INVESTIGATING AND IMPLEMENTING ENHANCEMENTS TO THE SIMULATION OF SHORT-TERM COLLISION HAZARDS

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ABSTRACT

A software tool, the Relative Collision Matrix[1] (RCM), has been developed to provide a quick-look representation of the shortterm collision hazard to space systems from a fragmentation event in Earth orbit. The software performs multiple fragmentation simulations of space objects to quantify the probability of collision for a satellite or a constellation of satellites nearby. Previously, the results were displayed in a color matrix format which showed the relative hazard of each constellation. The RCM can be used for scientific research and operational assessments even though it was designed for test and evaluation applications.

Because of its successful use as an analytical tool, the capabilities of RCM are being extended by enhancing the orbital hazard analysis routines, developing ballistic trajectory hazard analysis routines, and expanding the breakup modeling. Improvements are also being made to the RCM's useability and presentation quality by developing a graphical user interface and by providing graphical animated and nonanimated output.

INTRODUCTION

The US Space Command maintains a catalog of approximately 7,500 objects in orbit around the Earth. The orbital paths of many of these objects continually cross randomly in time and space. If one of these objects breaks up, debris is produced that could affect many of the nearby satellites. The velocities imparted to the debris as a result of the breakup produces a "cloud" of debris that spans a range of altitudes, inclinations and right ascensions and grows over time. The expanding cloud of debris is characterized by its spatial density, or number of fragments per unit volume, which also changes with time as the debris cloud and each fragment are acted on by atmospheric drag and the gravitational forces of the oblate Earth. Over a period of months to years the cloud of debris disperses and the remaining fragments become part of the background orbital population.

Due to the high velocities on-orbit (around 7 km/s) and wide range of possible encounter angles in space, a collision between a small piece of debris on-orbit and a space system can result in severe consequences. Most likely, a collision with debris roughly 10 cm in size and larger will result in complete destruction of the space system. Collisions with debris approximately 1 cm up to 10 cm in size can, depending upon the size of debris and the encounter conditions, completely destroy the system or, at a minimum, the debris can penetrate the satellite bus and disrupt or destroy a portion of the spacecraft. Debris less than 1 cm in size impacting a space system results, at a minimum, in spacecraft exterior surface erosion and possibly penetration of components. A good example of the effects of impacts by small debris is the Space Shuttle windows that have been replaced due to impacts with small particulates. There have been over 110 "impacts" on shuttle windows leaving features large enough to be recorded by ground inspection crews. About 38 of these features exceeded NASA safety specifications and the windows were replaced.

The combination of the time varying spatial density of a debris cloud and the potentially hazardous results from collisions with debris create the need to estimate the hazard associated with a fragmentation event. The RCM program is a computer simulation tool which was designed to analyze the hazard posed to particular space systems when another satellite nearby fragments. The original version of the RCM provides a first order representation of the hazard to space systems from a satellite fragmentation. The next version of RCM is in the developmental stages and will include the "quick-look" capabilities of the original RCM, but will have additional capabilities for higher order calculations, improved inputs and outputs, and will include a time-dependent analysis capability.

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ORBITAL DEBRIS FROM A SATELLITE BREAKUP

There have been over 120 satellite breakups in Earth orbit. They range in cause from antisatellite experiments, deliberate detonations, and accidental explosions. Depending on the mass of the fragmenting body, complete (highly energetic) breakups produce a large amount of debris in each of the size regimes previously mentioned. Ground based hypervelocity impact tests are performed to gauge the amount of debris produced. Results from these tests have shown hundreds of fragments are expected greater than 10 cm, several tens of thousands are expected between 1 cm and 10 cm, and millions are expected between 1 mm and 1 cm. Accurately determining the number of pieces generated smaller than 10 cm from an actual on-orbit fragmentation is impossible. Typically, the Space Surveillance Center (SSC), which is responsible for tracking and cataloging objects in space, cannot detect objects smaller than 10 cm in low Earth orbit on a normal operational basis.

Over time, the cloud of debris that results from a fragmentation event expands and eventually encompasses the Earth. Figure 1 depicts the various evolutionary stages of an expanding debris cloud. Immediately after a satellite fragments, the cloud of debris is spherical shaped. After a few minutes the cloud is shaped more like an ellipsoid than a sphere. However, due to the distribution of orbital periods and inclinations resulting from the velocity imparted to the debris, the cloud continues to expand in size and elongate along the orbital path of the original satellite. Eventually the leading edge of the cloud catches up with the trailing edge of the cloud and the cloud begins to take the general shape of a torus. Over a period of months to years, secular orbit changes from the Earth's equatorial bulge will dismantle the torus into a band about the Earth. Depending on the ballistic characteristics of each piece of debris and the altitude of the event, many fragments may reenter the Earth's atmosphere and disintegrate before the cloud reaches a band.

TYPES OF PROBLEMS RCM ADDRESSES

As we described earlier, the hazard debris in a debris cloud can pose to a satellite can be severe. The effects of the transfer of kinetic energy and momentum from an impact with even small debris can be undesirable. There are basically two categories of debris problems the RCM can address; 1) on-orbit fragmentation events, and 2) ballistic intercept tests. The next section will discuss these two categories and describe the RCM simulation of each.

On-orbit Fragmentation Events

Normally the exact time a satellite is destroyed is not known. Likewise, the exact position of all collateral satellites will not be known. Only the description of the orbit (apogee, perigee, and inclination) of the breakup object and objects at risk may be available. How then can one do an *a priori* analysis of the hazard a debris cloud can pose?

The RCM addresses these "time-independent" problems by simulating the maximum hazard the fragmentation of a nearby object can pose and then estimating the average hazard the fragmentation can pose. The maximum (e.g., worst case) simulations are performed by iteratively fragmenting each satellite in the list and evaluating the hazard to the remaining satellites treating each remaining satellite as if it were penetrating the debris cloud through the worst possible dimension (given the general orbit parameters) at the worst possible time. The average hazard is then based on the probability that the satellite(s) at risk will ever come into contact with the debris cloud assuming a random distribution of right ascensions. The results are summarized in a matrix form as shown in Figure 2. The columns of the matrix represent the fragmenting space object and the rows represent the objects at risk. The elements of the matrix represent the worst case or average probability of collision between the two pairs listed depending on which matrix is displayed. In the RCM, the simulations are performed and the output matrix is color coded to allow for quick and easy identification and evaluation of the object pairs who pose the greatest risk to each other.

In some cases, the time that a fragmentation can occur may be known. For example, an on-orbit test or operation of some type may be performed at a predetermined time that might result in a fragmentation. In such "time-dependent" cases, the actual probability of collision between a space object and the debris cloud is determined in the RCM. RCM simulates the fragmentation, the growth and evolution of the debris cloud, and the orbital motion of the nearby satellites. In these cases, the nearby objects may never be at risk from the debris cloud until the cloud has dispersed to the point in which it poses a small threat. On the other hand, it is possible to conceive of a situation in which the satellite at risk penetrates the debris cloud very soon after it was generated. If such a situation were to happen, there would be a non-insignificant probability that the satellite would be struck by debris. The RCM simulating in a "time-dependent" mode can address these situations.

The RCM can be used to determine the "time-independent" probability of collision using the "time-dependent" simulations. This is a Monte Carlo analysis for the average probability of collision for the satellites chosen to be at risk. The orbital parameters (right ascension of the ascending node, argument of perigee, and true anomaly) of the breakup object and objects at risk are allowed to vary uniformly between 0 and 360^{o}. The probability of collision is evaluated during each simulation and can be statistically combined to calculate the average probability of collision. This capability is useful to determine the best estimate of the average probability of collision.

The fragmentation of a space object either by explosion or collision is simulated using the widely used and documented Fragmentation Algorithms for Strategic and Theater Targets (FASTT) semi-empirical breakup model. FASTT conserves mass, momentum, and energy when simulating a breakup. The impact simulations have been derived from and compared to many ground based hypervelocity impact tests but are still heavily rooted in basic physics. The explosion simulations are derived from the Gurney explosion model. The cumulative number of debris above a given size is estimated. Also, the mass and ballistic characteristics of discrete fragments can be simulated using the statistical distributions within FASTT.

Ballistic Intercept Tests

Depending on the particulars of the scenario, debris resulting from an intercept between a projectile and a target during a ballistic missile intercept test may pose a hazard to low Earth orbiting satellites. Debris from the event may be given a sufficient velocity impulse such that at or near the apex of the flight the object would be at low Earth orbital altitudes. When a large amount of debris is dispersed, the resulting cloud could expand and pose a risk to operational satellites. This type of analysis will be useful when test programs for the Theater High Altitude Air Defense (THAAD) begin.

The simulation and analysis of this type of problem is analogous to the on-orbit events. Since, in fact, a ballistic trajectory can be considered an orbit with a periapsis below the Earth, the calculational aspects are similar to the on-orbit events with the major difference being the much shorter time frame. (Most of the debris in a ballistic trajectory will not last for more than one revolution, while on-orbit, most of the debris will last for many revolutions.) The RCM simulates this type of problem by breaking up the target vehicle due to the collision using the FASTT breakup model, simulating the motion and evolution of the debris cloud, and determining the hazard to nearby satellites.

The second simulation that RCM performs related to ballistic intercept tests is the ground footprint of the debris fragments as a result of the intercept. Generally speaking this a very difficult problem and is subject to varying aerodynamic and meteorological uncertainties. The footprint simulated by the RCM is intended to provide the analyst with a reasonable order approximation of the ground footprint so that sensitivities of the engagement parameters can be assessed and the location of the footprint to nearby population centers can be determined.

RELATIVE COLLISION MATRIX

General Description

The RCM system software operates on a Sun SPARCstation II in the Open Windows Version 3.0 and SunOS 4.1.X software environment. A color monitor and adequate internal RAM is necessary to support the simulation requirements. Hard disk space is also required for storing the RCM data elements — scenarios, constellations, and satellites. When the RCM user interface is used to create the parameters, the RCM software automatically generates the necessary files to store the information.

The ability for the user to specify scenarios (i.e., collection of satellites, satellite constellations, and fragmentation descriptions) is an enhanced feature of the RCM software. This procedure is explained in more detail in the following section. Note that this feature is available to the user, even during simulations, because the software was designed using separate processes. Communication between the software which controls scenario processing, probability and trajectory calculations, and the software which updates the simulation displays, occurs via a RCM system control software package. This system control software package is also responsible for displaying the main RCM menu, which allows the user to select/define scenarios, control a simulation, and request certain displays. All of the communications within RCM utilize the UNIX system Transport Interface mechanisms.

Setting Up Simulations

Once the RCM software is started, the user is presented with a main menu. The main menu has three operations which are associated with the definition of scenarios: *Open, Save, and Close.* The *Open* option allows the user to either create a new scenario or open an existent, pre-saved scenario. A scenario must be opened in order to actually execute a simulation, since this is how the RCM software knows which scenario to execute. Once a scenario is opened the user can make changes to a scenario, or execute one of three types of simulations. The three types of simulations are explained in the next section.

A scenario consists of all the satellites or satellite constellations involved in a simulation. Please note that satellite and constellation are not intended to be used interchangeably. The RCM simulates individual satellites or a system of satellites (constellation). In this paper, a constellation refers to a system of *one or more* satellites. The first screen shown to the user is the Scenario Definition screen (see Figure 3). This screen displays the scenario name, the number of satellite constellations in the scenario and a list of all the constellations. Constellations may be added, edited, deleted or viewed.

The next screen associated with the definition of a scenario is the Constellation Definition screen (see Figure 4). This screen allows the user to specify information about the satellite(s); type (two line element set, Satellite Catalog entry, or user-defined), debris dispersion type, and fragmentation type (collision or explosion). When the user wishes to use a satellite defined by either a two line element set or a Satellite Catalog, RCM displays the available file listings. The user can then specify the file (which contains the needed orbital data), a satellite number (which is actually an index into the file) and the mass of the satellite. The User's Manual provides typical satellite masses if actual masses are not known. There are two RCM user-defined satellite options which allow the user to define a constellation; 1) entering a complete set of classical orbital elements or 2) entering only "time-independent" (slowly time varying) orbital parameters which are needed at a minimum to perform a "time-independent" simulation. The third user-defined option allows the user to define the parameters of an object in a ballistic trajectory. Upon hitting *Continue*, screens are presented to the user for entering additional information depending on the data and options selected on this screen.

Simulation Processing

Once the user has fully defined the scenario and saved the scenario information, one of three simulations are available via the *Execution* menu option. These three simulations or modes of execution are: 1) first-order analytical hazard modeling, 2) "time-independent" higher order, or 3) "time-dependent" simulations. The first-order analytical simulation simulates the debris cloud and calculates probabilities of collision using simple, first-order expressions. This is essentially the original or prototype RCM. The higher-order "time-independent" simulation will simulate the debris cloud and calculate probabilities of collision using higher fidelity (also more time consuming) calculations. The "time-dependent" simulations are for those situations when a breakup time is known and the locations of nearby satellites are also known. The probabilities of collision determined in this mode are completely dependent on the phasings between the satellites at risk in their orbit and the debris cloud.

Displays

During and after a simulation, the user is provided with displays which animate the hazard calculations. Pictorial displays, which make identification of potential problems easier to recognize, is a major part of the RCM project. There are two basic types of displays available to the user: animated displays which track the satellites and debris from two different view angles and static displays which are available at the end of a simulation.

One of the dynamic displays shows the satellites and debris on a Mercator map projection. Figure 5 is a drawing of this display. The user selects which satellites are shown on this display, the breakup satellite, and associated parameters prior to the start of a simulation. The satellites change colors (green, yellow, red) to represent the associated hazard. Colors were chosen for visualization purposes as opposed to displaying only numerical values (i.e., probabilities). The color green represents no immediate hazard, yellow indicates the satellite is within the altitude boundaries of the debris cloud, and red indicates the satellite is currently passing through the simulated debris cloud.

The second animated view shows the same information from a side view. Figure 6 is a drawing of this display. This display maps altitude along the horizontal axis and longitude along the vertical axis. This view adds a dimensionality (altitude) which is not pictorially represented in the normal Mercator map display.

The available static (non-animated) displays are *PC vs. Time*, *Ground Footprint* and *Color Matrix*. Which displays are available at the end of a simulation depend on the type of simulation selected by the user. The *Color Matrix* display was the basis for the original RCM and consists of color coded versions of Figure 2 for worst case and average probability of collision. The *Ground Footprint* display shows the location of several debris fragments once they have reached the ground. The ground footprint locations are shown on a Mercator map projection. This display is available if the breakup object was on a ballistic trajectory. The *PC vs. Time* display is available following any high-order simulation. The display shows the cumulative probability of collision (for the user indicated satellite at risk) over time.

In addition to the graphical displays, data from the simulation is written to an output file. This data is available for analysis and post-processing after a session with the RCM is over.

SUMMARY

As a result of space object fragmenting, a large number of debris will be contained in a relatively small volume of space that changes with time. Because of the high velocities on-orbit, a space system interacting with this debris has a good chance of sustaining damage if not being complete destroyed. The RCM is used to analyze the relative hazards created to a list of space systems if one of these space systems fragments. The current version of the RCM has shown its usefulness in providing an understanding of the relative safety of space systems from a nearby fragmentation. The first version of the RCM has sufficient accuracy to provide an understanding of the parameters and the sensitivity of the parameters involved in a probability of collision analysis. Because of its usefulness as a hazard analysis and instructional tool, RCM is currently undergoing updates to improve the accuracy of the calculations, provide a time-dependent analysis capability, and create new inputs and outputs to expand the type of applications and the output representation of the simulation. The end result of the RCM project is a planning, testing, and educational tool for evaluating spacecraft orbital safety. The unique collision matrix representation and the animated satellite and debris cloud displays provide easily understood results to users of all ability levels.

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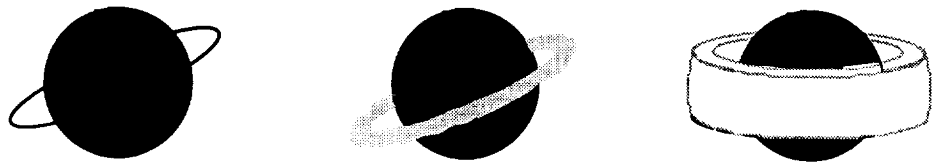

Figure 1: Over time, the cloud of debris that results from a fragmentation event will expand and eventually encompass the Earth.

Fragmenting System

System at risk	System 1	System 2	System 3	System 4 · · ·	System n
System 1	P_{11}	P_{12}	P_{13}	P_{14} · · · · · · · · ·	P_{1n}
System 2	P_{21}	P_{22}	P_{23}	P_{24}	
System 3	P_{31}	P_{32}	P_{33}	P_{34}	
System 4	P_{41}	P_{42}	P_{43}	P_{44}	
⋮	⋮			⋱	
System n	P_{n1}				P_{nn}

P_{ij} = probability of collision for satellite i as a result of satellite j fragmenting

Figure 2: The results from "time-independent" simulations are summarized in a matrix form. The columns of the matrix represent the fragmenting space object and the rows represent the objects at risk. The elements of the matrix represent the worst case or the average probability of collision between the two pairs listed depending upon which matrix is displayed.

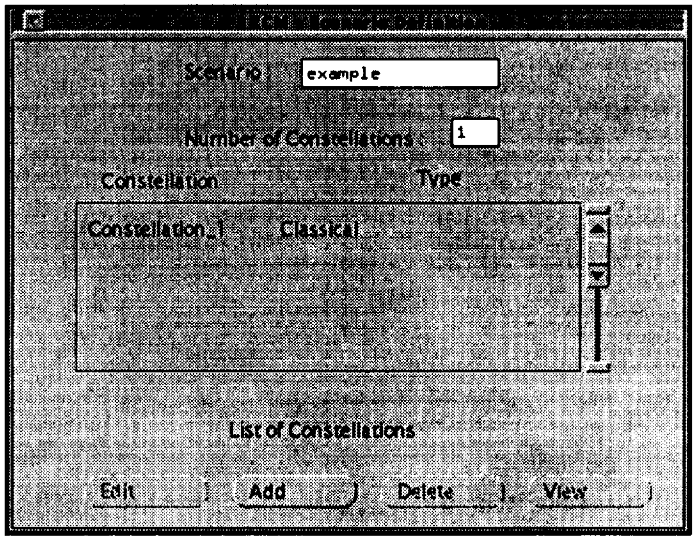

Figure 3: The *Scenario Definition* screen of the RCM. This screen displays the scenario name, the number of constellations, and the list of constellations in the scenario.

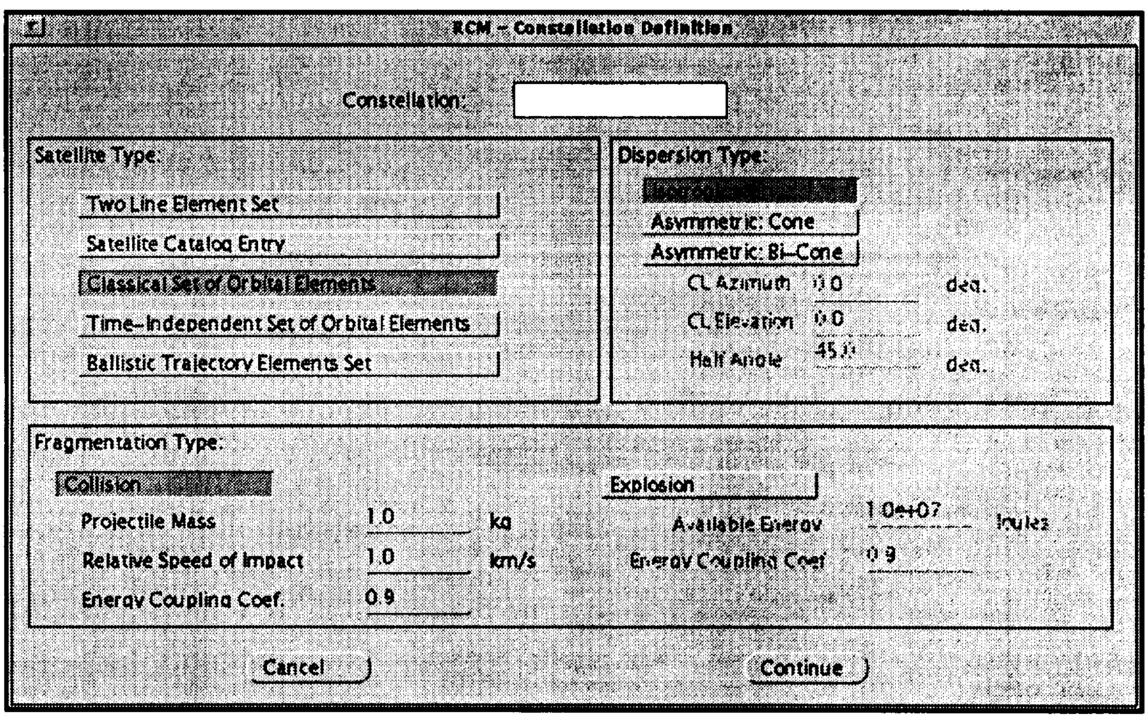

Figure 4: The *Constellation Definition* screen of the RCM. This window allows the user to specify information about the satellite(s) in each constellation.

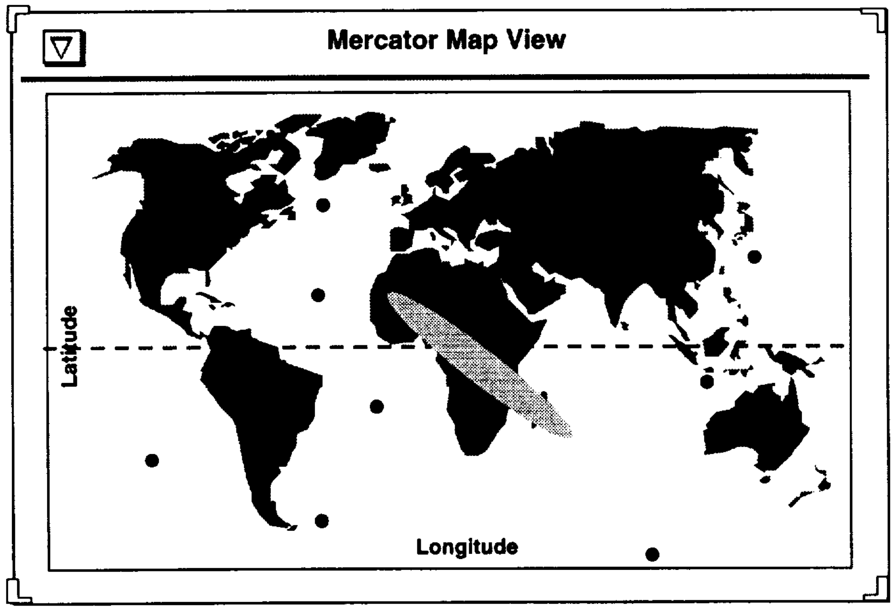

Figure 5: Drawing of the animated Mercator map projection in the RCM. The user selects which satellites are shown on this display, the breakup satellite, and associated parameters prior to the start of a simulation.

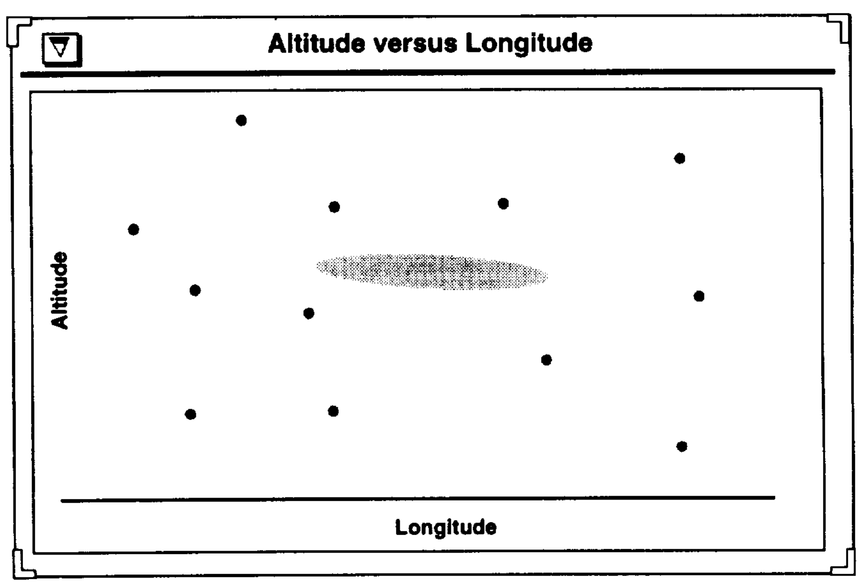

Figure 6: Drawing of the Altitude versus longitude view in the RCM. This display maps altitude along the horizontal axis and longitude along the vertical axis to add dimensionality to the Mercator Map view.