approaching at high angles which increases the likelihood that they will impact one of the side faces rather than the front. The front face is highly redundant and is protected by the breakdown of incoming particles moving at high

speed. However, the sides will be impacted more often by slow moving particles which will not breakdown on contact with the thermal blanket. In addition, the sides have less redundant components.

The number of hits occurring per face is a result to which there is no theory to compare. If a simple analysis is conducted, making the assumption that the k value used in equation 1-1 to generate the flux was 3.5, then the k values for each face of the satellite can be found. This is done by realizing that the average number of hits per unit time N is found in the following manner:

$$N = k * A_{avg} * f \quad (5-1)$$

where A_{avg} - is the weighted average area
 f - is the unadjusted for orientation flux and
 $k = 3.5$

It is also known that

$$N_s = k_s * A_s * f \quad (5-2)$$

where A_s is the actual area of the surface in question and not the visible cross-sectional area. For the positive X face this is
 $42'' \times 42.5'' = 1.1516 \text{ m}^2$

The fraction which has hit a given surface is:

$$F_s = N_s / N = 3.5 * A_{avg} / (k_s * A_s) \quad (5-3)$$

Therefore:

$$k_s = 3.5 * A_{avg} * F_s / A_s \quad (5-4)$$

Once the k values for the sides were established it was evident that the method used to

predict the number of hits and on what face they occurred was accurate. It is known that for a surface whose normal points in the same direction as the spacecraft velocity vector, in cases where the angle of incidence of the orbit is near polar, the k value will approach its practical maximum of 3.5. The RADARSAT satellite is in an orbit with an angle of incidence of 98.5 degrees which is near polar, and slightly retrograde, which leads to a high percentage of head on collisions. The positive X face of the satellite has a normal only 5 degrees pitched down from RADARSAT's velocity vector. Therefore the apparent k_x of approximately 3.3 appears to be a result which is consistent with the theory.

The other surfaces have k values lower than 1.0 meaning they are less likely to be hit than an equal surface area on a freely tumbling satellite. This result is also consistent with the theory since the velocity distribution of particles approaching RADARSAT leads to very few high angles of approach which means that most particles will see very little area other than the front surface.

Their order is appropriate as well since the positive and negative Y surfaces should present equal effective area to incoming particles except for the protecting lip which the space deck creates over the negative Y surface. Therefore the second most likely surface to be hit is and should be the positive Y surface followed by the negative Y surface. The space deck itself is the least likely per unit area to be hit by incoming particles because it can only be hit from the front and right and not the left, and because it is consistently at the highest oblique angle to the approaching particles.

The number of complete misses of all components that occur by a particle

which has impacted the satellite is significant. The number is surprisingly high given the density of components on the external surfaces. Few of these hits hold any significance since they pose no threat to the satellite. However, a few of the hits on the front face can penetrate the honeycomb sandwich plate and enter the bus module's interior. Of these fewer still represent a threat to the fuel tank. The effect of these hits on the overall survivability of the satellite could be as much as 14%. The method used to determine this result neglects the effect of the honeycomb and uses a worst case normal collision assuming that all hits of this type will impact the fuel tank. Given that this result is a maximum determined using a very conservative method it is very likely that this effect will fall within the range of variability of the overall result.

Of additional concern may be the number of ballistic collisions, that is those which have a velocity of 7.0 km/s or less, occurring which do not hit any component but hit only the thermal blanket, the honeycomb sandwich plate and then possibly enter the interior of the bus module. Very little is known about how to deal with a collision of this type, which would be at a highly oblique angle, with a honeycomb sandwich plate. Most of these collisions will occur on the side faces with a fairly high angle towards the rear of the satellite indicating that a hit of this type would most likely miss the central fuel tank which is the internal component of greatest vulnerability. The analysis completed does not produce a result for this type of occurrence but it is felt that this will also fall within the range of variability of the final result obtained.

To get an approximate idea if the number of lifetimes simulated is sufficient, one might compare the total number of strikes that occur on similar sized components. Due to shadowing and component placement some differences may occur in the area available to be hit but this is evident and can be considered in drawing the comparison. For example on the positive X surface there are several components of similar size and shape. Components 1 and 5 are very similar in size and neither are shadowed significantly by other components. These two components were hit 81 and 79 times respectively during the simulation. Components 8, 9 and 10 are identical in size and are rowed up together with 9 in the middle such that it is shadowed the most, while components 8 and 10 are shadowed approximately equally. The number of hits which each of these components faced was 35, 29 and 42 respectively. This indicates fairly consistent results.

It is apparent from the results that when examined individually on a component or particle size level that there exists a great deal of variability due to the rarity of certain occurrences. However, this has little effect on the overall results and the variability of the complete survivability of the spacecraft. Given the uncertainty inherent in attempting to make this sort of prediction it would be pointless to push for much greater accuracy at individual component or particle size levels. The exception to this rule may occur if one is attempting to reconfigure a spacecraft to optimize shielding weight while meeting certain survivability requirements which would require decisions on how to shield different components individually.

Chapter 6 : Conclusions and Recommendations

In this Chapter the effects of the results will be considered and how these may effect the RADARSAT satellite. A presentation will be made of how the RADARSAT vehicle might be improved with regards to shielding. Furthermore, consideration will be made as to the direction that further software development, and implementation, should take within this field.

6.1 Conclusions

The following set of conclusions can be drawn given the results of this study:

- 1) The RADARSAT satellite has a probability of approximately 0.99 of surviving the debris environment to which it is expected to be exposed.
- 2) Individual components are by far the most vulnerable to debris and the safety of a system can be virtually guaranteed by introducing a redundant pair.
- 3) The debris environment has grown to the extent that very accurate methods of predicting the environment to be faced and the result of collisions within this environment are required. Otherwise spacecraft will grow too heavy due to over-shielding due to overly conservative estimates of the danger posed.
- 4) Experimentation is required to develop updated equations which include the following considerations: oblique impacts on a variety of materials; impacts which occur within the shatter region of 3 km/s to 7 km/s; partial hits of

debris from a hypervelocity region; and further development of the existing equations for hypervelocity impacts. Testing of types described above should also be conducted with honeycomb sandwich plates as either or both of the bumper or back plate if this type of structure is to be used as a method of shielding.

- 5) The simulation shows very good accuracy with regards to overall results. This indicates that this software if expanded to deal with more complex models could produce very accurate estimates of the survivability of entire spacecraft.
- 6) Expanded versions of software of the type developed for this project could be quickly and easily applied to find individual component survivabilities which could be applied to shielding design.
- 7) Software could be developed for the purpose of optimizing shielding design which operated on the principal used in this project.

6.2 Recommendations

Given the high survivability of the entire bus module, it is possible that some weight savings could be made by adjusting the thicknesses of the faces of some of the component boxes. This could be done without significantly sacrificing this desirable result. For example, the decision was made by CSA during the 1991 period of analysis to thicken the front faces of the Sun Sensor Electronics boxes to 0.30 inches. The reason this was done was primarily due to the conservative method of vulnerability analysis. Due to the distance between the thermal insulating blanket and

these components a great deal of spread of debris occurs before these boxes are hit, and this being the case these three components are damaged only 35 percent of the times they are hit. Due to their small size they are not a particularly often hit group. Given that two are redundant with each other and the third is used only rarely this indicates that they are perhaps over-protected.

A further example of over-shielding is the Power Control Unit on the Negative Y surface. This component is large and presents a considerable target and does require the thicker 0.30 inch shielding on its front and left and perhaps top surfaces. However, this component has had every wall thickened to 0.30 inches and given the size of this component that is a significant weight which is unnecessary for most of the components surface. This component is the most damaged component but almost all of these hits occur on the surfaces mentioned above.

Another adjustment which should be made is to the Power Management Unit also located on the negative Y surface. This unit should have its front and left surfaces thickened. This component is not redundant and is damaged 37 times during the 20 000 lifetime study. This represents almost 20 percent of the critical damage that was predicted during the entire simulation.

The Attitude Control Processor's survivability could also be improved through increased shielding on its front, right and bottom sides. It is located on the positive Y face of the RADARSAT Bus module and should therefore be vulnerable exclusively on those surfaces. This component is also not redundant and is one of the more vulnerable components with 36 incidences of penetration during the 20 000 lifetimes.

This again is almost 20 percent of the critical damage predicted.

If the above recommendations were followed it is believed that the net effect if any on the bus module's survivability would be an increase. The vulnerability of the Sun Sensor's and the Power Control Unit should be increased only very little while the Power Management Unit and Attitude Control Processor should become far less vulnerable. It would also result in a net savings on weight of shielding.

This software displayed excellent potential for the analysis of the survivability of spacecraft. A more sophisticated solid modelling system would be required since the system employed in this study was difficult to interact with in certain ways. Of greatest difficulty was keeping track of object names and identities. This problem could easily be solved through the development of a package specifically to meet this need.

A software design team could easily adapt an existing software package to meet needs specific to the modelling of satellites and debris collisions. Objects and blocks could be named by the system according to a preset method which is conducive to use within this type of analysis. Another problem quickly solved could be the problem with creating certain complex solids which are produced by shadowing. These specific problems could be addressed.

The greatest problem encountered was attempting to create a piece of software which was completely compatible with, and which could operate within, the strictures of another software package. This could be eliminated altogether by creating a combined package specifically for this use.

However, the software is not the greatest inadequacy involved in the solution of this problem. Although improved software is of importance good accuracy cannot be obtained until equations are developed for a wider range of collision types and until a greater knowledge of the amount and size of debris in various orbits is improved. The time and expense involved in attempting to track smaller debris particles and in running experiments which allow for the development of complex impact equations is the greatest barrier.

Hopefully current programs designed to reduce the rate of accumulation of debris in orbit will be effective and this problem will not grow prohibitive to the launch and operation of low altitude spacecraft. If the problem is checked here then for most spacecraft the current information is sufficient to be used in conjunction with the methodology of this project to ensure, as much as possible, the safety of the spacecraft. However, if the problem is allowed to continue to grow then soon many of the assumptions required by this method of analysis may no longer be valid and will no longer lead to neglectable results.

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Appendix A : Procedure Call Tree

APPENDIX B: Complete Results of Simulation By Group

128

GROUP 1

Total number of lifetimes = 2000

Total number of hits = 1248

Total number of dangerous hits = 233

Total number of times damaged = 52

Total number of times critically damaged = 17

Face	Component	Redundant With	Number of Hits	Times Damaged	Probability of Damage
+X	1	N/A	6	3	0.00150
	2	N/A	1	0	0.00000
	3	4	2	2	0.00100
	4	3	3	3	0.00150
	5	N/A	2	2	0.00100
	6	7	1	0	0.00000
	7	6	3	1	0.00050
	8	9	3	1	0.00050
	9	8	5	1	0.00050
	10	N/A	5	1	0.00050
	11	12	7	1	0.00050
	12	11	7	2	0.00100
	13	14	1	1	0.00050
	14	13	4	2	0.00100
	15	16	2	2	0.00100
	16	15	7	5	0.00250
-Y	1	N/A	0	0	0.00000
	2	N/A	7	5	0.00250
	3	N/A	4	1	0.00050
	4	N/A	12	1	0.00050
+Y	1	N/A	4	2	0.00100
	2	3	2	0	0.00000
	3	2	9	6	0.00300
	4	5	3	3	0.00150
	5	4	2	1	0.00050
	6	7	2	0	0.00000
	7	6	4	1	0.00050
	8	N/A	8	5	0.00250

Diameter of Particle(mm)	Number of Hits	Number of Dangerous Hits	Number of Damaging Hits	Number of Critically Damaging Hits
1.0	822	70	15	7
2.0	285	22	7	5
3.0	75	75	18	4
4.0	28	28	3	0
5.0	13	13	2	0
6.0	11	11	3	1
7.0	3	3	0	0
8.0	4	4	1	0
9.0	4	4	1	0
10.0	3	3	2	0

GROUP 2

Total number of lifetimes = 2000

Total number of hits = 1318

Total number of dangerous hits = 251

Total number of times damaged = 60

Total number of times critically damaged = 18

Face	Component	Redundant With	Number of Hits	Times Damaged	Probability of Damage
+X	1	N/A	6	2	0.00100
	2	N/A	6	0	0.00000
	3	4	5	3	0.00150
	4	3	3	3	0.00150
	5	N/A	9	5	0.00250
	6	7	3	0	0.00000
	7	6	5	2	0.00100
	8	9	4	2	0.00100
	9	8	3	2	0.00100
	10	N/A	4	1	0.00050
	11	12	6	2	0.00100
	12	11	4	0	0.00000
	13	14	2	0	0.00000
	14	13	0	0	0.00000
	15	16	3	3	0.00150
	16	15	3	3	0.00150
-Y	1	N/A	2	1	0.00050
	2	N/A	3	3	0.00150
	3	N/A	2	1	0.00050
	4	N/A	13	7	0.00350
+Y	1	N/A	3	1	0.00050
	2	3	6	5	0.00250
	3	2	4	2	0.00100
	4	5	2	1	0.00050
	5	4	4	2	0.00100
	6	7	4	3	0.00150
	7	6	3	3	0.00150
	8	N/A	7	3	0.00150

Diameter of Particle(mm)	Number of Hits	Number of Dangerous Hits	Number of Damaging Hits	Number of Critically Damaging Hits
1.0	860	59	21	9
2.0	286	20	6	4
3.0	85	85	12	3
4.0	29	29	6	1
5.0	25	25	4	1
6.0	13	13	7	0
7.0	10	10	1	0
8.0	2	2	0	0
9.0	5	5	2	0
10.0	3	3	1	0

GROUP 3

Total number of lifetimes = 2000

Total number of hits = 1274

Total number of dangerous hits = 273

Total number of times damaged = 54

Total number of times critically damaged = 16

Face	Component	Redundant With	Number of Hits	Times Damaged	Probability of Damage
+X	1	N/A	5	2	0.00100
	2	N/A	3	1	0.00050
	3	4	2	1	0.00050
	4	3	0	0	0.00000
	5	N/A	8	7	0.00350
	6	7	8	5	0.00250
	7	6	11	3	0.00150
	8	9	6	1	0.00050
	9	8	6	0	0.00000
	10	N/A	4	2	0.00100
	11	12	8	1	0.00050
	12	11	2	1	0.00050
	13	14	3	0	0.00000
	14	13	4	1	0.00050
	15	16	5	4	0.00200
	16	15	5	3	0.00150
-Y	1	N/A	0	0	0.00000
	2	N/A	2	2	0.00100
	3	N/A	5	0	0.00000
	4	N/A	23	8	0.00400
+Y	1	N/A	3	1	0.00050
	2	3	2	1	0.00050
	3	2	4	2	0.00100
	4	5	2	1	0.00050
	5	4	2	1	0.00050
	6	7	2	1	0.00050
	7	6	3	3	0.00150
	8	N/A	8	2	0.00100

Diameter of Particle(mm)	Number of Hits	Number of Dangerous Hits	Number of Damaging Hits	Number of Critically Damaging Hits
1.0	812	66	13	3
2.0	283	28	7	4
3.0	94	94	13	5
4.0	31	31	6	0
5.0	18	18	4	1
6.0	5	5	1	0
7.0	9	9	4	1
8.0	5	5	1	1
9.0	9	9	5	1
10.0	8	8	0	0

GROUP 4

Total number of lifetimes = 2000

Total number of hits = 1321

Total number of dangerous hits = 271

Total number of times damaged = 70

Total number of times critically damaged = 17

Face	Component	Redundant With	Number of Hits	Times Damaged	Probability of Damage
+X	1	N/A	14	6	0.00300
	2	N/A	4	1	0.00050
	3	4	5	3	0.00150
	4	3	0	0	0.00000
	5	N/A	9	5	0.00250
	6	7	6	4	0.00200
	7	6	7	5	0.00250
	8	9	1	0	0.00000
	9	8	1	1	0.00050
	10	N/A	6	3	0.00150
	11	12	4	2	0.00100
	12	11	10	4	0.00200
	13	14	3	1	0.00050
	14	13	2	1	0.00050
	15	16	7	7	0.00350
	16	15	4	4	0.00200
-Y	1	N/A	0	0	0.00000
	2	N/A	4	4	0.00200
	3	N/A	2	0	0.00000
	4	N/A	12	2	0.00100
+Y	1	N/A	7	1	0.00050
	2	3	5	3	0.00150
	3	2	10	5	0.00250
	4	5	7	2	0.00100
	5	4	5	2	0.00100
	6	7	0	0	0.00000
	7	6	1	1	0.00050
	8	N/A	5	3	0.00150

Diameter of Particle(mm)	Number of Hits	Number of Dangerous Hits	Number of Damaging Hits	Number of Critically Damaging Hits
1.0	840	70	17	4
2.0	296	16	6	3
3.0	95	95	22	2
4.0	34	34	9	2
5.0	21	21	4	0
6.0	7	7	0	0
7.0	9	9	4	1
8.0	10	10	4	2
9.0	6	6	2	1
10.0	3	3	2	2

GROUP 5

Total number of lifetimes = 2000

Total number of hits = 1256

Total number of dangerous hits = 250

Total number of times damaged = 69

Total number of times critically damaged = 16

Face	Component	Redundant With	Number of Hits	Times Damaged	Probability of Damage
+X	1	N/A	9	5	0.00250
	2	N/A	8	2	0.00100
	3	4	1	0	0.00000
	4	3	0	0	0.00000
	5	N/A	12	9	0.00450
	6	7	5	2	0.00100
	7	6	4	4	0.00200
	8	9	4	0	0.00000
	9	8	4	2	0.00100
	10	N/A	6	3	0.00150
	11	12	9	3	0.00150
	12	11	3	0	0.00000
	13	14	3	2	0.00100
	14	13	4	1	0.00050
	15	16	8	8	0.00400
	16	15	5	5	0.00250
-Y	1	N/A	1	0	0.00000
	2	N/A	3	3	0.00150
	3	N/A	1	0	0.00000
	4	N/A	10	3	0.00150
+Y	1	N/A	1	0	0.00000
	2	3	5	2	0.00100
	3	2	8	5	0.00250
	4	5	4	3	0.00150
	5	4	2	2	0.00100
	6	7	1	0	0.00000
	7	6	4	2	0.00100
	8	N/A	6	3	0.00150

Diameter of Particle(mm)	Number of Hits	Number of Dangerous Hits	Number of Damaging Hits	Number of Critically Damaging Hits
1.0	811	55	17	5
2.0	272	22	8	2
3.0	97	97	18	3
4.0	32	32	10	0
5.0	18	18	6	1
6.0	11	11	3	2
7.0	6	6	3	1
8.0	6	6	2	0
9.0	2	2	1	1
10.0	1	1	1	1

GROUP 6

Total number of lifetimes = 2000

Total number of hits = 1231

Total number of dangerous hits = 240

Total number of times damaged = 63

Total number of times critically damaged = 29

Face	Component	Redundant With	Number of Hits	Times Damaged	Probability of Damage
+X	1	N/A	10	6	0.00300
	2	N/A	6	2	0.00100
	3	4	3	2	0.00100
	4	3	1	1	0.00050
	5	N/A	9	4	0.00200
	6	7	4	4	0.00200
	7	6	3	0	0.00000
	8	9	2	1	0.00050
	9	8	1	1	0.00050
	10	N/A	3	2	0.00100
	11	12	5	0	0.00000
	12	11	6	3	0.00150
	13	14	0	0	0.00000
	14	13	1	0	0.00000
	15	16	3	2	0.00100
	16	15	4	4	0.00200
-Y	1	N/A	3	1	0.00050
	2	N/A	6	5	0.00250
	3	N/A	1	0	0.00000
	4	N/A	13	3	0.00150
+Y	1	N/A	7	3	0.00150
	2	3	4	1	0.00050
	3	2	5	4	0.00200
	4	5	1	1	0.00050
	5	4	2	1	0.00050
	6	7	5	3	0.00150
	7	6	0	0	0.00000
	8	N/A	13	9	0.00450

Diameter of Particle(mm)	Number of Hits	Number of Dangerous Hits	Number of Damaging Hits	Number of Critically Damaging Hits
1.0	801	60	18	12
2.0	275	25	10	7
3.0	80	80	12	3
4.0	28	28	6	2
5.0	15	15	5	0
6.0	10	10	5	3
7.0	9	9	3	1
8.0	7	7	1	0
9.0	5	5	2	1
10.0	1	1	1	0

GROUP 7

Total number of lifetimes = 2000

Total number of hits = 1231

Total number of dangerous hits = 248

Total number of times damaged = 68

Total number of times critically damaged = 25

Face	Component	Redundant With	Number of Hits	Times Damaged	Probability of Damage
+X	1	N/A	2	1	0.00050
	2	N/A	4	1	0.00050
	3	4	2	1	0.00050
	4	3	4	4	0.00200
	5	N/A	7	6	0.00300
	6	7	4	2	0.00100
	7	6	3	3	0.00150
	8	9	3	0	0.00000
	9	8	3	0	0.00000
	10	N/A	3	3	0.00150
	11	12	6	2	0.00100
	12	11	1	0	0.00000
	13	14	1	1	0.00050
	14	13	2	0	0.00000
	15	16	6	6	0.00300
	16	15	4	3	0.00150
-Y	1	N/A	0	0	0.00000
	2	N/A	8	7	0.00350
	3	N/A	3	2	0.00100
	4	N/A	11	7	0.00350
+Y	1	N/A	7	3	0.00150
	2	3	5	2	0.00100
	3	2	1	0	0.00000
	4	5	1	0	0.00000
	5	4	4	2	0.00100
	6	7	3	3	0.00150
	7	6	7	5	0.00250
	8	N/A	6	4	0.00200

Diameter of Particle(mm)	Number of Hits	Number of Dangerous Hits	Number of Damaging Hits	Number of Critically Damaging Hits
1.0	798	62	18	10
2.0	271	24	10	5
3.0	90	90	16	5
4.0	26	26	4	1
5.0	12	12	3	1
6.0	14	14	6	1
7.0	7	7	3	0
8.0	6	6	4	1
9.0	4	4	1	1
10.0	3	3	3	0

GROUP 8

Total number of lifetimes = 2000

Total number of hits = 1275

Total number of dangerous hits = 257

Total number of times damaged = 65

Total number of times critically damaged = 14

Face	Component	Redundant With	Number of Hits	Times Damaged	Probability of Damage
+X	1	N/A	14	5	0.00250
	2	N/A	4	0	0.00000
	3	4	2	2	0.00100
	4	3	3	3	0.00150
	5	N/A	8	4	0.00200
	6	7	6	2	0.00100
	7	6	3	1	0.00050
	8	9	4	0	0.00000
	9	8	1	0	0.00000
	10	N/A	2	1	0.00050
	11	12	9	2	0.00100
	12	11	3	2	0.00100
	13	14	1	1	0.00050
	14	13	3	2	0.00100
	15	16	7	6	0.00300
	16	15	9	9	0.00450
-Y	1	N/A	1	0	0.00000
	2	N/A	3	3	0.00150
	3	N/A	2	1	0.00050
	4	N/A	18	5	0.00250
+Y	1	N/A	3	0	0.00000
	2	3	3	2	0.00100
	3	2	7	4	0.00200
	4	5	9	6	0.00300
	5	4	5	2	0.00100
	6	7	1	1	0.00050
	7	6	1	1	0.00050
	8	N/A	3	0	0.00000

Diameter of Particle(mm)	Number of Hits	Number of Dangerous Hits	Number of Damaging Hits	Number of Critically Damaging Hits
1.0	821	55	10	3
2.0	273	21	10	3
3.0	89	89	17	6
4.0	38	38	11	0
5.0	15	15	4	0
6.0	11	11	1	0
7.0	13	13	8	1
8.0	6	6	0	0
9.0	2	2	1	0
10.0	7	7	3	1

GROUP 9

Total number of lifetimes = 2000

Total number of hits = 1259

Total number of dangerous hits = 235

Total number of times damaged = 47

Total number of times critically damaged = 15

Face	Component	Redundant With	Number of Hits	Times Damaged	Probability of Damage
+X	1	N/A	7	0	0.00000
	2	N/A	4	0	0.00000
	3	4	2	0	0.00000
	4	3	3	3	0.00150
	5	N/A	5	3	0.00150
	6	7	3	0	0.00000
	7	6	3	2	0.00100
	8	9	1	0	0.00000
	9	8	0	0	0.00000
	10	N/A	4	3	0.00150
	11	12	3	0	0.00000
	12	11	8	2	0.00100
	13	14	0	0	0.00000
	14	13	0	0	0.00000
	15	16	2	2	0.00100
	16	15	3	3	0.00150
-Y	1	N/A	1	1	0.00050
	2	N/A	4	3	0.00150
	3	N/A	3	0	0.00000
	4	N/A	17	6	0.00300
+Y	1	N/A	5	2	0.00100
	2	3	6	4	0.00200
	3	2	5	4	0.00200
	4	5	5	0	0.00000
	5	4	3	2	0.00100
	6	7	6	2	0.00100
	7	6	4	2	0.00100
	8	N/A	6	3	0.00150

Diameter of Particle(mm)	Number of Hits	Number of Dangerous Hits	Number of Damaging Hits	Number of Critically Damaging Hits
1.0	827	55	20	10
2.0	275	23	7	4
3.0	79	79	9	0
4.0	42	42	6	0
5.0	10	10	0	0
6.0	11	11	2	1
7.0	5	5	1	0
8.0	8	8	2	0
9.0	2	2	0	0
10.0	0	0	0	0

GROUP 10

Total number of lifetimes = 2000

Total number of hits = 1230

Total number of dangerous hits = 261

Total number of times damaged = 56

Total number of times critically damaged = 12

Face	Component	Redundant With	Number of Hits	Times Damaged	Probability of Damage
+X	1	N/A	8	1	0.00050
	2	N/A	6	1	0.00050
	3	4	4	1	0.00050
	4	3	2	2	0.00100
	5	N/A	10	8	0.00400
	6	7	4	1	0.00050
	7	6	6	3	0.00150
	8	9	7	2	0.00100
	9	8	5	3	0.00150
	10	N/A	5	1	0.00050
	11	12	6	1	0.00050
	12	11	2	0	0.00000
	13	14	2	2	0.00100
	14	13	2	1	0.00050
	15	16	4	3	0.00150
	16	15	4	4	0.00200
-Y	1	N/A	0	0	0.00000
	2	N/A	3	2	0.00100
	3	N/A	3	0	0.00000
	4	N/A	19	3	0.00150
+Y	1	N/A	4	1	0.00050
	2	3	5	1	0.00050
	3	2	11	5	0.00250
	4	5	2	1	0.00050
	5	4	3	3	0.00150
	6	7	1	0	0.00000
	7	6	3	2	0.00100
	8	N/A	9	4	0.00200

Diameter of Particle(mm)	Number of Hits	Number of Dangerous Hits	Number of Damaging Hits	Number of Critically Damaging Hits
1.0	794	58	7	3
2.0	254	21	4	1
3.0	89	89	16	3
4.0	32	32	11	0
5.0	23	23	4	1
6.0	6	6	1	0
7.0	8	8	4	2
8.0	11	11	4	1
9.0	7	7	2	0
10.0	6	6	3	1

END

3 1 - 0 5 - 9 5

FIN

Chapter 4 : Simulation Determinations - Parameters, Probability and Accuracy

This chapter will examine the usage of the software that was developed. The methods used to determine input parameters are explained and the results of those determinations are given. There is also an explanation of how certain probabilities are determined and how the accuracy of a simulation is found.

4.1 Simulation Strategy

The strategy being employed to determine the probability of the RADARSAT satellite surviving the intended mission is a life simulation type. The entire lifetime of the satellite will be simulated to determine the entire sequence of collision events which may occur in a given lifetime. A given lifetime may have any number of collisions from a variety of different sized particles or may have no collisions whatsoever.

A large series of these possible lifetimes will be simulated to determine how often a critical failure will occur. For example if 200 simulated lifetimes indicate critical component damage while another 9800 indicate survival then it will be assumed that there is a 98% chance that the RADARSAT satellite will survive its mission.

This method is used because of its simplicity in determining the probability of