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Integration of dynamic models in range operations

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ABSTRACT

This work addresses the various model interactions in real-time to make an efficient internet based decision making tool for Shuttle launch. The decision making tool depends on the launch commit criteria coupled with physical models. Dynamic interaction between a wide variety of simulation applications and techniques, embedded algorithms, and data visualizations are needed to exploit the full potential of modeling and simulation. This paper also discusses in depth details of web based 3-D graphics and applications to range safety. The advantages of this dynamic model integration are secure accessibility and distribution of real time information to other NASA centers.

INTRODUCTION

Space launch is inherently risky and accidents are not uncommon. Because space launch activities and associated safety practices are highly scientific and technical, they depend on various models interaction which improves efficiency and reduces costs. In the history of the U.S. space program, neither member of the general public or launch site workers have been killed or seriously injured during a launch accident. The primary hazards from launch accidents are associated with debris, toxic effects, and blast overpressure. Debris is created by aerodynamic forces that break up the vehicle, by explosions caused by system malfunctions, or, in many cases, as the intended result of initiating flight termination. Toxic effects may be caused by effluents from launches or catastrophic accidents. Vehicle explosions may also create blast overpressure, which can break windows and cause injuries from glass fragments miles from an accident site. Modeling of these effects is needed for launch safety.

Specific pre-launch modeling is done and the results constitute the launch operations decision making process for public safety. The nominal vehicle trajectory and states (e.g., velocity, thrust and staging events) are provided to the range safety and mission planning divisions. Uncertainties in vehicle and control system characteristics and wind variability are used to define three-sigma limits to the trajectory profile. The nominal and three-sigma limits are used as references during launch and are depicted on the range safety display system. This forms the baseline data for the path of the vehicle which is essential to any safety study. Probable failure modes (including command destruct) are identified for a given launch based on previous experience and modeling by range safety personnel.

Statistics on monthly or seasonal winds are developed at each range to determine the likely trajectories of expended stages or debris. These data include the average wind magnitude and wind direction as a function of the altitude, as well as the statistical variability of these parameters. During the time of launch, the actual measured winds from aerial soundings are used to improve pre-launch estimates. The wind data are used with the data on ballistic coefficient and energy to determine debris trajectories. During launch, wind and aerodynamic effects are omitted when computing the Instantaneous impact point (IIP), but measured winds are used to depict probable debris impact points on the range safety display system.

Population data are extracted from the TIGER census database for the continental US and other areas of the world. A population distribution is used to compute expected human risk due to launch accidents. The shelter probabilities are assigned depending on the time of launch (day, evening or night). Data relating object energy and the likelihood that an object will cause injuries or deaths are used to determine the smallest objects that should be included in subsequent analyses. This analysis is used to determine the minimum size of debris that could endanger aircraft and ships. Safety metrics, such as casualty expectation (Ec) and the individual hit probability for aircraft or ships (Pi) are calculated throughout the launch trajectory by computing the probability of failure at any given time; determining the potential failure modes, debris types, and energies; propagating the debris using wind and aerodynamic models; and estimating casualties for the debris types and energy, the affected area, shelter types, and population densities. On launch day, the measured wind profile is compared with the previously developed maximum wind constraints. Winds in excess of these values will result in a launch hold because Ec could be increased beyond the accepted standard. In the following sections, the launch and range virtual test bed architecture is described in detail and underlying models are also explained.

LAUNCH AND RANGE TESTBED ARCHITECTURE

The launch and range simulation test bed (Bardina and Rajkumar 2003) uses the latest information technology to bring a real time simulation to the web. The test bed consists of four dedicated servers which cater the complex simulation, modeling, data acquisition, processing and storage. Tomcat servers serve as web servers and Java Servlets, Applets act as the front-end graphical user interface (Bigus and Bigus 2001; Watson 1997). There are legacy codes (written in FORTRAN) which are running as backend processes supplying input data to other models. Java applications acquire remote data for weather models. The decision model is based on a backward chaining expert system where rules are derived from flight launch rules. The overall architecture of the intelligent launch and range test bed is shown in figure 1. The 'ILR01' server is an independent web server, which processes various weather factors and automatically updates launch status for 'GO/NO-GO' scenarios (Rajkumar and Bardina 2003). On the back end, data acquisition, and processing of data is performed periodically by running a *cron* daemon. The 'ILR02' server provides an analysis of different types of orbits for different types of rockets. The orbital dynamics is provided in three dimensions, so that telemetry data can be captured which will provide enhanced knowledge of flight status (NASA 1988).

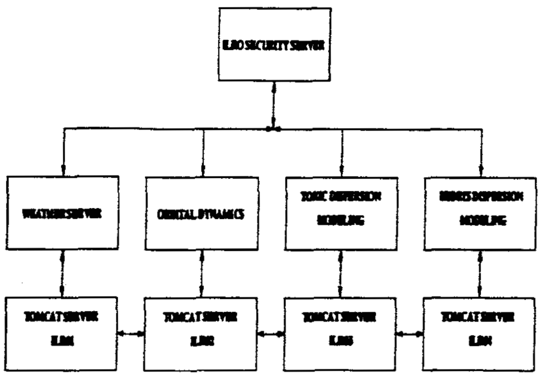

Figure 1 Intelligent launch and range test bed architecture

The toxic dispersion modeling coupled with geographical information system is served by 'ILR03' server. The dispersion models used are based on Gaussian dispersion model concepts (Boyd 1985). The dosage and concentration formulas are defined in rectangular coordinates (NRC 1998 and 2000). The x-axis is directed along the axis of the mean wind direction and the y-axis is directed perpendicular to the mean wind direction. Normally the origin of the coordinate system is placed at the launch pad. The 'openmap' is a Java Beans based toolkit for building applications and applets needing geographic information. Openmap allows multiple layer integration to represent information about population density, gas dispersion, risk contours, etc.

The 'ILR04' supports the debris dispersion model, when there is a need for aborting a mission due to malfunction during launch. In the present model, we have considered gravitational effect, air resistance, and particle/ground friction during settling of the particles. All particles are projected to disperse in an elliptical form where the particles hit the ground. If the particle has not reached the ground, there is a rotational effect for each particle in the air. In the following section we explain each model in detail and how these complex models interact with each other during simulation.

MODELS

There are four major components involved in the simulation of launch and range safety systems to derive a 'GO/NO-GO' situation and they are : (i) Weather expert system (WES) (Rajkumar and Bardina 2003) (ii) Toxic gas dispersion model (Boyd 1985) (iii) Human health risk assessment model (Bennett and McDonald 1999, Hudson et. al. 1999, FAA 1999 and Yassi 1998) (iv) Debris dispersion model and orbital dynamics (Jensen et.al 1962 and Lengyel 2004).

Weather Expert System

The weather expert system is launched by a dedicated server as mentioned earlier and in the following sections the user interface, inference engine and knowledge base are discussed (Watson 1997).

User Interface

Java Servlet technology is adopted for accepting the user inputs and further analysis. In figure 2, there are 16 different buttons.

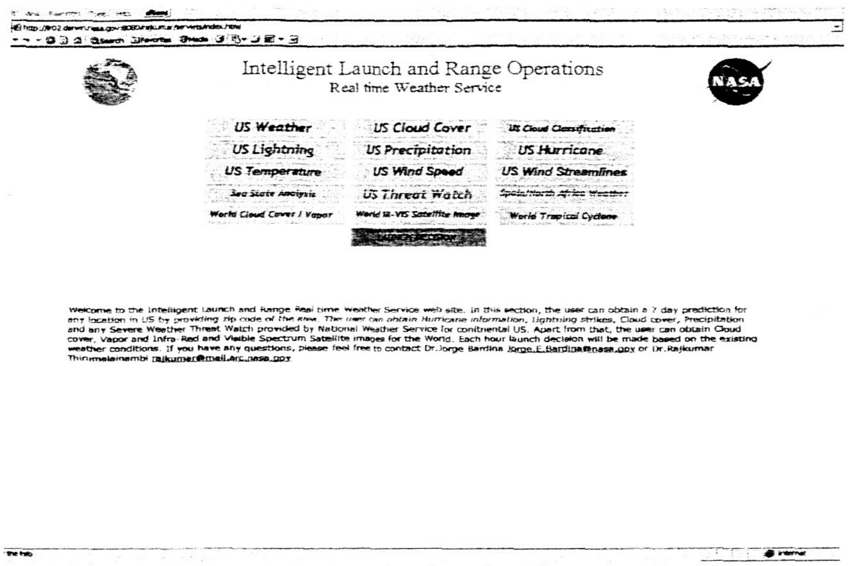

Figure 2 Graphical user interface of weather web server

The first four button rows deal with the US and North American continental weather system. The fifth button row provides information on global weather system including tropical cyclones. The "Launch Decision" button activates the expert system and provides the expert decision for the shuttle launch. Except for the launch decision button, all other buttons invoke corresponding servlets. The servlets get the data or images from various sources across the US. The US weather button provides a 7 day weather forecast for a given zip code in the continental US. It provides a national weather service radar image and satellite image with daily weather forecasting. Apart from these images, specific weather details like humidity, wind speed, barometric pressure, heat index, and dew point are updated in hourly intervals. The U.S. Cloud classification obtained from the U.S. Naval postgraduate school at Monterey, California, lightning data from the National Lightning Detection Network, surface temperature, and wind speed from the National Weather Service are updated at 30 minute interval. Rawinsonde data are updated every day from the 45th Air Force wing located at Cape Canaveral, Florida. The sea state analysis is provided to the user to understand the booster rocket recovery. Weather criteria from NOAA in Spain and North Africa are monitored in case the need arises for an emergency landing at Transoceanic Abort Landing Site (TALS). The downloaded data are processed for Florida state and Cape Canaveral and form an input to the expert system. When the user presses the "Launch Decision" an expert system inference engine checks the values against the weather rules and it provides the Shuttle launch decision by GO or NO-GO.

In figure 3, the expert decisions for the Shuttle launch are shown below the button groups. The green value contributes to the GO situation whereas red value contributes to the NO-GO situation.

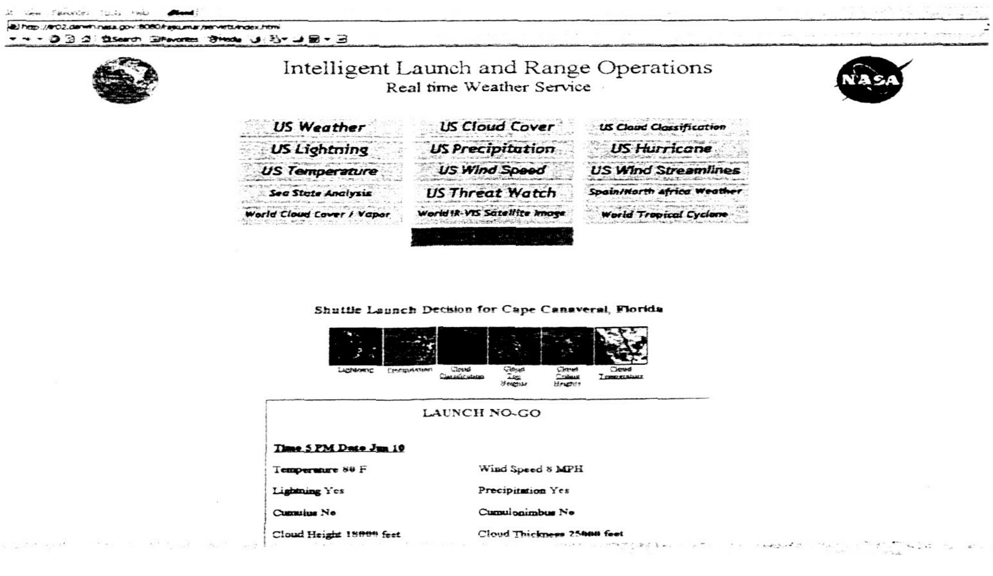

Figure 3 Weather expert system output

For GO to occur, every value in the lower frame must be green. The present expert system provides the decision for a generic Shuttle launch. For specific Shuttle launches, more stringent rules have to be added to the knowledge base.

Inference Engine

The inference engine looks at the goal variable of the expert system. The inference engine adopts a backward chaining mechanism because it only processes rules that are relevant to the questions and goals. It simply traverses the rule base trying to prove that clauses are true in a systematic manner. The rule is triggered, if all antecedent clauses are set to be true. The clause conditions are derived for each vehicle type.

Knowledge Base

The knowledge bases can be represented by production rules. These rules consist of a condition or premise followed by an action or conclusion (IF Condition .. THEN Action). Most of the rules for weather expert systems are derived from weather contingency rules developed over several years by NASA. Depending upon the type of launch vehicle, rocket propellant and payload, the weather rules change. The knowledge base consists of rules for GO and NO-GO situations. Depending on the prevailing weather conditions the expert system advises the end user. The details of Rawinsonde and other weather parameters form inputs for the toxic gas dispersion model.

Toxic Gas Dispersion Model

The required inputs for the gas dispersion model are vertical profiles of wind direction, wind speed, air temperature, atmospheric pressure and dew point or relative humidity between the earth's surface and 3000 m. This information is obtained during launch support activities from Rawinsonde measurements routinely measured at scheduled times throughout the pre-launch count down and after launch has occurred. The wind measurement system is a series of 30 m towers located throughout Kennedy Space Center and one 152 m meteorological tower instrumented to measure wind direction, wind speed, turbulence and air temperature. Based on the inputs, the toxic gas dispersion model computes the dimensions of the ground cloud as a function of the height, distribution of vehicle exhaust products within the cloud as a function of height, and position in space of the rising ground cloud as a function of time after launch until the internal cloud temperature equals the ambient air temperature (Boyd 1985; and Beychok 1995). The dosage concentration at an interval of 1 km from downwind of the launch pad is computed. For a normal launch, the assumption is made that all engines and the pad deluge system operate normally. In the case of a launch failure (single engine burn on pad), one solid engine does not ignite and the vehicle remains on the launch pad. In case of failure to lift off, an on pad explosion will cause scattering of solid rocket propellant. The fuel expenditure rates for normal launches are obtained by averaging fuel expenditure rates for the engines over the approximate period from lift off until the vehicle is about 3000 m above the surface. The fuel expenditure rates for the single engine burn are an average for the normal firing period of the engine. The exhaust cloud constituents are HCl, CO_2, and CO. The inputs to the toxic dispersion model are shown in figure 4.

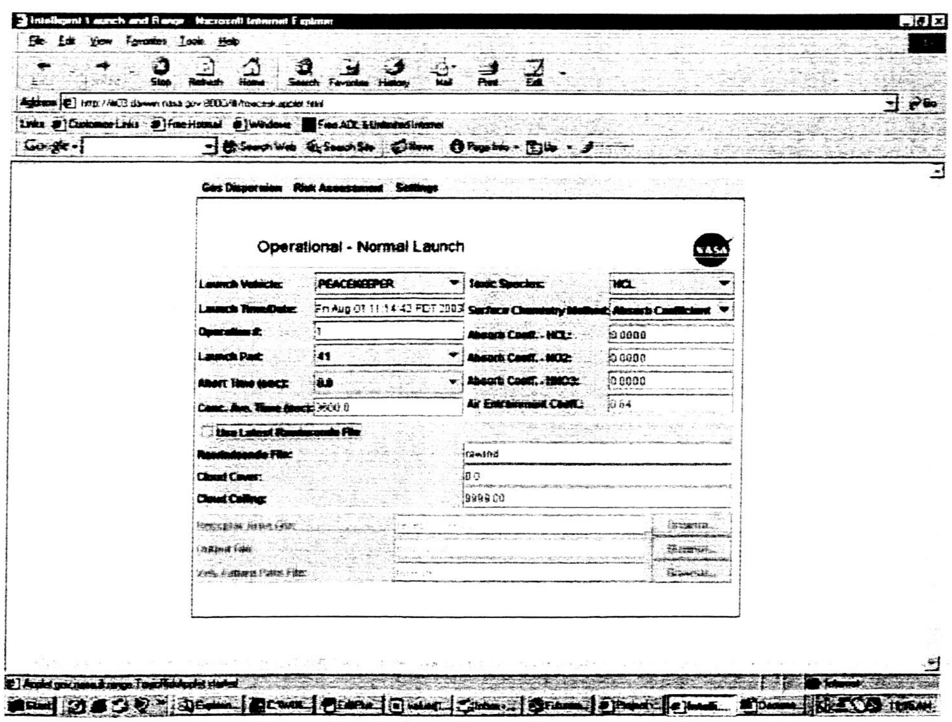

Figure 4 Inputs for toxic gas dispersion model

In figure 4, the user can select type of rockets, launch time and date, launch pad (39 A or B), concentration, time (i.e., 5min., 10 min., 1 hour) interval, characteristics of cloud cover, rawinsonde data, chemical species (HCL, NO_2, and HNO_3), surface chemistry and necessary coefficients. Once the user has provided all details, the backend of the server using FORTRAN code, computes chemical concentration at the ground level for a particular species. The chemical dosage is converted into contours and it is displayed in figure 5 via an openmap interface. The concentration is expressed in parts per million (ppm) and five levels of contours are computed from minimum to maximum concentration. The contour simulation is performed by an applet. The concentration computed at the ground is available for humans to inhale. The flight launch rules have an allowable limit of ground concentration for specific chemicals. If the simulated concentration exceeds the allowable limit, the mission will be kept on hold. The chemical concentration is monitored by real time sampling of ambient air after launch. The real time data and simulated data are compared and act as surrogate data for other launches.

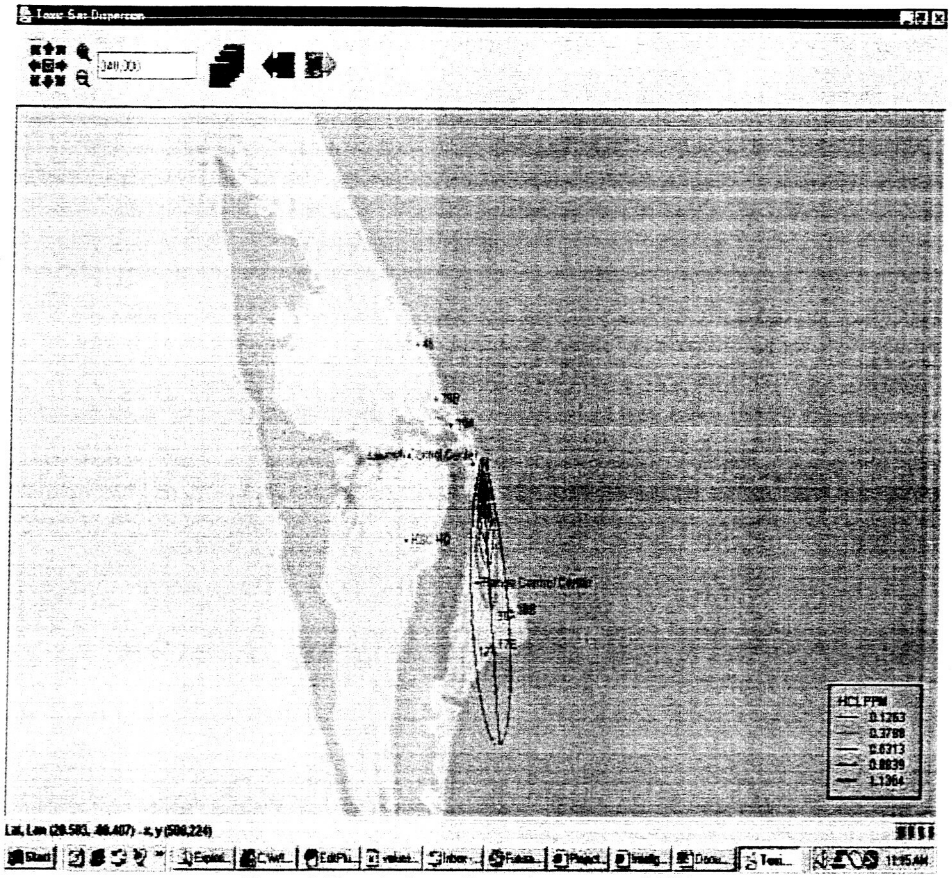

Figure 5 Chemical gas dispersion contour (HCL)

Human Health Risk Assessment Model

A binomial distribution is used to simulate the variance (uncertainty) associated with the predicted number of people affected. The potential for combined effects of exposure to more than one compound is estimated by developing joint probabilities of effect from the individual toxicants probabilities of effect. The LATRA model estimates exposure risk for HCL, NO_2, and HNO_3. The available toxicological data for humans on the specified rocket emission toxicants are currently limited. The exposure response functions in the LATRA model are currently based on 1 hr time weighted average concentrations and ceiling values. Until more toxicological data is available, the hazard quotient model developed by USEPA would be the most appropriate.

The hazard quotient is the ratio of an observed or predicted exposure to an allowable exposure. The allowable exposure limit is set at a lower value by selecting an uncertainty factor that is sufficient to protect sensitive individuals. When the ratio of estimated exposure concentration (EEC) to the reference toxicity value (RTV) is less than 1, effects are considered unlikely. When the quotient is greater than 1, some effects might occur in some individuals. As the value of EEC/RTV increases, both the severity and incidence of effect are likely to increase, but the ratio is not used to predict incidence or severity. An additional advantage of the hazard quotient model is that it allows an estimation of the number of people at risk of additive effects from simultaneous exposure to two or more substances that is not possible in a traditional risk assessment. The risk to the exposed population is calculated by multiplying the individual risk and the number of exposed population (this should take into consideration age, other susceptibility factors, population activities, etc.). In our model, the risk value is computed for a given latitude and longitude in a specified region of interest. The risk contour is generated based on the risk values and five levels of contour are plotted. The values are expressed in terms of 1 in one million. The risk values are compared against the acceptable risk values and GO and NO-GO status is decided for the launch.

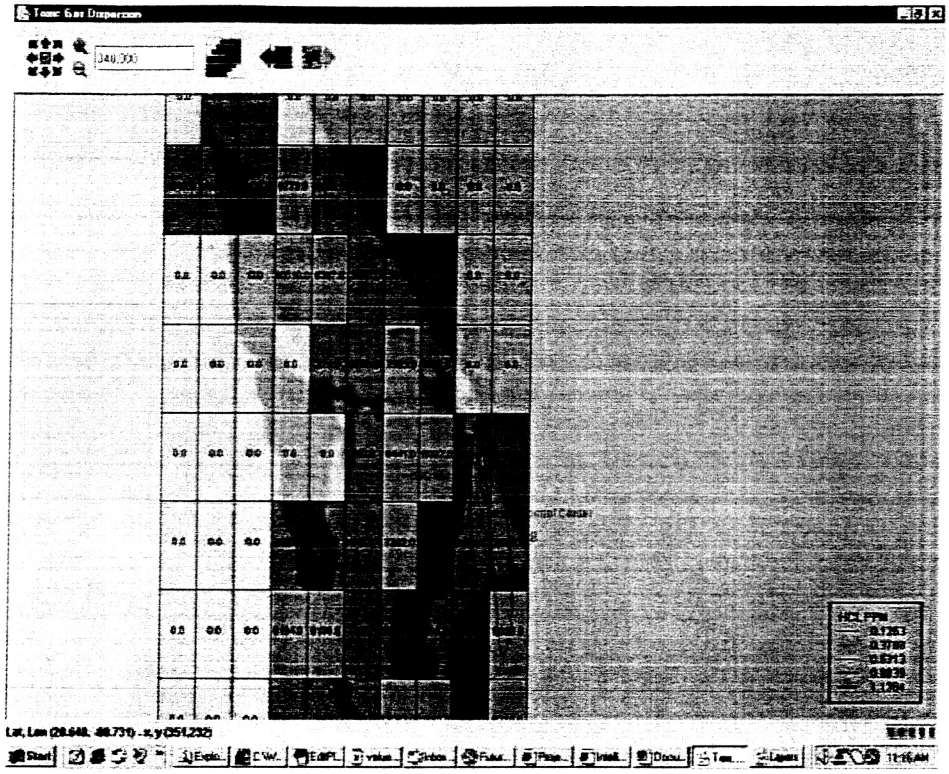

Figure 6 Population grids over Cape Canaveral

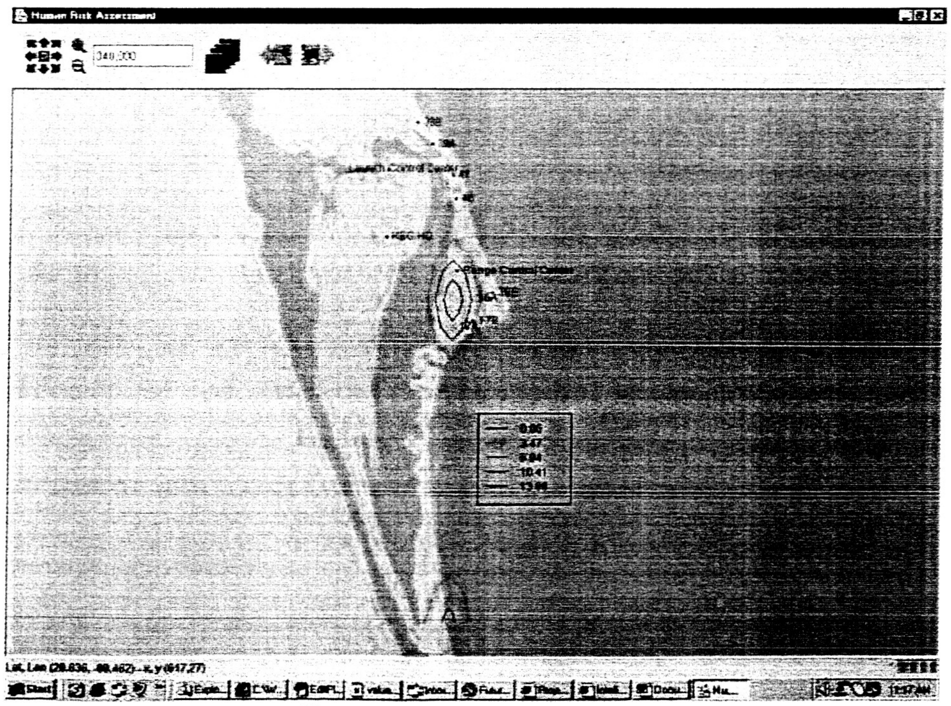

Figure 7 Human health risk contour

Figure 6 shows a population grid and it is added as a layer in openmap. The user can define any number of layers and they can be added dynamically. The population grid displays a selected region of interest and divides it into 10 x 10 grid of equal intervals. The centroid of each square is computed by adding all populations in the grid. The computed chemical concentration and population are translated into risk values based on the hazard quotient model. The risk contour is shown in figure 7. Presently two dimensional contours are plotted and a zoom feature is added via openmap interfaces.

Debris Dispersion Model

Range safety personnel evaluate various scenarios of failure during a launch. If there is a malfunction in separation of rockets or any other failure, then Range Safety Officers can decide to terminate the mission. During termination, flight safety personnel will see that there is a minimum impact of debris scattering inland. There are various flight rules which have to be satisfied before destructing the mission. In the present debris dispersion model, gravitational effect is implemented with air resistance.

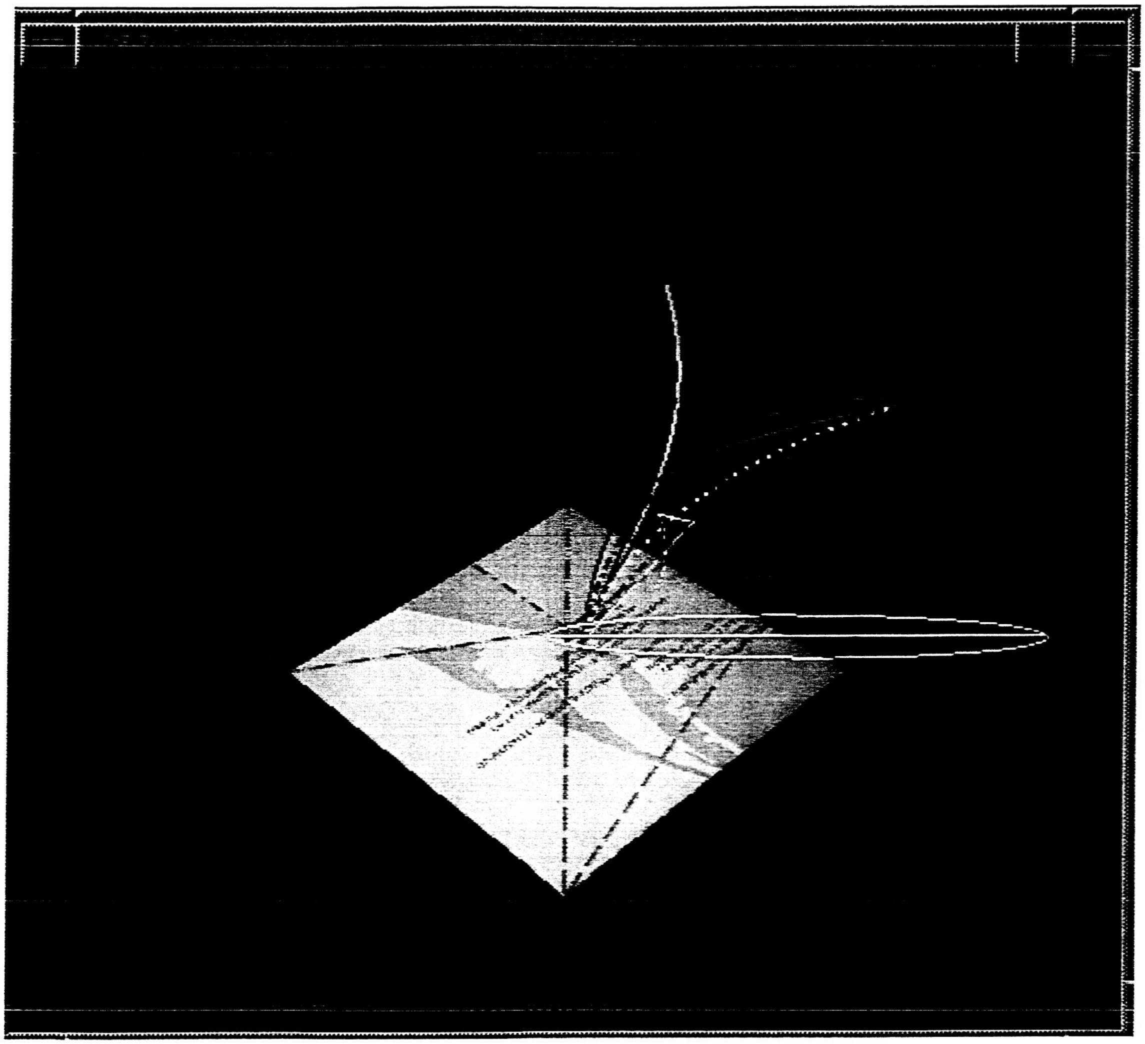

Figure 8 Debris dispersion model

The debris dispersion model is developed in Java 3D with orbital dynamics and it is shown in figure 8. Trajectories are constructed using *Bezier* curves and cubic splines. The Java 3D behaviors are customized to suit our dispersion and orbital dynamics characteristics. Presently all models interact with four web servers by issuing http requests. Since models are web based, it is easy to access from different corners of the world. The model parameters can be remotely provided to execute a specific model and the output can be redirected to other models by http protocol.

CONCLUSION

The simulation and modeling test bed is based on a mockup of a space flight launch and range operations which include data and model from experimental, physical, procedural, software, hardware and psychological aspects of space flight control operations. The test bed consists of a weather expert system to advise on the effect of weather in launch operations. It also simulates toxic gas dispersion, impact of human health risk, and debris dispersion with 3D visualization. Since all modeling and simulation is based on the internet, it could reduce the cost of operations of launch and range safety by conducting extensive research before a particular launch. Each model has an independent decision-making module to derive the best decision for launch and range operations. Further research is planned to develop intelligent agents for each simulation and a decision support system to fully automate space launch initiatives. Since we use Java, it is compatible with any platform and operating system. The virtual test bed technology enables an entire suite of applications and models for launch and range safety operations.

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