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ANALYSIS AND INTEGRATION OF A DEBRIS MODEL IN THE VIRTUAL RANGE PROJECT

by

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B.S. Academia Politécnica Militar, 2002

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Modeling and Simulation in the College of Engineering and Computer Science at the University of Central Florida Orlando, Florida

Fall term
2004

Major Professor: José A. Sepulveda
ABSTRACT

After the accident of the STS 107 Columbia Space Shuttle, great concern has been focused on the risk associated to the population on the ground. Before this accident happened, re-entry routes as well as risk calculation of $E_c$ were not of public concern. Two issues that have been raised from this lamentable accident relate to spacecraft security and to public safety.

The integration of a debris model has been part of the original conceptual architecture of the Virtual Range Project. Its integration has been considered as a specific research due to the complexity of the models and the difficulties to obtain them since the commercial off-the-shelf available software seems to be less accessible.

This research provides solid information concerning what debris fragmentation models are, their fundamentals, their weaknesses and strengths. The research provides information of the main debris models being currently used by NASA which have direct relationship with the space programs conducted.

This study also addresses the integration of a debris model into the Virtual Range Project. We created a provisional model based on the distribution of the Columbia debris fragments over Texas and part of Louisiana in order to create an analytical methodology as well. This analysis shows a way of integrating this debris model with a Geographic Information System as well as the integration of several raster and vector data sets which will provide the source data to compute the calculations.

This research uses population data sets that allow the determination of the number of people at risk on the ground. The graphical and numerical analysis made can lead to the
determination of new and more secure re-entry trajectories as well as further population-related security issues concerning this type of flights.
ACKNOWLEDGEMENTS

I appreciate the support of many as I have worked on this thesis. I am thankful to my advisor, Dr. Jose Sepulveda (PhD) for his continuous support, and to Dr. Luis Rabelo (PhD) for the information provided in order to make this thesis possible. I am grateful to Lieutenant Colonel Sergio Quijada (Chilean War College), Mayor Carlos Neira and Eng. Alvaro Pinochet (both from the Military Geographic Institute of the Chilean Army) for the support and the information they provided on Geographic Information System related issues. I am indebted to my wife, Carolina, and to my four daughters for being there, beside me, at all times.
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CHAPTER 1: OVERVIEW

This cause of exploration and discovery is not an option we choose; it is a desire written in the human heart..., We find the best among us, send them forth into unmapped darkness, and pray they will return. They go in peace for all Mankind, and all Mankind is in their debt.


1.1 Problem Statement

Due to the increasing public concern of the possible risk associated to the people on the ground –as well as to the general aviation aircraft– for an eventual shuttle breakup during re-entry, and according to specific studies already made (Columbia Accident Investigation Board [CAIB Report], 2003), NASA is facing one of the biggest challenges of all time: the survival of the Space Transportation System Program. The best way to decrease the associated risk of this kind of enterprise is to reduce the risk to the people on the ground by implementing different measures and by improving how that risk is being calculated.

Efficiently predicting the debris dispersion hazards will be one of the main issues for the following years. Re-entry routes, spaceports, schedule time and other important factors will be circumscribed to important software tools such as debris dispersion models.

This research addresses debris dispersion models and integration methodology to the Virtual Range Project (VRP) which will have a very important role in risk evaluation for future space missions.
1.2 Background

On February 1, 2003, the Columbia Space Shuttle disintegrated during its re-entry phase, 38 miles over the earth’s surface. The accident had fatal consequences and the spacecraft was torn into more than 80,000 pieces which spread as 40 tons of debris in rural parts of Eastern Texas and Western Louisiana. At that time, the Columbia had an estimated speed of Mach 21, and the probability of survivability was zero. The explosion resulted in a debate over several issues, and one of the most important being the possible danger debris could have to the public.

In order to investigate the probable causes of such an accident, the Columbia Accident Investigation Board (CAIB Report, 2003) was established, and its investigation provided several conclusions about the causes and effects of the accident and proposed recommendations.

The Columbia Accident Investigation Board released Vols. II-VI of the CAIB's Final Report (Sept. 2003). These volumes contain appendices that provide the supporting documentation for the main text of the Final Report contained in Volume one, which was released on August 26, 2003. Through this report the board suggested a need for analysis of debris risk to the public due to a Space Shuttle breakup during re-entry. The number of casualties from the large number of Columbia fragments was null, but was this lack of casualties the expected consequence or was it just good fortune? For this reason, the University of Central Florida became involved in scientific research that will present a way to assess and evaluate possible risks related to this topic.

The VRP provides a modeling and simulation environment for space ranges to determine the population at risk and the expected casualties ($E_c$) as a result of an explosion consequence (VRP, 2004). It will integrate various models of blast, debris dispersion, and gas dispersion for
the first 120 seconds after launch from Kennedy Space Center (KSC), and again during the re-entry phase according to pre-established re-entry routes given by NASA. This is done in order to calculate the possible $E_c$ given a “loss of vehicle”; factors like wind, temperature and humidity will influence the model.

As part of the aforementioned project, major concern was given to public safety considering possible debris fragments risk, and sheltering of the people located in the projected re-entry route. Additionally, simulation of a debris cloud, a probabilistic impact dispersion for the falling debris, and other points that may be included as casualty models for people in the open and in structures, along with aircraft risk assessment, and validation of computed data and sensitivity evaluation.

Even if we consider that the public will remain as the most critical concern, aircraft safety is, as mentioned before, a big issue. Despite the steady increase of space launches over the past few years, the current procedure for ensuring aircraft safety is to restrict all air traffic from flying over a very large region of Special Use Airspace and/or Altitude Reservations within the respective range (Van Suetendael, 2003).

The collected data of the Columbia accident shows that most of the recovered debris was found over a large area in mostly rural parts of eastern Texas and Louisiana while “the lack of casualties according to the investigation lead by ACTA inc., showed that the lack of serious injuries on the ground was the expected outcome for the location and time,” the risk was not insignificant. “There was about a nine to twenty four percent chance of at least one person being seriously injured by the disintegration of the orbiter” said the report (CAIB Report, 2003).
The determination of debris risk to the public due to the Columbia breakup during re-entry is considered in Appendix D.16 of the CAIB Report. This work shows that a probability of less than 0.5 but greater than 0.05 existed for a possible casualty. The probability of debris hitting general aviation aircraft was higher than would be allowed for unrestricted aircraft operations by the Federal Aviation Administration (FAA).

Another conclusion of the report is that, to decrease public risk from re-entry and possible breakup, the shuttle should land during the middle of the night, when almost everyone is inside a shelter and few aircraft are in flight (CAIB Report, 2003).

NASA made a meaningful collaboration by sharing the actual database (Excel files as shown in Appendix A) of all debris fragments gathered from more than 84,000 pieces, and with a data of 75,440 pieces of recovered debris with included coordinates. This amount of debris fragments represents around 38% of the expected orbiter and payload landing weight (CAIB Report, 2003). The spreadsheet also contained some useful descriptive information including some dimensions for about 15,470 pieces of debris, and general characteristics of some recovered debris.
1.3 **Operational Environment**

The research is part of the VRP. We particularly focus on debris effect models and integration methodology. These two factors will have the biggest impact on determining population risk from a possible disaster’s various manifestations. If, as we saw in the Columbia accident mentioned before, the debris resulting from a breakup during the re-entry phase reaches
populated areas during the daytime, the results of these falling pieces can be disastrous. There is an urgent need to predict falling debris according to:

- Trajectory of the spacecraft (re-entry route, flight vector, altitude)
- Speed of the spacecraft
- Breakup sequence of the spacecraft
- Breakup type (explosive, thermal, and/or structural)
- Survivability of debris
- Quantity of debris (by mass and number)
- Casualty area of each debris piece
- Lethality of surviving debris
- Sheltering of the population at risk
- Variability in each of the above factors

We should be able to add specific factors for debris pieces such as:

- Drag coefficient of individually falling debris pieces
- Exposed surface area of the fragment
- Velocity of the fragment (related to speed of spacecraft and explosion)
- Coefficient of lift
- Density of the air
- Wind speed and related meteorological issues
- Weight of the fragments
Based on these concepts and requirements, the VRP will have to deal with all issues concerning range managing, command, tracking and monitoring the spacecraft required to meet the range mission; therefore the VRP will have to integrate a range safety simulation model, a Geographic Information System (GIS), population data, a gas dispersion model, a debris effect model, and weather information.

The VRP has a very flexible architecture (Sepulveda, Rabelo & Compton, 2003). To perform risk analysis, a debris effect model such as the Common Real-Time Debris Footprint Model (CRTF®) could be integrated with the commercial off-the-shelf (COTS) applications such as ARENA ® software for simulation, ArcView® as a Geographic Information System, and Calpuff® for gas dispersion simulation.

To get the overall idea, we necessarily need to know a little bit more about the Space Transportation System and some mission planning of previous flights.

To ensure public safety, space missions are controlled by Range Operation Control Centers (ROCC) to monitor a large region of airspace surrounding a launch site (CAIB Report, 2003). For launches at Kennedy Space Center and Cape Canaveral, range safety is maintained by the ROCC located at Cape Canaveral Air Force Station. This center is actually using CRTF® as a way to calculate and manage risk associated with debris dispersion from possible catastrophic failures at launch and re-entry phases.

Risk calculation is based on the probability of the occurrence of an event that can affect a populated area. Factors and statistical methods used to calculate this risk depend on the probability of each of these events and also the possible hazards and consequences for each of those events.
These risks are usually expressed in terms of $E_c$. Its general equation is\textsuperscript{1}:

$$Ec_i = \sum_{i=1}^{n} Ec_i \quad \text{and} \quad Ec_i = P_i \left( \frac{Ac_i}{A_i} \right) N_i$$

Where $Ec_i$ is the expected casualty for an individual event

$P_i$ is the probability that a single fragment will impact an area $A_i$

$Ac_i$ is the casualty area for the exposed population within impact area $A_i$

$N_i$ is the number of people within impact area $A_i$

$Ec_t$ is the total expected casualty

1.4 Synopsis of the thesis

The research presented in this thesis addresses several concepts and procedures. It begins with a literature survey, found in Chapter 2, that introduces us into the principal concepts we are going to use in this research, as the concept of the Virtual Range, Debris models, Geographic Information Systems, etc. Chapter 3 gives a more technical and detailed explanation of the mechanics of the debris dispersion models, and identifies some specific commercial-off-the-shelf debris models. In Chapter 4, a methodology for the integration of a debris model into the Virtual Range Project is presented. It includes the analysis of STS 107 Columbia debris, gathered and geo-referenced by NASA, as well as the determination of the geographic representation through this data, and its affected areas according to trajectory and spatial analysis. Finally, Chapter 5 establishes conclusions and future work.

\textsuperscript{1} Federal Aviation Administration Office of Commercial Space Transportation, 2002
CHAPTER 2: LITERATURE SURVEY

2.1 The Virtual Range

The VRP, as mentioned in the previous chapter, is involved in the determination of expected casualties ($E_c$) as a result of a spacecraft explosion during its launching or re-entry phase.

The system will help local authorities to estimate the population at risk in order to plan for areas to evacuate, and/or for the resources required to provide aid and comfort, and to mitigate damages in case of disaster (Sepulveda, Rabelo & Compton, 2003).

The VRP emulates this range by integrating a Range Safety Simulation Model, Geographic Information Systems (GIS), population data, gas dispersion models and weather information, and in the near future, a fragmentation model (Sepulveda, Rabelo & Compton, 2003). A graphic representation is shown in Figure 3.

Figure 3, The concept of range (figure adapted from Advanced Range Technologies working group).
We can define range as the volume through which the vehicle must pass on its way to and from space, and all the command, tracking, and monitoring functions required to meet the range mission.

For a planned flight path trajectory, the system should project an appropriate “envelope” or footprint of the projected impact area, either with respect to gas dispersion or, the focus of our concern, debris fragmentation for a given risk component.

Figure 4, Debris path of the STS 107 with a 20 km. buffer zone made in EDGE® software by Forest Resources Institute.

The Virtual Range model should be kept as flexible as possible in order to allow the integration of commercial off-the-shelf (COTS) applications such as Arena®, ArcView®, Calpuff® and any available debris model, as elements of the system so they can be applicable to
other shuttle models and/or other areas of launch and re-entry operation with minor modifications (Sepulveda, Rabelo & Compton, 2003).

Geographical data will be restricted to the point of interest. In the specific case of re-entry analysis, different re-entry tracks may be included. The system should allow dynamic and multiple track analysis.

The current system is focused on gas dispersion, as it is shown in Figure 5. In the near future, the system should allow for the introduction of a debris model. This debris model would have to be related to the Monte Carlo simulation which would give the probabilities of failure for a given simulation, according to a given re-entry track route. Only this debris model would allow the system to produce a footprint overlay on ArcMap® due to a simulated break up at a certain altitudes, direction vector, speed and some other factors. This overlay would produce results according to the information contained in the GIS database.

The projected footprint will allow the determination of population at risk according to their sheltering status, to the time of the day, or to the day of the week (All three variables will certainly vary the probability for a person being hit by a debris piece).
We must assume that no big risk would be associated with the launching of a spacecraft with respect to debris or fragmentation as a result of an explosion, mainly due to the security given by the respective spaceports or ranges (Eastern or Western). In the case of Florida, a launching area is seen in Figure 6 as part of the Eastern Range (NASA STS Newsref, 2004):
The Eastern Range includes Cape Canaveral Air Force Station and Kennedy Space Center, owned or leased facilities on downrange sites such as Antigua and Ascension, and in the context of launch operations, the Atlantic Ocean, including all surrounding land, sea, and air space within the reach of any launch vehicle extending eastward into the Indian and Pacific Oceans. Figure 6 shows the typical launch sector for launches from the Eastern Range.

In general, vehicles must be launched in an easterly direction and on an azimuth that provides protection for land masses and populated areas on and off the facility, including the Caribbean Islands, Bermuda, the northeast coasts of South America, and Africa (Sepulveda, Rabelo & Compton, 2003).
Although we mention launching conditions, our primary focus is on re-entry. It is in this phase where the maximum risk conditions with respect to fragmentation-related casualties are met. This phase will have to be integrated to the model through the use of a debris model, as we have mentioned before.
2.2 **The Space Shuttle**

![Space Shuttle Launch](image)

*Figure 9, STS 107 during its launch (CAIB Report, 2003).*

Over 32 years of history have made the space shuttle program the leading program in the world capable of sending reusable spacecrafts to space, allowing enormous scientific gains over dozens of successful missions, however with a couple of devastating costs. In 1986, the Challenger exploded during launch procedures, and on February 1, 2003, the Columbia broke up during re-entry over Texas and Louisiana.

In 1972, President Nixon announced that NASA would develop a reusable space shuttle or space transportation system (STS). NASA decided that the shuttle would consist of an orbiter attached to solid rocket boosters and an external fuel tank because this design was considered safer and more cost effective (Freundenrich, 2004).

After several years of construction and testing, the first flight was accomplished in 1981, ironically with the Columbia spacecraft (other three were built as well). At this time, space
shuttles have flown about one-fourth of their expected lifetime (each one was designed for 100 missions) (NASA STS Newsref, 2004).

NASA’s 40-plus years of space exploration, have led to three major efforts in human space flight, the moon landing program, the Space Shuttle program and the International Space Station program (NASA News Reference Manual, 2004). The space shuttle remains as the only reusable spacecraft in the world capable of simultaneously putting multiple-persons crew and heavy cargo loads into orbit. Spacecrafts have a particular flight profile. The space shuttle has a near vertical trajectory during the short 80-90 seconds it passes through airspace, reaches Mach 2 at about 50,000 ft., and continues accelerating until orbit. When returning, the descent angle is about 15-18º with very limited maneuvering. It hits the atmosphere at about 400,000 ft., reaching a speed of 17,000 mph. When the shuttle reaches 200,000 ft., it gets the highest external temperature, nearly 3,000º F (Wertz & Larson, 1995).

The space shuttle is made of the following components:

- Two solid rocket boosters (SRB) – critical for the launch
- External fuel tank (ET) – carries fuel for the launch
- Orbiter – carries astronauts and payload

A typical mission consists of:

- Getting into orbit
  - Launch
  - Ascent
  - Orbital maneuvering burn

- Orbit
The flight profile, shown in Figure 10, gives us a general understanding of the space shuttle mission process. From the launching up to the landing, many risks are involved. We will analyze what is necessary to the VRP at its re-entry phase, since this phase is the one that would involve greater risk situation for the people on the ground.

Figure 10, Flight profile of STS operations (Freundenrich, 2004).
2.3 **Re-entry Trajectory and Procedures**

The re-entry phase of flight begins when the orbiter is placed into the proper position for a safe landing. When a mission is finished and the shuttle is halfway around the world from the landing site (Kennedy Space Center, Edwards Air Force Base), it has reached an opportunity “window.” This window will allow the orbiter to land at the desired place; otherwise, the orbiter should wait and orbit around the earth until another window is available.

The re-entry phase of flight begins approximately five minutes before the entry interface (EI), which occurs at an altitude of 400,000 ft.. At EI minus five minutes, the orbiter is at an altitude of about 557,000, and traveling at a speed of 25,400 ft. per second, and is approximately 4,400 nautical miles from the landing site (NASA STS Newsref, 2004).

The entry phase is divided into three separate phases because of the unique software requirements. Entry extends from EI minus five minutes to terminal area energy management interface at an altitude of approximately 83,000 ft., and at a velocity of 2,500 ft. per second (NASA STS Newsref, 2004).

The orbiter at the beginning of this re-entry phase will fire the RCS thrusters to turn the orbiter tail first. After its tail is facing the earth’s surface, it will fire the OMS engines to slow down the orbiter in its descent to earth. From this moment, it will take around 25 minutes for the shuttle to reach the outer atmosphere. During this time, the orbiter will fire its RCS thrusters again in order to pitch itself over so that the bottom faces the atmosphere first (around 40°). The inclination will allow the orbiter to resist the friction through the ceramic layer. The nose of the orbiter, due to the enormous speed (17,000 mph, or 28,000 km/h) and consequent friction, is not
capable of resisting the heat (around 3000º F, or 1650º C). Furthermore, the leftover fuel from the forward RCS will be burned as a safety precaution (Freundenrich, 2004).

The orbiter will use the aft steering jets to keep itself at the same 40 degree angle. When re-entry is successful, the orbiter will encounter the upper atmosphere, and it will be able to fly like an airplane. The orbiter will make a series of S-shaped banking turns to slow its descent speed while approaching the runway (Freundenrich, 2004).

Figure 11, Reference path for re-entry (NASA News Reference Manual, 2004).

During the re-entry phase, guidance of the STS will always attempt to keep the orbiter on a trajectory that provides protection against overheating (it has to maintain an angle of around 40º in order to protect the upper surfaces from extreme heat), overdynamic pressure and excessive normal acceleration limits. To do this, the orbiter sends commands to flight control to
guide the orbiter through a tight corridor limited on one side by altitude, velocity requirements for ranging (in order to make the runway), and orbiter control, and on the other side by thermal constraints. Ranging is accomplished by adjusting drag acceleration to velocity so that the orbiter stays in the corridor. Drag acceleration can be adjusted primarily in two ways: by modifying the angle of attack, which changes the orbiter’s cross-sectional area with respect to the airstream, or by adjusting the orbiter’s bank angle. Drag acceleration will affect lift and thus the Orbiter’s sink rate into denser atmosphere, which in turn affects drag (NASA STS Newsref, 2004).

The extreme physical conditions found in this kind of flight are highly demonstrated by looking at the results of the few accidents the STS have had during its history. One of the known causes of the STS-107 Columbia accident is manifested in CAIB Report, volume one where it says “The physical cause of the loss of the Columbia and its crew was a breach in the thermal protection system on the leading edge of the left wing. The breach was initiated by a piece of insulating foam that separated from the left bipod ramp of the External Tank and struck the wing in the vicinity on the lower half of the reinforced carbon-carbon panel 8 at 81.9 seconds after lunch. During re-entry this breach in the Thermal Protection System allowed superheated air to penetrate the leading-edge insulation and progressively melt the aluminum structure of the left wing, resulting in a weakening of the structure until increasing aerodynamic forces caused loss of control, failure of the wing, and break up of the Orbiter” (CAIB Report, 2003).
2.4 Debris Models and Geographic Information Systems

2.4.1 Debris Models

One of the key aspects of this research is based on the accessibility of the current and state of the art debris models. The debris model currently in use by NASA, and its spaceflight program, is the Common Real-Time Debris Footprint (CRTF) developed by ACTA Inc., which actually operates inside the Range Risk Analysis Tool (RRAT) to perform risk analysis. The CRTF program was originally developed to support the range safety work at the Air Force Eastern and Western Ranges (CAIB Report, 2003).

Initially, we hoped to get an older version of this model in order to analyze, feed, test, conclude and integrate the model and its results to the VRP. Due to the difficult access to information, we could only explore the following programs: the CRTF program, the Basic Taps program, which analyzes aircraft debris trajectory (Oldham, 1990), and a debris model developed by A.P.T. Inc called DEBRA (Debris risk assessment tool) (APT Research Inc², 2004).

The importance of the model has a direct relationship with the dispersion of the debris impact location given an initial state vector. This is illustrated in Figure 12, which shows the primary sources in the case of the Columbia breakup. The main uncertainties are ballistic coefficient, wind and velocity perturbation.

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² APT Inc. stands for Analysis, Planning & Test Research Inc.
The results of this debris dispersion will be represented in a GIS. Actually, the VRP is using ArcMap®, as part of ESRI’s best geographic software, ArcView®.
2.4.2 Geographic Information System

The Geographic Information System (GIS) can be defined as “a computerized system comprised of a digital map linked to a database of attributes describing these features, along with software permitting the creation, retrieval, and analysis of these features” (Hutchinson, 2004). A GIS has three main components: the geographic component, which deals with maps and spatial locations; the informational component, which considers attributes and intelligence; and the system conformation component, which includes organization and process (Hutchinson, 2004).
The GIS actually being used in the VRP is ArcView®, which is software that provides data visualization, query, analysis, and integration capabilities with the ability to create and edit geographic data. ArcView® can create intelligent, dynamic maps using data from virtually any source and across most computing platforms. It provides the tools to work with maps, database tables, charts, and graphics all at once. Multimedia links can be used to add pictures, sound, and video to the maps.

ArcView® is designed with an intuitive Windows user interface and includes Visual Basic applications for customization. ArcView® consists of three desktop applications: ArcMap®, ArcCatalog®, and ArcToolbox®. ArcMap® provides data display, query, and analysis. ArcCatalog® provides geographic and tabular data management, creation, and
organization. ArcToolbox® provides basic data conversion. Using these three applications together allows performance of GIS tasks both simple and advanced, including mapping, data management, geographic analysis, data editing, and geo-processing.

![ArcGIS® through ArcMap® and ArcInfo® screenshots.](image)

The most important feature of a GIS is overlaying. This process constitutes a way to graphically obtain valuable information. Even this overlaying analytical process is nothing new. The introduction of a quantitative element in the overlay process ultimately facilitated the use of computers in performing this type of analysis (Davis, 2000).

We have to understand as well that spatial data in any GIS is represented in the computer in one of the two primary spatial data formats: vector and raster (NASA News Reference Manual, 2004). In the vector data model, all features are defined explicitly by a series of X-Y
coordinates that define the shape of that feature. The use of coordinates is analogous to surveying the bounds of a feature in real life. It implies the measurements taken and recorded that define the extent of that feature. It is necessary though, to have a relationship with the rest of the features belonging to an image. This relationship involves the definition of specific rules for encoding the location of features relative to all adjacent features—that is, the connectivity of that feature. The adjacency of all features is referred to as Topology.

The raster data model uses grid cells to represent features. The spatial location of each grid cell is determined by a combination of the origin of the matrix (the lower left hand coordinate, or 1,1 shown in Figure 18, and the size of each cell.

Figure 17, Vector representation.

<table>
<thead>
<tr>
<th>Point ID</th>
<th>X, Y Coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2,3</td>
</tr>
<tr>
<td>2</td>
<td>4,2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Arc ID</th>
<th>X, Y Coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1,5 2,5 3,6</td>
</tr>
<tr>
<td>2</td>
<td>4,6 5,7 6,7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Polygon ID</th>
<th>X, Y Coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4,4 4,5 5,5 6,6</td>
</tr>
<tr>
<td></td>
<td>7,6 7,3 6,2</td>
</tr>
</tbody>
</table>
A good example of joint effort in gathering data and GIS usage was the collection (and data collection afterwards) of the thousands of pieces of fallen debris from the Columbia space shuttle near the City of Lufkin, Texas. A week after the accident, hundreds of volunteers and law enforcement officers searched eastern Texas. GPS and GIS technology was used and organized under NASA and the Federal Emergency Management Agency (FEMA).
Figure 19, Generated three-dimensional view of a lake bed in Eastern Texas using ArcScene® (ESRI, 2003).

Figure 20, Close-up view of the shuttle debris recovery effort map showing combined air and ground search status (ESRI, 2003).

Our project would have the capability of importing GIS data source such as the Columbia recovered debris database. The VRP can work with a Landscan image layer, through ArcMap®, and queries can be made according to the raster characteristic of the image. The raster format
allows the classification of the pixels according to color, and associates every color with a specific population density. This density comes from the Landscan global population database, a public domain database of the world’s population (Landscan, 2001).

The GIS in the VRP shows, at this time, a toxic effect overlay (through Calpuff®) and will show (through queries) the information according to the overlay extracted from the different pixels exposed to the original toxic overlay.

Figure 21, Landscan population image (Landscan, 2001).

For a debris model, we may consider the use of both formats, vector and raster. For vector format we may use the map from the 2000 U.S. Census (TIGER) obtained through ESRI or the USGS Ref layer (ESRI, 2003). Both layers can be used together to improve query results.
2.5 Risk Analysis and Sheltering

2.5.1 Risk Analysis

Risk analysis should be made in order to assess risk associated to ground level assets and aircraft debris collision.

To obtain a realistic environment inside the VRP, we should get more information about the vehicle we are going to include. The space shuttle progress should give, through NASA, all information regarding the vehicle break up model and probability of failure for re-entry. NASA has mainly considered the probability of failure for launch which continues to be worked on inside the VRP project. Attention should then be given to the re-entry phase, especially after the accident of the Columbia space shuttle, due to the growing interest in knowing the risk of a spacecraft falling into pieces over a populated area.

Debris risk will necessarily be considered in any launching and landing site evaluation. Furthermore, a quantitative risk analysis should provide defensible evidence to support identification of generic high speed/altitude entry corridors for the vehicle considered in the analysis (U.S. ARMY Corps of Engineers et al, 2001).

Policies and procedures for planned and unplanned generated debris by flight tests and space launches are considered in a document generated by the Range Commanders Council (Risk and Lethality Commonalty Team et al, 2002), U.S. Army.

There are six steps in the procedure used to quantify the risks associated with a specific flight test (Sandia National Laboratories, 2004):
• Analyze failure modes and probabilities. A detailed systems analysis should be performed in order to determine possible failure modes and their associated probabilities. Any previous failures in flight vehicles should be analyzed

• Determine effects of failures on flight behavior. Various system failures should be grouped by their effects on the flight behavior of the vehicle. Those failures that would result in a mission failure, but would not cause a deviation of the vehicle from its planned flight path, should not be included

• Develop perturbed trajectory simulations. For each group of failures, six-degree-of-freedom Monte Carlo trajectory simulations should be made from the time of failure until a destruct action is taken by the range safety officer or the vehicle begins to break up

• Develop destruct/debris model. Debris models are developed on the basis of the vehicle's structural characteristics and the characteristics of the flight termination system. Thermal demise of pieces during re-entry is considered when desired

• Conduct debris-trajectory simulations. Monte Carlo trajectory simulations of each of the debris pieces are conducted to observe ground impact

• Generate probability density function for the casualty expectation. The ground impacts of the Monte Carlo trajectory simulations are used to generate a statistical footprint, a probability density function (PDF). This PDF is then combined with map and demographic data to calculate probabilities of impact within keep-out zones and the probability of injury to people –the casualty expectations
As mentioned before, the former guideline was created by Sandia National Laboratories. General estimations for probability of failure during entry should be made in order to evaluate candidate predefined trajectories. The risk associated to the ground population should also be in accordance to *Debris Footprint-Based Methodology*. This methodology, which will be developed in Chapter 4, will allow a future computed risk under either the Range Commanders Council’s expectation of fatality –less than 30 fatalities per million missions– or the range safety requirements of the Eastern and Western Ranges (EWR) which require an expectation of 30 casualties per million missions.

Results given by any risk analysis should provide entry corridors. These proposed corridors should also include the probability of an aircraft impact less than the RCC standard of one impact in 100 million missions.

For planned and unplanned debris generated by flight tests and space launches, a safety common risk criteria for national test ranges was issued in April 2000 by the RCC safety group (Risk and Lethality Commonality Team et al, 2002). In this paper, a consensus on reasonable common standards for debris protection criteria and analytical methods was reached.

This council provides data to assist in applying its common risk criteria. A summary is presented on Table 2-1, where all mandatory requirements are set –except those highlighted by an asterisk, which are advisory requirements. This data will be useful to make individual considerations related to certain debris ratio on predicted areas of a given spacecraft re-entry trajectory into the VRP.
<table>
<thead>
<tr>
<th>Max. Acceptable Probability</th>
<th>Undesired Event</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1E-7</td>
<td>Individual Fatality (General Public)</td>
<td>One Mission</td>
</tr>
<tr>
<td>1E-6</td>
<td>Individual Fatality (General Public)</td>
<td>One Year</td>
</tr>
<tr>
<td>3E-5</td>
<td>Total Fatalities (General Public)</td>
<td>One Mission</td>
</tr>
<tr>
<td>1E-3*</td>
<td>Total Fatalities (General Public)</td>
<td>One Year</td>
</tr>
<tr>
<td>3E-6</td>
<td>Individual Fatality (Mission Essential)</td>
<td>One Mission</td>
</tr>
<tr>
<td>3E-5</td>
<td>Individual Fatality (Mission Essential)</td>
<td>One Year</td>
</tr>
<tr>
<td>3E-4*</td>
<td>Total Fatalities (Mission Essential)</td>
<td>One Mission</td>
</tr>
<tr>
<td>1E-2*</td>
<td>Total Fatalities (Mission Essential)</td>
<td>One Year</td>
</tr>
<tr>
<td>1E-7</td>
<td>Non-Mission Aircraft</td>
<td>One Mission</td>
</tr>
<tr>
<td>1E-6</td>
<td>Mission Essential Aircraft</td>
<td>One Mission</td>
</tr>
<tr>
<td>1E-6</td>
<td>Non-Mission Ships</td>
<td>One Mission</td>
</tr>
<tr>
<td>1E-5</td>
<td>Mission Essential Ships</td>
<td>One Mission</td>
</tr>
<tr>
<td>1E-7</td>
<td>Manned/ Mannable Spacecraft</td>
<td>One Revolution</td>
</tr>
</tbody>
</table>

We will also be able to see the probability of fatality from debris impacts on Figure 22.

To calculate the probability with a given kinetic energy, one must multiply the probability of impact by the probability of fatality. The probability of impact is a function of the amount and size of the debris and the area of the person (Risk and Lethality Commonalty Team et al, 2002).

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3 Risk and Lethality Commonalty Team et al, 2002
This report also considers debris hazards to aircrafts. Debris is potentially lethal to an aircraft when producing enough damage to cause a loss of life or necessitate emergency response by the crew to avoid a catastrophic consequence. The two ways that debris can be hazardous to an aircraft include:

- Fragment penetration of a critical aircraft structure or the windshield
- Fragment ingestion by an engine

Table 2-2 provides standardized information from the smallest debris mass needed to produce these events.

Figure 22, Average Probability of Fatality from Debris Impacts (Risk and Lethality Commonalty Team et al, 2002).
Finally, this report also includes information regarding skin penetration and trauma injuries to people as well as to vessels from lethal fragments.

2.5.2 Sheltering

Information on sheltering will be obtained from existing statistics of population and building types. The most practical information source nowadays is found through the Census, which provides detailed population count and other data that can be used as a basis for determining sheltering for risk analysis.

Sheltering can be determined as sheltering from housing, school, and employment as a general reference (U.S. ARMY Corps of Engineers et al, 2001). Time of the day should also be considered in order to obtain a valuable output.

These aspects should be considered when analyzing the information from the Census (Tiger Census, 2001). All these will determine the feasibility of a flight due to a safety concern.

---

4 Risk and Lethality Commonalty Team et al, 2002
If the analysis determines a high probability of failure, then only very narrow corridors will be available. If the probability is low, then wide corridors will be available only if the Expected Casualties ($E_C$) are between the limits of what is established by the Eastern and Western Ranges (EWR 127-1, 2000).

NASA, through the CAIB Report, refers to sheltering models allocating people in buildings, vehicles or by just being in the open. Consideration must be given to building and vehicle roofs and building sub-floors where protection from inert debris might be obtained. ACTA has already developed a debris roof/floor penetration model (CAIB Report, 2003), as shown in Table 2-3.
Table 2-3, Debris roof/floor classification\textsuperscript{5}

<table>
<thead>
<tr>
<th>INDEX</th>
<th>NAME</th>
<th>BUILDING DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Open</td>
<td>Exposed people without benefit of an overhead roof</td>
</tr>
<tr>
<td>1</td>
<td>Wood-roof</td>
<td>Wood roof</td>
</tr>
<tr>
<td>2</td>
<td>Wood-1\textsuperscript{st}</td>
<td>1\textsuperscript{st} floor beneath roof of wood framed structure</td>
</tr>
<tr>
<td>3</td>
<td>Wood-2\textsuperscript{nd}</td>
<td>2\textsuperscript{nd} floor beneath roof of wood framed structure</td>
</tr>
<tr>
<td>4</td>
<td>Steel-roof</td>
<td>Steel roof</td>
</tr>
<tr>
<td>5</td>
<td>Steel-1\textsuperscript{st}</td>
<td>1\textsuperscript{st} floor beneath steel roof structure</td>
</tr>
<tr>
<td>6</td>
<td>Steel-2\textsuperscript{nd}</td>
<td>2\textsuperscript{nd} floor beneath steel roof structure</td>
</tr>
<tr>
<td>7</td>
<td>Concrete-roof</td>
<td>Reinforced concrete roof</td>
</tr>
<tr>
<td>8</td>
<td>Concrete-1\textsuperscript{st}</td>
<td>1\textsuperscript{st} floor beneath concrete roof</td>
</tr>
<tr>
<td>9</td>
<td>Concrete-2\textsuperscript{nd}</td>
<td>2\textsuperscript{nd} floor beneath concrete roof</td>
</tr>
<tr>
<td>10</td>
<td>Light-metal</td>
<td>Roof of pre-engineered metal structure (or vehicle)</td>
</tr>
<tr>
<td>11</td>
<td>Composite</td>
<td>Layered roof made up of light-weight, non metallic materials</td>
</tr>
<tr>
<td>12</td>
<td>Tile-roof</td>
<td>Tile roof</td>
</tr>
<tr>
<td>13</td>
<td>Tile-1\textsuperscript{st}</td>
<td>1\textsuperscript{st} floor beneath tile roof of wood-framed structure</td>
</tr>
<tr>
<td>14</td>
<td>Tile-2\textsuperscript{nd}</td>
<td>2\textsuperscript{nd} floor beneath tile roof of wood-framed structure</td>
</tr>
</tbody>
</table>

The perspective given in the \textit{Final Quantitative Risk Analysis for Generic Unmanned Lifting Entry Vehicle Landing at Edwards Air Force Base} (U.S. ARMY Corps of Engineers et al, \textsuperscript{5} Risk and Lethality Commonalty Team et al, 2002)
2001) establishes a developed effort for population distribution and sheltering models, mainly for a large region. Small regions, such as military bases, are addressed through direct surveys.

The large regions are better covered through the Census which, as a result, provides detailed population counts and other data that can be used as a basis to determine sheltering for risk analysis.

Mapping the data of the Census according to the number of people in “heavy,” “medium,” and “light” structures, and the number of people in the open is a whole new and more complicated process that should be made in the event that the researcher wants to be more specific. This particular problem can be broken down into activities that people are doing at certain moments, and the sheltering associated with each activity (U.S. ARMY Corps of Engineers et al, 2001).

The Census does not directly provide sheltering information; therefore, a mapping procedure must be used in order to obtain heavy, medium, light and open categories extracted from the Census data. The variables used to obtain and define sheltering will be discussed in Chapter 4.

2.6 Summary

Until the STS-107 accident, not much importance was given to the re-entry trajectory and the population affected by the spacecraft debris in case of an explosion. Most debris-related documents and journals refer to space debris and how this debris affects spacecrafts. There is a lack of research in debris models and the consequences of fallen debris to population on the ground.
The debris-related model information is not yet widely available. This situation makes this research unique since it covers a little known topic which, in time, will become relevant for all space missions.
CHAPTER 3: DEBRIS DISPERSION MODEL

3.1 Introduction

The possibility of an aircraft having a failure was never a big concern with respect to public safety. Even after the unfortunate explosion of the Columbia space shuttle, no one attempted to predict the consequences that such an accident could cause to the people on the ground.

Debris models were developed to predict, given certain information, the trajectory and possible impact area of a single aircraft fragment normally caused by an explosion.

The development and working mechanisms of the debris models are far from being public, and the main reason for this restriction might be the safety consequences of currently working contracts between certain companies and the government. NASA, for instance, has a direct contract with one of the biggest defense related companies in the area, ACTA Inc. Therefore, all the research made on this particular topic is a kind of business issue, and it is not to be released for two main reasons: it costs money, and the companies will not allow the model to be checked.

Any debris model should fairly predict a fragment trajectory given some information like initial trajectory, size, weight, ballistic coefficient, drag, altitude, and weather conditions. While most actual models do predict specific debris trajectories, aircrafts in real life do not break up in small defined pieces; they do spread debris over a wide area, particularly the kind of aircraft we are investigating –the space shuttle– which travels at a very high velocity and has low maneuverability.
Should we then group pieces in order to predict something more accurately? This grouping approach seems to be the answer and we will analyze it in the next chapters.

3.1.1 Definition

A debris model is a theoretical model that calculates the motion, impact locations and areas, and the probabilities and risks associated with debris falling within a finite area (Van Suetendael, 2003). It is a mathematical model, a simulation, of debris cloud and probabilistic impact dispersion for the debris impact (CAIB Report, 2003).

3.1.2 Mechanics

Debris dispersion models are deterministic in nature and use the basic equations of motion to calculate the behavior of the debris. Newton’s second law of motion establishes (Young & Freedman, 1996):

\[ \sum F_i = ma_i \]

Where \( F_i \) is the sum of forces in the \( i \)th direction acting on mass \( m \) causing acceleration \( a_i \) in the \( i \)th direction.

Forces acting on the mass of a debris fragment include gravity, wind, lift, and drag (friction). There are other forces acting on the debris at the time of the explosion or disintegration. Those forces are assumed to be instantaneous and are not considered in deterministic calculations. It is also assumed that the moment right after the explosion or
disintegration, the debris is no longer experiencing acceleration forces from the rocket engines (Van Suetendael, 2003).

We should consider Newton’s third law where fragments experience a force opposite to its direction on motion through the air. We must consider the aerodynamic drag force between the consequent factors following this law.

The general aerodynamic drag force \( F_D \) equation is (Van Suetendael, 2003):

\[
F_D = \frac{1}{2} C_D A \rho v^2
\]

where: \( C_D \) is the coefficient of drag;

\( A \) is the exposed surface area of the fragment;

\( \rho \) is the density of the air;

\( v \) is the velocity of the fragment.

Depending on the shape of the fragment, lift forces may also be present. Its general equation for aerodynamic lift \( F_L \) is given as (Van Suetendael, 2003):

\[
F_L = \frac{1}{2} C_L A \rho v^2
\]

where: \( C_L \) is the coefficient of lift;

\( A \) is the exposed surface area of the fragment;

\( \rho \) is the density of the air;

\( v \) is the velocity of the fragment.

Lift and Drag coefficients have a direct relationship with the shape and mass of the fragment but, before proceeding further, we must consider that any debris has an initial state
vector defined by a position and velocity vector (six total components): “This vector may be
perturbed from by an explosion that imparts a velocity and a consequential adjustment to the
velocity vector; There is no adjustment to the initial position because the velocity is added
impulsively. The gravity and aerodynamic forces affect the fall of the debris” (CAIB Report,
2003).

The dominant variable affecting the trajectory of any debris will be the Ballistic
Coefficient ($\beta$) for any computation on any debris trajectory prediction model. The formula for
the Ballistic Coefficient is (Van Suetendael, 2003):

$$\beta = \frac{W}{C_D A}$$

Where: $W$ is the weight of the fragment;
$C_D$ is the drag coefficient;
$A$ is a characteristic area associated with the drag coefficient.

This formula represents the ratio between inertial effects ($W$) and drag effects ($C_D A$).
All objects with low weight to drag ratio fall slower than objects with a high weight to drag ratio.

Any fragment traveling with an initial velocity holding a horizontal component will travel
farther if it has a higher ballistic coefficient. As debris falls, it will get into equilibrium between
its weight and its drag when reaching terminal velocity. Terminal velocity, without the presence
of wind, may be represented as the fall of a fragment in a vertical direction with respect to the
earth’s surface.

Wind is another major factor that affects the fall of debris. Debris with lower ballistic
coefficients will fall closer to its point of origin, in the absence of wind. Debris with higher


ballistic coefficient will fall farther because of the wind’s influence. This is illustrated in Figure 23.

Figure 23, The influence of the ballistic coefficient, $\beta$, and wind upon debris impact points (CAIB Report, 2003).

3.1.3 Development of Reference Trajectories

In order to predict the place where a fragment, or group of fragments, are going to land and to obtain the $E_c$ as the final result, it is necessary to know either the initial position and velocities for the reference trajectories where the orbiter –or any other RLV\(^6\)– was last observed, or an already defined point for an eventual explosion –which may be the most critical point during re-entry– for different reasons.

We should consider that any prediction will have to be admitted with a great range of flexibility since there have been only two accidents and therefore, two causes of explosions. The prediction of the impact location of debris will be immediately influenced by the cause and

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6 RLV stands for Reusable Launch Vehicle. A vehicle that, as opposed for what was known before the Space Shuttle
conditions that affected how this debris was formed. It is different to model falling debris from an orbiter full of fuel than from an orbiter during its re-entry phase where all the unnecessary fuel has been burned out.

It is known that, until the STS-107 accident, not much attention was given to the re-entry trajectory. In all space shuttle history, only one accident occurred, and it was during take off (Challenger).

Probability of failure for take off and re-entry has been calculated\(^7\) and NASA has a whole method of Probability Risk Assessment (PRA) developed over time (Friedensen, 1999). This agency has a whole set of students and researchers that are continuously using methods and techniques not open to the public (black box). They continue to investigate their own risk evaluation which didn’t consider the probability of a failure during re-entry and, even more importantly, the chance of affecting people on the ground. NASA has always had a policy of traditionally approaching a launch decision with the assumption that a mission is not safe to fly. Subordinates are then required to prove that such is not the case before the launch is permitted. The null hypothesis, therefore, is that the mission should be aborted\(^8\). This is one of the reasons why this topic becomes so relevant. Safety is a public concern.

3.1.4 Development of Breakup State Vectors and Associated Debris Groups

The breakup state vectors are based on a progressive breakup of the orbiter, or RLV, initiated at the moment of the explosion or disintegration. It is supposed in order to make a good

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\(^7\) It was not possible for the author to obtain this probability of failure due to NASA restrictions

\(^8\) Heimann, 1997, page 5
prediction that a possible breakup model must be obtained from the manufacturer. It is this model which will indicate, roughly, the way the debris is going to behave. We have to consider, for the case of the STS-107, that nobody ever thought for a second there was going to be a generation of more than 80,000 pieces. The amount of recovered fragments represents around 40% of the space shuttle mass so it is certain that there is still a big amount of uncertainty about the remaining 60% (disintegration, fallen into the sea, not found, etc). As a consequence, debris will have to be analyzed as groups, and with direct relation to the orbiter’s trajectory and velocity at the time of the event.

Any debris dispersion model will necessarily have to support a breakup model which, as a general approximation, will have to account a determined quantity of debris. This debris may be grouped by components (as a manufacturer would do) or be calculated according to possible ballistic coefficients following certain distribution (as a consequence of a study case; e.g. Columbia recovered debris).

As we can see in Figure 24, a breakup model has been developed by NASA according to recovered, weighted, and measured debris from the Columbia space shuttle. It illustrates the progressive nature of the breakup process. In this figure, the fragmentation process is plotted according to observations, and also the time these observations were made. Groups were formed considering ballistic characteristics (range) and number of fragments as a function of the time and trajectory the space shuttle had until point of impact. We can also observe the fragmentation process of the vehicle where the fuselage represents the biggest amount of debris produced.
In Appendix B we can actually see the approximated number of parts of each category recovered from the Columbia space shuttle. The amount of recovered pieces counts for approximately 84,000 pieces into 56 categories.

If we consider that the shape of each fragment determines the drag effect during free fall, and that the parameter that quantifies this atmospheric influence is determined as the ballistic coefficient of the fragment, adding the uncertain nature of the breakup of the vehicle, each fragment can only be assigned into a range of ballistic coefficients (U.S. ARMY Corps of Engineers et al., 2001).

Grouping pieces into classes (between certain ballistic coefficient ranges) will diminish the impact uncertainty of debris. For this reason, each group should follow certain distribution of different ballistic coefficient fragments conforming a ballistic coefficient uncertainty model itself.
(may use Monte Carlo sample generation for each fragment category prior to the initiation of the free fall propagator, as CRTF⁹ does).

3.2 Debris dispersion models available

In our current research, we have been able to obtain some debris dispersion models, but information regarding its internal functioning has always been kept as a big secret by the manufacturing companies. It is understandable that high cost state of the art software will never be open sources and, by all means, its prediction methodology can’t get analyzed as well. These factors might be another big reason why only a few people answered our emails.

3.2.1 Basic Taps program of Debris Trajectory Analysis (Oldham, 1990)

This software was designed for trajectory analysis of aircraft debris. It has been modified for MS Excel ® calculations and display. It is a simple debris trajectory analysis that reports the ballistic trajectory characteristics and relative scatter patterns of in-flight airframe separations debris, specific to air-show environments. Nonetheless, we must consider having certain flexibility in order to accept such a program for research purposes.

The separation and the ballistic trajectory of individual parts of an airplane can be predicted using standard mathematical analytical techniques. Each part can be predicted using its weight, assuming its drag characteristics, making wind corrections, and inputting its initial separation velocity and angle.

⁹ CRTF stands for Common Real-Time Debris Footprint, a Debris propagation model developed by ACTA.
The author of the software considers certain sources and assumptions which can be seen as part of the references on his website (Oldham, 1990). The results of the calculations will be dependent upon the estimates used for the separation conditions, component drag coefficients, and wind aloft. This evaluation must be considered not as a precise one, and its results should only be used as guidance.

The software deals mostly with the following input requirements (Oldham, 1990):

- Initial altitude of disintegration
- Initial density altitude
- Altitude of impact at ground level
- Wind velocity and direction
- Horizontal true airspeed at disintegration
- Rate of climb or sink at disintegration
- Weight of projectile
- Projectile drag coefficient
- Projectile frontal area

The outputs that the program gives are:

- Horizontal distance from disintegration at impact
- Horizontal, vertical, and total velocities
- Terminal velocity
- Flight-path angle at impact
- Ground speed of projectile at impact and x and z components of that velocity
Even though the model focuses on getting the appropriate distance for the public regarding the acrobatic maneuvers area, some effort can be made to associate this particular population sample, to a population affected by a pre-determined flight trajectory (as the space shuttle has). This topic may be a matter of a more detailed research in case the VRP could not get a useful (and affordable) debris model.

Some important features from the mathematical model this software presents\textsuperscript{10} are wind and density altitude calculation, horizontal true airspeed at disintegration, rate of climb or sink at disintegration, projectile drag coefficient and projectile frontal area.

Coefficient for any particular piece will be grouped based on size and shape of the projected object. This data is presented on Table 3-1.

Particular importance is shown in drag coefficient assumptions. The author considers that drag coefficient will be represented as Reynolds’ numbers\textsuperscript{11} ranging between $10^{7}$ to $3 \times 10^{5}$.

\textsuperscript{10} The full text version of this analysis presents all mathematical aspects for individual variable calculations (Oldham, 1990)

\textsuperscript{11} Data from McDonald Douglas Corporation’s Weapons Systems Division (Oldham, 1990)
Table 3-1, Drag Coefficients for TAP Model

<table>
<thead>
<tr>
<th>Geometric Figure</th>
<th>Characteristic</th>
<th>Drag coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sphere</td>
<td></td>
<td>0.44</td>
</tr>
<tr>
<td>Disk (flat side to flow)</td>
<td></td>
<td>1.12</td>
</tr>
<tr>
<td>Flat plate (flat side to flow)</td>
<td>Length/breadth = 1</td>
<td>1.16</td>
</tr>
<tr>
<td>Circular Cylinder (flat side to flow)</td>
<td>Length/breadth = 20</td>
<td>1.50</td>
</tr>
<tr>
<td></td>
<td>Length/diameter = 1</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>Length/diameter = 2</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>Length/diameter = 7</td>
<td>0.99</td>
</tr>
<tr>
<td>Airfoil</td>
<td></td>
<td>0.04</td>
</tr>
<tr>
<td>Circular Cylinder (flat side parallel to flow)</td>
<td>Length/diameter = 1</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td>Length/diameter = 20</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>Length/diameter = infinity</td>
<td>1.20</td>
</tr>
<tr>
<td>Late model automobile as low as</td>
<td></td>
<td>0.34</td>
</tr>
</tbody>
</table>

3.2.2 Debris Risk Assessment Model (DEBRA)

This model is developed by APT Research Inc., which is an employee-owned, small business based in Huntsville, Alabama. DEBRA, particularly, is an APT developed model for flight safety analysis that assesses the risks of RLV failure modes. DEBRA first determines the hazard area from the user input about nominal trajectory and failure mode information. DEBRA

12 Data from McDonald Douglas Corporation’s Weapons Systems Division (Oldham, 1990)
compares that hazard area with a population database to quantify the risks to the surrounding population (APT Research Inc., 2004).

As it is stated on its website, DEBRA models major RLV failure modes from malfunction turns (trimmed or tumbling), explosions / breakups from any origin (on board fuel explosion, dynamic loading, or destruct), onto engine shutdown failures. For each time increment of each selected failure model, the program generates a hazard footprint by propagating the debris to impact. The expected fatalities are computed separately for each failure mode in a risk table, which allows to quickly identifying those failure modes which drive the overall mission risk.\footnote{A good example may be seen at “Using the RCC 8-Step Process to perform Quantitative Risk assessment on Reusable Landing Vehicles, Strom & Newton, APT Document # TP-01-04” where a Risk Assessment is made for the X-34 RLV}

A graphical output example can be viewed at the APT website (APT Research Inc., 2004). Its representation includes, as shown in Figure 26, plot depictions of a vehicle flying into a target area. The ellipses represent potential debris from various failure modes of a vehicle. Table 3-2 shows the output results from this particular prediction.
Table 3-2, Expected fatalities from X-34 Flight Program

<table>
<thead>
<tr>
<th>Trajectory</th>
<th>Nominal</th>
<th>Abort</th>
<th>Subtotal</th>
<th>AB</th>
<th>MT</th>
<th>EXP</th>
<th>Subtotal</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure Modes</td>
<td>ES/AB</td>
<td>MT</td>
<td>EXP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.8 E-06</td>
</tr>
<tr>
<td>Expected Fatality</td>
<td>2.31 E-06</td>
<td>1.26 E-06</td>
<td>2.25 E-07</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The basic risk equation this model uses is (Strom, 2001):

\[ E_F = P_E \times P_{F/E} \times E_{PH} \]

Where:

- \( E_F \) (Expected Fatality) is the expected risk of fatality due to the planned test flight
- \( P_E \) (Probability of Event) is the probability that an event will occur that has the potential to create a hazard
- \( P_{F/E} \) (Probability of a fatality given an event) is the probability that a person will be killed given that the hazardous event occurs
- \( E_{PH} \) (Expected population hazarded) is the parameter that represents the number of people expected to be hazarded in a debris area or footprint. If there is no population in the footprint, the \( E_F \) for that footprint is zero

53
The tree shown in Figure 25, describes how the 10 failure modes contributed to the overall $E_F$. The probability of a fatality given an event is obtained from the division of the total lethal area and the total area hazarded by the event. The total lethal area is the sum of the lethal areas of all fragments considered deadly. The total area hazarded by primary debris is calculated by DEBRA based on inputs by impact. The increase of the total hazarded area due to secondary explosions was accounted by adding a buffer around each piece of debris with an explosion potential. The safety buffer is added to account for the TNT equivalent of on board fuel contained in the fragment (Strom, 2001).

The $E_{pH}$ is calculated according to population statistics which, in this case of study, are derived from raw Census data.
Finally, the output from DEBRA model includes $E_f$ values and debris footprint overlaid over population maps as we can see in Figure 26.

![Figure 26, DEBRA graphical output example from the X-34 spacecraft risk assessment (Strom, 2001).](image)

3.2.3 Common Real Time Debris Footprint (CRTF) (Carbon, 2003)

This program was developed under the joint sponsorship of the Eastern and Western Ranges, and its main characteristic (potentiality) is that it is probabilistically based. It also develops all dispersion data in real time and, therefore, it uses the current state vector of the spacecraft as the starting point for the dispersion analysis.

This software uses a series of bi-variate normal distributions, where impact distributions are made separately for each debris category. These distributions will provide the basis for the
probabilistic model which will also be used in a risk model in the program in order to compute risk in real time.

The software establishes that the two most dominant effects on footprint length and shape are ballistic coefficient of the debris and wind. Figure 23 shows the influence of the ballistic coefficient related to the breakup point and wind direction.

CRTF was designed to operate in real time with an updating of 10 times per second. It contains a set of models that estimate the range free-fall and impact locations of fragments resulting from a vehicle breakup. This model tries to quantify the uncertainties that exist in the vehicle location at the moment of breakup, in the characteristics of the generated fragment debris, and in the external conditions during free-fall (CAIB Report, 2003).

There are six uncertainty models included in CRTF. Four of them use a Monte Carlo technique. Monte Carlo is used to handle some of the uncertainties and develop impact distributions that contribute to the total uncertainty. Other impact uncertainties are developed using linear equations and covariance propagation. By this way, the program behaves as a hybrid, taking advantage of the best of both statistical modeling methods (CAIB Report, 2003).

The six models included in CRTF are:

- Real-time state vector, utilizing tracking data from one or more sources
- Course change at the time of malfunction
- Explosion velocity uncertainty for fragments at the moment of break up
- Ballistic coefficient for each fragment due to the uncertain nature of the break up of the vehicle
- Fragments’ free fall lift effect (lift to drag coefficient)
• Strength of the wind since last measurement

CRTF was designed to compute and analyze the dispersion that defines an instantaneous scenario of a vehicle breakup and dispersion of debris. CRTF can be used as part of a Risk Analysis program which would generate some state vectors and subsequent accident/failure condition and its associated probabilities (U.S. ARMY Corps of Engineers et al, 2001).

3.2.4 Virtual Range provisional debris model

As mentioned before, the accessibility to gather data from an existing debris model was very difficult. Except for Hugh Oldham’s software, BASIC TAPS, the rest of the information was obtained from several different sources that, at the end, led to ACTA’s CRTF and DEBRA’s ATF models (both companies are NASA contractors). None of them ever released a sample version.

In order to determine a methodology for debris model integration into the VRP, we had to create a particular, and very simple, debris dispersion model. The provisional model must have the following assumptions:

• We will consider specific spacecraft breakup altitude due to the risk associated with the re-entry. Source data is assumed at an altitude of 200,000 ft. and a given initial vector where the spacecraft is suppose to loose lift and become ballistic\(^{14}\)

\(^{14}\) As established by the “Debris Footprint Team” led by NASA at the time of occurrence, where an initial estimation was made
• The spacecraft speed will be considered constant. It is assumed a speed of Mach 18 even though there were fluctuations between Mach 22 and Mach 18 from the moment the Columbia shuttle entered the U.S. soil

• The atmospheric factors and weather conditions (including wind) will remain constant. This point should be implemented in a future research

• The disintegration of the spacecraft shall behave as seen in the STS-107 Columbia\textsuperscript{15}, but we will assume that debris will be grouped into some specific areas related to the trajectory line\textsuperscript{16}. The model will just represent an oblique projected cone with its focal point at the point of explosion (assumed), and the two ellipse focus points following the projected trajectory line

• The model will allow modifying the altitude of the explosion/disintegration, therefore the area of the ellipse. Real data shows that at an altitude of 200,000 ft., the main concentration of debris will have a major axis distance of 200 miles and a minor axis distance of 25 miles (CAIB Report, 2003)

\textsuperscript{15} The Appendix D.16 of the Columbia Accident Investigation Board shows how the Columbia fragments spread over Texas and Louisiana. Mathematical models considered the location of recovered data as corroboration of their predictions

\textsuperscript{16} In the Columbia accident, there were more than 20 early debris shedding events to finally reach the main concentration over Texas and part of Louisiana
The projected ellipse will have its two foci at some given point and its projected line distance will be from the highest concentration points of fallen debris (initial and terminal) following the re-entry route.

This particular cone has an elliptical cross section which reflects an ellipse, obtained by the intersection of the geometric figure with an inclined plane (Spiegel & Abellanas, 1997) as it is shown on Figure 28.
This ellipse will consist of the two main focus (foci), $F_1$ and $F_2$, and its shape will be directly related with the eccentricity\textsuperscript{17}. 

\begin{equation*}
\frac{c}{a} < e < 1
\end{equation*}

\textsuperscript{17} This must be interpreted as the position of the focus as a fraction of the semimajor axis. This eccentricity has direct impact on the shape of the ellipse. It is defined as $0 < e < 1$ where $e = \sqrt{1 - \frac{b^2}{a^2}}$
\[ \sqrt{(x + c)^2 + y^2} + \sqrt{(x - c)^2 + y^2} = 2a \]

Where \( F_1 \) and \( F_2 \) are in coordinates \((-c,0)\) and \((c,0)\) respectively.

In order to represent the particular coordinates of both ellipse foci, their position will represent the beginning of the debris concentration area following Pareto’s chart. That is, the main ellipse area will be assumed would concentrate 80% of the debris, and the remaining amount would be distributed over concentric ellipses following the trajectory line, having the same focus points but with different axis. The semi major axis will have a ratio of 1/8 to the semi minor axis (as a result of direct field observations\(^{18}\)).

The provisional debris model will be a simple representation of the ratio, given by a living experience, between the altitude and speed at the time of explosion/disintegration, and the affected area on the ground. With this ratio, we will be able to analyze \( E_C \) that a specific re-entry route over populated areas can have. Furthermore, this would allow us to choose different alternative routes and sheltering conditions.

\(^{18}\) This is an assumption according to the observed ratio given by the ellipses formed by the fallen debris of the Columbia space shuttle
CHAPTER 4: INTEGRATION METHODOLOGY FOR A DEBRIS MODEL INTO THE VRP

4.1 Debris Model Integration

The integration of a debris model into the VRP is considered one of the key factors for creating a suitable modeling and simulation environment (Sepulveda et al, 2003). Its integration methodology considers several topics such as architecture update, debris grouping and modeling, geographic representation, spatial analysis, and sheltering.

In this chapter we propose an architecture for the VRP which includes a debris fragmentation model and other related aspects; we propose the use of grouped debris; we present a provisional debris model which will allow us further representation of a given debris footprint; and we finally represent and analyze debris footprints according to a given trajectory and population database in order to obtain $E_c$.

4.1.1 VRP Architecture updating

The current VRP architecture is designed to calculate the $E_c$, given a gas dispersion model, using Monte Carlo distribution to generate probabilities of occurrence of certain events.

The inclusion of a debris model will necessarily have to be reflected in the architecture of the VRP. The proposed modification is established in Figure 30.
4.1.2 Debris grouping

Most of the recovered debris from the Columbia space shuttle represented around 40% of its mass. This debris, as mentioned before, spread over a large part of Texas and a part of Louisiana. In order to simplify the analysis, and to further use a definitive debris model, debris pieces will be considered as previously NASA formed groups.
For VRP purposes, we will use debris grouping given by NASA, through the Columbia database (recollected debris). In further research, these groups should be used to analyze affected people in specific points, to generate statistics, and to estimate sheltering between many possible uses. The debris grouping can be seen in Appendix B.

4.1.3 Provisional debris model

As mentioned in Chapter 3, the provisional debris model will be used to obtain the vector coordinates (initial and terminal) given a certain altitude, speed, and direction. This altitude dictates the approximate affected area covered by the falling debris which will allow us to do analysis. The model is not intended to include and obtain all variable interactions existing in this kind of event. Its goal will just be the representation (through a methodology) of the event in order to allow further analysis. The VRP will necessarily have to obtain and integrate a definitive debris model. What model should be used and what should the model includes will be some of the questions this research intends to uncover.

Table 4-1 shows an example of an adopted re-entry route where some coordinates were given. This re-entry route represents some of the main debris gathering points of the Columbia breaking up sequence, and an estimated length and width of the ellipse was obtained according to the altitude of the explosion/disintegration.
Table 4-1, Provisional model results of a given re-entry route

<table>
<thead>
<tr>
<th>Geographical Coordinates of F1</th>
<th>Debris length (Kms.)</th>
<th>Debris width (Kms.)</th>
<th>Altitude (Ft.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-122.95</td>
<td>38.707</td>
<td>231</td>
<td>231,000</td>
</tr>
<tr>
<td>-116.9</td>
<td>37.93</td>
<td>227</td>
<td>227,000</td>
</tr>
<tr>
<td>-114.57</td>
<td>37.49</td>
<td>221</td>
<td>221,000</td>
</tr>
<tr>
<td>-110.55</td>
<td>36.52</td>
<td>216</td>
<td>216,000</td>
</tr>
<tr>
<td>-106.24</td>
<td>35.21</td>
<td>210</td>
<td>210,000</td>
</tr>
<tr>
<td>-101.82</td>
<td>33.82</td>
<td>205</td>
<td>205,000</td>
</tr>
<tr>
<td>-92.56</td>
<td>30.78</td>
<td>200</td>
<td>200,000</td>
</tr>
</tbody>
</table>

Our provisional model, as mentioned before, is based on the representation of the gathered debris of the Columbia space shuttle. This debris spread as an ellipse shape over the terrain. This debris should also follow our given re-entry trajectory. This is validated in Figure 31 where we can see part of the Columbia recovered debris database provided by NASA, where we included the first 7000 fields. Some minor changes were made in order to allow the plotting.
Each of these debris-represented points are associated to a debris database which may include some specific characteristics as date of collection, size, material, or even drag coefficient. All these features should be included in the database and should be migrated to a text file, which in this case is represented through Notepad®, so they can be plotted in the GIS by adding X-Y data. This procedure is explained in “4.2.4 Trajectory” later in this chapter.

4.2 Geographic representation

4.2.1 Conditions

The VRP is actually working on a GIS platform, using a raster image of the U.S. This image comes from Oak Ridge National Laboratory (Landscan) and represents a population
estimation associated with a given database. The last version keeps the same resolution (one km.) but enhances details referred to state and county limits.

Some limitations considered into this kind of image relates to geo-referencing. The ArcView® program used in the VRP (ArcMap®) allows the inclusion of any type of image. According to this, our major concern will be maintaining a proportional relationship between terrain and what is actually represented on the screen, and furthermore, to allow the inclusion of coordinates. Actual raster images will certainly need to be geo-referenced, or if the error is exaggerated, they will need to be rectified.

4.2.2 Geo-referencing

The Landscan image (version 2001) used in the VRP was added to our active dataframe in ArcMap®. The spatial data set in the target coordinate system was found at USGS Ref\(^1\). This spatial data set provided a known coordinate system, WGS 84 (GCS_North_American_1983, as cited in the source properties of the layer), and it is based in the 1983 North American Datum (D_North_american_1983, as cited in the source properties too).

To geo-reference the image from the raster data set to a real world coordinate system, location of various recognizable features had to be identified. These features represented control points, and they were given by the control layer mentioned in the paragraph before (USGS Ref).  

\(^1\) At [http://www.geographynetwork.com](http://www.geographynetwork.com), as a vector layer
Through the geo-referencing toolbar provided inside ArcMap®, links were added between the control and the raster layer. The more links added, the more accurate the transformation. At a minimum, three links are needed for a first-order transformation, six links for a second-order transformation, and 10 links for a third-order transformation. After the points were added, the Auto Adjust function from the geo-referencing menu should be activated. Now the raster is geo-referenced to the coordinates of the control layer, as shown in Figure 32.

Figure 32, Landscan image overlaid on a vector map (USGS, 2004).

4.2.3 Overlaying

The original image used in the VRP was a raster that allowed us to obtain information related to population. This raster image was linked to a database that provided information according to the luminosity of every pixel inside.
Landscan 2001 version provided a more realistic image, and its data source was improved by adding specific features to state and county level. Despite these enhanced features, the resolution obtained when zooming the image is not good enough to make detailed analysis. For this reason, an extra layer was added so even the resolution decreases as we zoom in, the overall features will persist due to the vector data set introduced.

Over these layers, as seen in Figure 31, we will analyze the recollected information in order to establish the actual (one of them) re-entry route used by the space shuttle, and the passing through some populated areas (in this case over Texas and Louisiana as a result of the Columbia accident).

The overlaying process will allow us to reflect any information given by the Calpuff® gas dispersion model, and our provisional debris model (and any definitive debris model that shall be introduced in the future).

4.2.4 Trajectory

We will represent a trajectory based on the re-entry route actually used by the STS program. This trajectory is reflected in Table 4-2 and includes the coordinates of some number of identified debris concentration points (CAIB Report, 2003) as seen in Figure 33.
Table 4-2, Re-entry trajectory route \(^{20}\)

<table>
<thead>
<tr>
<th>Geographic reference</th>
<th>W</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>California coast line</td>
<td>-122.9518</td>
<td>38.70748</td>
</tr>
<tr>
<td>California/Nevada limit</td>
<td>-116.8958</td>
<td>37.93257</td>
</tr>
<tr>
<td>Nevada/Utah</td>
<td>-114.5723</td>
<td>37.492</td>
</tr>
<tr>
<td>Arizona crossing</td>
<td>-110.546</td>
<td>36.51765</td>
</tr>
<tr>
<td>New Mexico</td>
<td>-106.2389</td>
<td>35.2148</td>
</tr>
<tr>
<td>North of Texas</td>
<td>-101.819</td>
<td>33.818</td>
</tr>
<tr>
<td>Texas/Louisiana</td>
<td>-92.556</td>
<td>30.78107</td>
</tr>
<tr>
<td>Florida</td>
<td>-81.298169</td>
<td>28.786866</td>
</tr>
</tbody>
</table>

In order to represent a specific route, the respective coordinates must be written in a text file, in this case using Notepad® as a simple word processor. The data has to be integrated as a layer through the “Add X-Y Data” tool function. The data set will be added as a table containing X-Y coordinates. This file should be browsed and rescued.

\(^{20}\) This re-entry route represents one of the many possibilities that NASA manages in its different spatial programs.
Figure 33, Trajectory of STS 107 Columbia.

The file must include the reference system we are going to use—in this case, the X and Y coordinates which we must remember is the coordinate system this GIS uses. If necessary, a data source may be set according to one of the previous layers displayed in order to take reference from its coordinate system.

When the output file has been obtained (coordinates from the debris model), and been added as an X-Y data, it must be spatially referenced to any known system. ArcMap® provides several. For this, we edited the spatial reference coordinate system description, and we selected a predefined coordinate system that will necessarily have a relationship with the system we are currently using. We chose between geographic coordinate systems, North American Datum 1983 (Known as WGS84) and we will keep this consistent for the rest of the analysis.
4.3  **Spatial Analysis**

4.3.1  Layer integration

In general terms, spatial analysis is made upon a model. This model, as a representation of reality, will have to consider the complexity of the world and the interactions produced in it.

Spatial analysis is based on calculations made over raster data sets. It can even consider, as mentioned before, vector data sets in order to improve the results of querying and analysis. As we can see in Figure 34, we put together several layers that composed our data set frame for beginning our analysis.

![Figure 34, Image of all layers.](image-url)
These layers are made up of two basic raster images from the Landscan population database which provided the fundamentals for population calculation (one of them based on gray-scale values for land shape, and the other based on given cells’ colored-related values for population density) and a couple of vector layers from the United States Geodesic Survey (USGS) that provided state and county information (limits, boundaries, names, urban areas, water bodies, roads, streams and rivers), and the Census population data base that provided population information as well.

Two more layers were added. One represents the trajectory used in this analysis (it can actually be modified in order to do trajectory analysis) by the Columbia space shuttle, and the other represents a sample of provided debris coordinates\textsuperscript{21}. Both layers were created by adding X-Y data according to the text format information saved in Notepad\textregistered, as shown in Figure 35.

\textsuperscript{21} Based on the Columbia data base in Appendix B
As a result of this layering process, we were able to analyze the re-entry route by using the “buffering” option of ArcMap®, as seen in Figure 36. This function allows analyzing all possible re-entry routes by determining the population at risk. Figure 35 shows a 25 kms. wide buffer with respect to the re-entry route.
As we saw in Figure 31, we included a representation of the first 7000 debris pieces. This representation allowed us to integrate this debris concentration as a layer. Through this layer we can query the GIS to obtain information.

4.3.2 Population based analysis

In order to obtain the $E_C$, a definitive debris model will be needed. Nonetheless, our model was used based on map density. The ratio between the projected altitude and debris-covered area from the Columbia accident was the base for the remaining calculations. Table 4-1
gives us the projected length and width distances of the proposed ellipse along the trajectory vector.

Given a specific point over the terrain, which we will consider as one of the foci (F1), we obtained a multiple buffer-based ellipse. Each of these buffers (3) was considered to be equidistant (25 kms.) as we can see in Figure 37.

![Figure 37](image.png)

Figure 37, Three equidistant buffers along the trajectory vector.

Our calculation of map density refers to the value assigned to every pixel in the Landscan image. These values, spread and distributed over a surface, will allow us to obtain a calculated

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22 A map density calculation is considered only with raster data. All vector data is been used as reference and validation information
cell value in the output raster. A special design application, as it is been used in the VRP Calpuff® software, will be needed in order to obtain numeric data. Other way to do this is by implementing ArcView® through Spatial Analyst®, 3D Analyst®, Database connection®, Geoprocessing®, and Image Analysis® among others.

As we can see in Figure 38, a buffer of 0.5 kms. was made to every debris fragment. This kind of visual examination can give us a very good and fast analysis in order to obtain or predict affected zones.

Figure 38, 0.5 kms. buffer to individual debris fragments.
We can obtain numerical data by buffering consecutive times. Figure 39 shows a buffer of 25 kms. along the trajectory, reaching 51 counties and a population of 3,184,345 people.

![Figure 39, 25 kms. buffer to end of re-entry route.](image)

We also did a buffer analysis of 50 kms. along the last part of the re-entry route where we found out that 81 counties were reached, affecting a population of 6,563,034 people. This can be seen in Figure 40.
Finally, we did a buffer analysis of 75 kms. along the last part of the re-entry route where we found out that 106 counties were reached, affecting a population of 7,568,655 people. This is seen in Figure 41.
4.3.3 Querying

Density calculation belongs to one of the spatial analyst features and it has two different types of calculations, simple or kernel. In the simple calculation points and lines included in the search area are added and divided by the search area size to get a density value for each cell. In the kernel calculation, a weight for points or lines located near the center is given. This last calculation allows a smoother distribution of values (ESRI, 2002).
In Figure 42, a query through Spatial Analyst showed the density by calculating all affected people over a 10 mts. debris buffer. The result shows a smooth distribution of an average of 5 people within the average radius of the fragment.

A good way to do graphical analysis is through the “Select by location” box, where the different features inside any of the multiple layers can be selected, and information can be obtained according to their relative location into each of these layers. Figure 43 shows the “Select by location” box.
By combining queries, we are able to perform more complex searches. We now want to find all populated areas that our buffered zone (main debris concentration) intersects. Figure 44 shows the graphical representation of this search.
Figure 44, Select by location feature. Intersection of two layers.

This intersection allows us to know all populated areas within a distance of 75 kms. from the trajectory vector, included in the buffer zone.
In Figure 45, we wanted to see the concentration of all debris pieces from the Columbia database and we wanted to compare them with our own model. The concentration seems to be on the first buffer. This feature will allow us to do a combined spatial analysis as we will see later on.

If we want to obtain more detailed information, we may use querying (as a SQL integrated function) by “Selecting by attribute.” This selection means, in our case where we have loaded several layers, that we can obtain all population included in our queries. We can vary our selection method in order to use point, line or polygon features that overlap the features in the
same layer or another layer if we want. Figure 46 shows a direct query of populated areas over a Census layer. The highlighted features represent all populated areas into a distance of 200 kms. from the trajectory vector.

![Figure 46, Selection by attribute, query of populated areas at a distance no more than 200 kms. from trajectory vector.](image)

Selecting visual features permits us to obtain fast and accurate information. Figure 47 shows a layer combining the query seen in Figure 46 with Census population by county. We can actually see that this information makes sense. What is not so clear is the distribution of county population over populated areas (cities, towns, villages, etc.). This aspect can easily be seen in
Figure 47. Graphical estimations of affected population can be determined as seen in the table of contents at the left side of the picture.

Figure 47, Selection by attribute, query of populated areas at a distance no more than 200 kms. from trajectory vector plus Census population by county.

Figure 48 shows another query that may be useful to determine the impact of a main concentration debris zone. It can be used for re-entry route selection as well.
Figure 48, Counties affected by debris footprint.

Figure 49, in the following page, shows a layer with density population surrounding the debris zone. We can see that the debris footprint affects a city with a population between 660,000 and 990,000 inhabitants. The outer boundary affects a population between approximately 330,000 and 660,000 inhabitants.
Figure 49, Population affected by the debris footprint.

Finally, in Figure 49 we can see also that a query resulted in graphical and numerical values. More detailed queries and resulting data will be obtained through the use of the several extensions of ArcGIS® software.

4.4 **Sheltering**

Through the 1990 U.S. Census, data for the “number of house units in structure” may be obtained (U.S. ARMY Corps of Engineers et al, 2001). This Census contains information for
each housing unit such as the size of the building. This data can be used to obtain, in future research, the sheltering categories for people at home.

Census information can lead, as mentioned in Chapter 3, to the determination of sheltering due to school (joining the number of enrolled people in primary, elementary, or high school to obtain further conclusions), and due to employment (joining variables as the number of hours worked per week, and the number of weeks worked per year to obtain further conclusions; It can use the number of people in each occupation as well).

Sheltering determination can also be obtained from other sources. State housing estimations, county estimations, land use, etc. Figure 50 shows land use layer from http://www.geographynetwork.com data.
4.4.1 Basic impact casualty model

The probability for a person of being hit by an individual piece of debris is considered in a study made by NASA (CAIB Report, 2003) where some of the following aspects were taken into consideration:

- Angle of impact of the debris
- Possible bound effect, roll or secondary break up
- Vulnerability of the body to debris impact
This scale considers a level 3 or higher, from 0 to 6, as an injury. This scale is presented in Table 4-3, and is used by the Federal Aviation Administration (FAA), and the Air Force Eastern and Western Ranges for launch vehicle risk assessment.

Table 4-3, Abbreviated Injury Scale (AIS)

<table>
<thead>
<tr>
<th>AIS</th>
<th>Severity</th>
<th>Type of injury</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>1</td>
<td>Minor</td>
<td>Superficial</td>
</tr>
<tr>
<td>2</td>
<td>Moderate</td>
<td>Reversible injuries; medical attention required</td>
</tr>
<tr>
<td>3</td>
<td>Serious</td>
<td>Reversible injuries; hospitalization required</td>
</tr>
<tr>
<td>4</td>
<td>Severe</td>
<td>Life threatening; not fully recoverable without care</td>
</tr>
<tr>
<td>5</td>
<td>Critical</td>
<td>Non-reversible injury; not fully recoverable even with medical care</td>
</tr>
<tr>
<td>6</td>
<td>Virtually unsurvivable</td>
<td>Fatal</td>
</tr>
</tbody>
</table>

According to the kind of calculation that the VRP is going to do, we assumed that the $E_c$ will just be considered, as we saw throughout this chapter, as the amount of people affected “by the debris cloud or footprint”. We even considered the density of this footprint by obtaining concentric ellipses that were drawn along the trajectory and according to the impact zone.
Even we do not present deeper information about this model, we still considered necessary to include this information due to the possibility of obtaining a definitive debris model that may eventually handle this kind of variables.

4.4.2 Exposure and sheltering

An exposure model will have to consider people (number and location) at risk on the ground to the impacting debris. People inside or outside of structures or vehicles have to be considered in the model as well. In addition, a degree of sheltering offered by roofs and upper floors, most likely for categories of structures (CAIB Report, 2003), will have to be included in the region of debris impact. NASA is using a “population model with sheltering” of Texas and Louisiana, covering the area where debris of the STS-107 Columbia was found.

It will be necessary to consider a specific research that deals with sheltering model development. NASA considers (CAIB Report, 2003) four types of data: people counts (i.e. Census), demographic/economic statistics, structural/engineering reports or knowledge, and georeferencing information (association of coordinates with named places).

The exposure will be related to the estimation of the number of people who are at home, work, or school. This issue is very difficult to estimate because these numbers change according to the time of the day and the season. In addition, another two factors have to be considered: time of the year (especially for students), and weekday/weekend differences.

For sheltering calculation of $E_c$, people have to be allocated in the open, to buildings or inside vehicles. ACTA developed a roof penetration model (CAIB Report, 2003). This model
considers roof types and level of protections for people located on top of floor, one floor lower and for everyone farther from the roof, as we already mentioned in Chapter 2.

The estimation of people at work, or in the open, or just protected under a roof or inside a vehicle is somewhat complicated. This topic requires a bigger and joint research effort in order to obtain adequate estimations through appropriate algorithms. This would allow for instance, the estimation of the number of people at work on a Saturday morning, assumed to be 2% according to NASA (CAIB Report, 2003).

Algorithms that determine the allocation of working people to structure categories based on occupation will have to be created, considering that NASA used its own engineering judgment based on experience in order to develop a translation from demographic data to building distribution (CAIB Report, 2003). Building distribution was estimated, based on the experience of independent experts, using the 2000 U.S. Census. The election of data items that had direct correlation with structure type only allowed the inclusion of only a few tables. The results ended up in an average sheltering distribution shown in Chapter 2, Table 2-3.

There will be no sheltering footprint evaluation in this research because building sheltering model requires a full time independent research effort which, by all means, escape from the specific objective this research is focused on. Despite this, we considered prudent to cite some of the general-pertaining aspects involved in this topic.
4.5 **Summary**

This chapter describes the integration methodology necessary to enhance the functionality of the VRP. The inclusion of a debris model is a key factor to allow this project to create a suitable modeling and simulation environment.

We proposed a general architecture update shown in figure 30. We proposed debris grouping as a way to simplify further calculations. We have to keep in mind that, once implemented, the model should handle rapid calculations over different routes given the respective population datasets, with different vehicles.

In order to do the integration and calculation with the use of a GIS, we created a provisional debris model that would represent the debris footprint created from an eventual spacecraft explosion over a populated area based on field data gathered. This model was represented by debris fragments plotted on a digital map. We included over 7000 pieces collected from the STS-107 database, which represented the geometric figure considered for this purpose.

The geographic representation included in this chapter represented our main effort. It required extensive employment of GIS software. Several images and geographic data bases were scrutinized in order to allow geo-referenced plotting and overlaying. A given trajectory was used for spatial analysis (layer integration, population analysis, and querying) while trying to keep a good representation of reality by using free-access geographic information databases such as Landscan®.
Calculations of $E_c$ were considered only as part of the geographically represented area given by the model. Further analysis may allow debris groups to be tracked –random generation offers a good approach– and their consequences to be analyzed.

We included some information about sheltering but, as we discovered in our research, this is a complex topic that requires explicit dedication and further research.

The next step of this research would likely be focused on the debris model itself. As we mentioned in this thesis, there is not much information on debris models related to space or aircraft disintegration. All efforts are directed towards space debris models (space debris fragments that could possibly harm satellites or spacecrafts in outer space). The inclusion of a debris model will face two options: either acquiring a working model or building a debris model from scratch. From our point of view, the first option is more reasonable since the effort of the project will be towards risk assessment instead of software development, assuming a thorough analysis of the chosen model.

Finally, our integration methodology presented a way of putting things together. At the beginning of this research, there was not much information about what a debris model would include, how a debris model should work, and how it should behave in a GIS. At the end, we found ourselves with many restrictions, as well as conclusions. There is definitely a need of continuing this research in order to be “on the cutting edge” with spacecraft-related debris fragmentation models, especially now that NASA is urging to recommence the Space Shuttle program with new flights.
CHAPTER 5: CONCLUSIONS

5.1 Conclusions

In an effort to determine a methodology of integration of a debris model into the VRP, this research has covered a series of topics, from debris model fundamentals to debris model implementation and use through a GIS interface. We have explored some debris models in order to acquire a basic understanding of how these models work and what models are currently being used.

We suffered some difficulties accessing this particular kind of information. Most debris models, even though they are supposed to be commercial-off-the-shelf software, have restricted user access to their mathematical code. The companies that are involved in this field usually have contracts with the government. The use of this kind of software is still restricted to a small number of particular studies, most of them related to accidents under investigation.

Considering this restrictions, we had to focus on getting the concepts and fundamentals of what a debris model is and what it intends to solve, as well as its strengths and weaknesses. We had to get involved in the use and employment of a GIS, its tools, and its joint application with an external software. We also had to create a provisional model in order to represent the effects of debris fragments over different layers, and then determine an integration methodology applied to the VRP.

We analyzed some of the partially available debris models in the market, especially those currently being used in NASA space programs. We analyzed the input information, as well as what to expect for output. We also created a provisional debris model in order to propose an
integration methodology. Through this model we were able to determine specifically affected zones by establishing footprints.

The results of the analysis in Chapter 3 allowed us to determine an integration methodology. This methodology covered in Chapter 4 will permit us integrate any available debris model into the VRP. We proposed an architecture update, and we noted that specific attention must be given to input details as debris groupings, spacecraft fragmentation sequence, etc.

Our research suggested that our integration methodology should continue the use of a GIS. It also suggests merging several layers of vector and raster data sets in order to increase the weight of geographic analysis into the VRP process. While we consider population density and sheltering constitute key factors in $E_c$ analysis, sheltering itself deserves further research.

Due to the nature of this research, we were not able to get deeper in some very important topics, but as we can see, the information provided will surely be helpful for predicting $E_c$. With the provisional model created (ellipse representation) we can determine a working sequence which should include, for further analysis, variables like: determination of associated debris groups for each future spacecraft to be analyzed; determination of breakup vectors as a function of time, and associated to ballistics coefficient for each debris groups or individual debris pieces; generation of altitude, existing-wind velocity and direction, and drag coefficient; determination of probable failure modes, as seen in Table 3-2 for the X-34 flight program; and determination of the probability of events and impact distribution inside the model (Monte Carlo simulation).
Debris modeling, GIS integration, population density calculation and sheltering modeling represent demanding fields of study that will have to be considered separately in order to obtain the desired results the VRP demands.

This research provides a valuable tool for future definitive debris model integration into the VRP. Through its particular approach, especially through the inclusion of a provisional debris model based on field data, it may help to assess the possible determination of re-entry routes, as well as provide a way of determining $E_c$ by using a GIS.

5.2 Future Work

The definitive integration of a debris model into the VRP will have to be the following work, the continuation of a research that uncovered some of the main issues this kind of model involves.

One of the main difficulties will be acquiring the abovementioned software. Having solved this matter, integration and further use of a debris model will boost the VRP, and we may presume, it will give the VRP a relevant position due to the enormous importance of this specific analysis to public safety, especially after the Columbia accident.

As the future integration of a debris model takes place, further research may be directed to the determination of sheltering and $E_c$ considering that this point ascertain the variation of probabilities of being hit by debris depending on different shelter conditions (open field, under buildings, schools, at home, etc.). Most sheltering-related studies use data that is not directly related to the analysis. Most of them are based on a 14-year-old Census that is presumably the
only official data source that actually gives information related to housing conditions. A thorough research must be made on this in order to get more accurate results.

Another important topic that will have to be addressed is the way most debris models work. An evaluation has to be made in order to determine the way these models calculate debris trajectory. Is it good to use a model that calculates specific debris trajectories by integrating debris categories for its calculation? Is it accurate and reliable to do this grouping? Will this grouping deliver accurate $E_c$ determination? Will it be necessary to do some internal probabilistic distribution generation inside each debris group and between these groups (Monte Carlo maybe)?

Continuing this line of investigation will position the VRP as an important project since NASA is trying to resume its spaceflight program on 2005. Safety to the public will necessarily be in the mind and soul of all researchers. The result of this project will hopefully help to improve it.
APPENDIX A

COLUMBIA RECOVERED DEBRIS DATABASE (PARTIAL)
<table>
<thead>
<tr>
<th>SIDD ID</th>
<th>Eng Description</th>
<th>EPA Comments</th>
<th>Lat From EPA</th>
<th>Long From EPA</th>
<th>Length (in)</th>
<th>Width (in)</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>1940</td>
<td>Specific location not determined</td>
<td>6:35 PM, collected. Absent START.</td>
<td>31.59812</td>
<td>-94.66094</td>
<td>24</td>
<td>7</td>
<td>N/A</td>
</tr>
<tr>
<td>1940</td>
<td>Unidentifiable, unknown TPS</td>
<td>6:35 PM, collected. Absent START.</td>
<td>31.59812</td>
<td>-94.66094</td>
<td>3</td>
<td>3</td>
<td>TPS</td>
</tr>
<tr>
<td>1940</td>
<td>Unknown STR/MECH</td>
<td>6:35 PM, collected. Absent START.</td>
<td>31.59812</td>
<td>-94.66094</td>
<td>18</td>
<td>6</td>
<td>N/A</td>
</tr>
<tr>
<td>0</td>
<td>Non-Identifiable – Unknown TPS</td>
<td></td>
<td></td>
<td></td>
<td>1.5</td>
<td>1</td>
<td>TPS</td>
</tr>
<tr>
<td>0</td>
<td>This part was never received at KSC. Went straight to JSC.</td>
<td></td>
<td>6</td>
<td>6</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>BAY 8 STBD LONGERON WITH (1) PRIMARY PASSIVE LATCH</td>
<td></td>
<td>66</td>
<td>26</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>1/2 x1&quot; piece metal Crew Module Internal Structure Unknown Location-Unknown Rack U</td>
<td></td>
<td>9</td>
<td>6</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>35985</td>
<td>Section of aft thrust structure with SSME gimbal bearing still attached. Gimbal bearing separated at ball.</td>
<td>Parish: Vernon Description: (3) items: (1) small metal pieces; (1) large, round mechanical part; (1) unknown</td>
<td>31.11748</td>
<td>-93.31267</td>
<td>28</td>
<td>18</td>
<td>metal</td>
</tr>
</tbody>
</table>

---

23 This is a representation of an extensive database of approximately 84,000 debris fragments corresponding to the STS-107, which represent around 40% of its mass. This database was given to the VRP by NASA.
APPENDIX B

COLUMBIA RECOVERED DEBRIS, APPROXIMATED NUMBERS OF PARTS IN EACH CATEGORY
<table>
<thead>
<tr>
<th>Number</th>
<th>Category</th>
<th>Parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AFT Fuselage</td>
<td>150</td>
</tr>
<tr>
<td>2</td>
<td>Avionics/Electrical</td>
<td>2646</td>
</tr>
<tr>
<td>3</td>
<td>Body Flap</td>
<td>45</td>
</tr>
<tr>
<td>4</td>
<td>ECL/PRSD/ PVD</td>
<td>1892</td>
</tr>
<tr>
<td>5</td>
<td>Engines/SSME</td>
<td>249</td>
</tr>
<tr>
<td>6</td>
<td>Flight Controls/APU/Pyro</td>
<td>366</td>
</tr>
<tr>
<td>7</td>
<td>FRCS</td>
<td>43</td>
</tr>
<tr>
<td>8</td>
<td>Freestar</td>
<td>215</td>
</tr>
<tr>
<td>9</td>
<td>FWD Fuselage</td>
<td>305</td>
</tr>
<tr>
<td>10</td>
<td>HYD</td>
<td>4</td>
</tr>
<tr>
<td>11</td>
<td>Left Hand Gear</td>
<td>8</td>
</tr>
<tr>
<td>12</td>
<td>LESS/RCC</td>
<td>718</td>
</tr>
<tr>
<td>13</td>
<td>LH IB/OB Elevon</td>
<td>92</td>
</tr>
<tr>
<td>14</td>
<td>LH OMS Pod</td>
<td>16</td>
</tr>
<tr>
<td>15</td>
<td>LH RCC</td>
<td>356</td>
</tr>
<tr>
<td>16</td>
<td>LH Wing Lower</td>
<td>64</td>
</tr>
<tr>
<td>17</td>
<td>LH Wing Upper</td>
<td>26</td>
</tr>
<tr>
<td>18</td>
<td>Mid Fuselage</td>
<td>302</td>
</tr>
<tr>
<td>19</td>
<td>Molten Metal</td>
<td>61</td>
</tr>
<tr>
<td>20</td>
<td>MPS</td>
<td>220</td>
</tr>
<tr>
<td>Number</td>
<td>Category</td>
<td>Parts</td>
</tr>
<tr>
<td>--------</td>
<td>----------------------------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>21</td>
<td>Non-Shuttle Related</td>
<td>1391</td>
</tr>
<tr>
<td>22</td>
<td>Oms Pod Composite</td>
<td>849</td>
</tr>
<tr>
<td>23</td>
<td>Payload/FCS/PSA</td>
<td>95</td>
</tr>
<tr>
<td>24</td>
<td>PLBD</td>
<td>2591</td>
</tr>
<tr>
<td>25</td>
<td>Radiator</td>
<td>1686</td>
</tr>
<tr>
<td>26</td>
<td>RH IB/OB Elevon</td>
<td>55</td>
</tr>
<tr>
<td>27</td>
<td>RH OMS Pod</td>
<td>23</td>
</tr>
<tr>
<td>28</td>
<td>RH RCC</td>
<td>406</td>
</tr>
<tr>
<td>29</td>
<td>RH Wing Lower</td>
<td>149</td>
</tr>
<tr>
<td>30</td>
<td>RH Wing Upper</td>
<td>87</td>
</tr>
<tr>
<td>31</td>
<td>RH/LH OMS Pod</td>
<td>612</td>
</tr>
<tr>
<td>32</td>
<td>RH/LH Vertical Stabilizer</td>
<td>68</td>
</tr>
<tr>
<td>33</td>
<td>Right Hand Gear</td>
<td>6</td>
</tr>
<tr>
<td>34</td>
<td>Space Hab</td>
<td>2029</td>
</tr>
<tr>
<td>35</td>
<td>STR/MEQ/Glass/Dome Heat Shield</td>
<td>4519</td>
</tr>
<tr>
<td>36</td>
<td>Tanks</td>
<td>42</td>
</tr>
<tr>
<td>37</td>
<td>Unknown Composite</td>
<td>4298</td>
</tr>
<tr>
<td>38</td>
<td>Unknown Electrical</td>
<td>4269</td>
</tr>
<tr>
<td>39</td>
<td>Unknown Honeycomb</td>
<td>563</td>
</tr>
<tr>
<td>40</td>
<td>Unknown Metal</td>
<td>9354</td>
</tr>
<tr>
<td>41</td>
<td>Unknown plastic/fabric/miscellaneous</td>
<td>5730</td>
</tr>
<tr>
<td>42</td>
<td>Unknown STR</td>
<td>6041</td>
</tr>
<tr>
<td>43</td>
<td>Unknown Tubing/Fluids</td>
<td>439</td>
</tr>
<tr>
<td>Number</td>
<td>Category</td>
<td>Parts</td>
</tr>
<tr>
<td>--------</td>
<td>-------------------------------------------------------------------------</td>
<td>-------</td>
</tr>
<tr>
<td></td>
<td>Tiles are divided up by the following:</td>
<td></td>
</tr>
<tr>
<td>44</td>
<td>LH Wing Tile/Tile Table</td>
<td>530</td>
</tr>
<tr>
<td>45</td>
<td>RH Wing Tile</td>
<td>111</td>
</tr>
<tr>
<td>46</td>
<td>TPS Unknown</td>
<td>16228</td>
</tr>
<tr>
<td>47</td>
<td>FRCS/FWD/NLGD</td>
<td>467</td>
</tr>
<tr>
<td>48</td>
<td>Body Flap</td>
<td>308</td>
</tr>
<tr>
<td>49</td>
<td>Elevon LH IB/OB &amp; RH IB/OB</td>
<td>289</td>
</tr>
<tr>
<td>50</td>
<td>Lower Fuselage/Surface/Lower Surface</td>
<td>371</td>
</tr>
<tr>
<td>51</td>
<td>Upper Fuselage/Upper Surface</td>
<td>440</td>
</tr>
<tr>
<td>52</td>
<td>Unknown Wing</td>
<td>886</td>
</tr>
<tr>
<td>53</td>
<td>Identified Lower LH Wing Tiles/LESS Tiles/Lower Wing/Lower Wing Unknown/RH Wing/Unknown RH Wing/Unknown LH Wing Lower</td>
<td>363</td>
</tr>
<tr>
<td>54</td>
<td>Carrier Panel/Midbody/TPS Unknown 1.5 or Less/Unknown Tiles other than Wing/Unidentifiable Tiles/TPS Soft Goods/TCS</td>
<td>461</td>
</tr>
<tr>
<td>55</td>
<td>Leading Edge Vert/Vertical/ Silts Pod/OMS/Base Heat Shield/ OMS/BHS/AFT</td>
<td>523</td>
</tr>
<tr>
<td>56</td>
<td>Wing Glove/Unknown Wing MID</td>
<td>326</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td><strong>74383</strong></td>
</tr>
</tbody>
</table>
APPENDIX C

INTEGRATION FLOW DIAGRAM
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