ABSTRACT: The Virtual SpacePlane (VSP) is a realistic prototype of the Manned SpacePlane (MSP) and simulates a number of the MSP missions in a realistic manner. To increase the realism of the space environment and space mission planning, we inserted a portrayal of space weather into the VSP’s virtual environment. In this paper we present background on the VSP project, space weather, and describe the requirements, goals and objectives for the space weather insertion research. We discuss the design and implementation of the software that we used to insert space weather into the virtual environment and describe the changes that we made to the user interface to provide a space weather visualization capability. The paper concludes with a presentation of our results and suggestions for future work.

1. INTRODUCTION
The advent of requirements for worldwide deployment of space assets in support of Air Force operational missions has resulted in the need for a spacecraft that can support these missions with minimal preflight and minimal in-orbit support from a mission control center. To address this need, the Air Force is developing a Manned SpacePlane. The Manned SpacePlane (MSP), which is in the earliest stages of concept development would perform military missions including transportation, reconnaissance and deployment of space assets supporting the strategic and tactical goals of theater commanders. After launch, the MSP would operate independently of ground support, with the only contact being uploaded changes to mission plans and objectives; re-planning and executing the mission within consumables and time constraints would be the crew’s responsibility. As a result, successful mission accomplishment will depend almost completely upon the Manned SpacePlane crew and upon the on-board capabilities of the spaceplane. However, the development of the full range of desired capabilities is not a straightforward process since the capabilities are only broadly defined and it is not clear which of those capabilities are technologically feasible. Additionally, there is very little doctrine established for space operations, and as a result, requirements for the MSP are based on best guesses of the needed capabilities and applications of space assets for reconnaissance purposes.

To attempt to reduce some of the uncertainty associated with MSP requirements and capabilities development and to attenuate the risk for the MSP project, the Virtual SpacePlane project was initiated. To insure that the crew has the needed capabilities on-board the craft, Air Force Research Laboratory (Phillips Laboratory) initiated the Virtual SpacePlane (VSP) project. The Virtual SpacePlane is a virtual prototype of the Manned SpacePlane and must be able to perform MSP missions in a realistic and tactically sound manner within a distributed virtual environment (DVE). The goals of the VSP project are to develop and validate the MSP user interface requirements, design and implement an intelligent user interface, and to design and implement a prototype virtual spaceplane that can be used to demonstrate MSP missions and to conduct preliminary training in support of the Manned SpacePlane. The Virtual SpacePlane is based upon the existing Virtual Cockpit, Solar System Modeler, and Common Object Database systems that have been developed in our Labs. The VSP must demonstrate the functionality and capabilities of the MSP throughout its entire flight regime, from takeoff through space operations and landing. The VSP’s architecture is based upon the Common Object DataBase. The Common Object DataBase is a data-handling architecture that uses classes, data containers, and a central runtime data repository to store and route data between the major objects in an DVE application. The Common Object DataBase contains the entire state of the DVE, as well as all the public or exported information for each object within the VSP application.

The current capabilities of the VSP include flight and maneuvering in the atmosphere and while in orbit around the Earth. The VSP can manually and automatically takeoff and land. The VSP can also perform two missions, the release of a satellite from its cargo hold, and a rendezvous with any of the many satellites already in orbit. The VSP provides a user interface that enables the operator to manage the spaceplane through the various missions. This interface consists of a number of control panels, a heads up display (HUD), and an unconventional flight...
control environment in which the pilot uses a mouse and control panel to change the VSP’s speed and orientation, instead of the conventional stick and throttle. The VSP can display the various constellations in the starfield background as an aid to navigation.

In the VSP, we allow the pilot to control the virtual spacecraft from within a half-shell set of displays and controls arranged as though they were upon an extremely large set of displays. A panel can be placed at any location in the interface depending upon the task at hand and the information required. The lighter, vertical area of the console is generally dedicated to providing out-of-VSP information and controls for activities outside of the VSP. The darker, horizontal table-top like section contains controls for the VSP and displays of VSP information. The cockpit provides a self-location reference for the user within the DVE as well as for building the interface. In the VSP, we group information according to mission functionality across the entire interface and within a panel. Because of this grouping, the interface can readily be reconfigured at any point in the mission to present relevant information pertaining to a specific aspect of a mission profile, and hide the information that does not. For example, during a satellite deployment, the user may not need target information. In this case, the interface would present information appropriate to satellite deployment and hide information associated with target acquisition. Currently, the hiding and display of panels is performed at the user’s direction. Within the VSP virtual environment, we use a variety of icons, such as trails and locators, to indicate the location and motion of objects.

An important component of the design and operation of the VSP is modeling its motion. The VSP must model the flight of an aerospace vehicle capable of operation in the atmosphere and in low-earth orbit, as well as model horizontal takeoffs and landings at conventional runways. When in orbit, the VSP must also model the capability of the MSP to perform a rendezvous and co-orbit with a satellite or space station. To achieve these capabilities, many different propulsion models are required by the VSP due to the diverse regimes in which simulation entities operate, as shown in Figure 1. The AeroProp dynamics model is used for atmospheric flight, the AstroProp model is used in Earth orbit, the TaxiProp model is used for runway operations, and the OrbitEntryProp model is used for operations in the trans-atmospheric region.

Figure 1: Altitude of Operation for the Virtual SpacePlane Dynamics Models

The development of the VSP interface and of a suite of dynamics models for VSP are two components of the VSP simulation environment, the third is the virtual space environment for the VSP. The initial version of the VSP concentrated mostly on the visual presentation of the space environment by modeling the position and color of stars, planets, the sun and the earth, and the correct modeling of the planets’ and earth’s motion and rotation. Our initial work did not address space environmental factors that will affect MSP operations. One of the most important shortfalls in space virtual environments used for training is the absence of space weather conditions. The most prominent of these weather conditions is the distortion of the magnetosphere and the resulting electron density change due to the solar wind. The absence of space weather in virtual environments will become more of an issue as the US Air Force and nations around the world increase their presence in and exploitation of space. To improve the realism of space virtual environments, provide an orbital planning aid, and to increase the ability of the VSP to operate without outside assistance, we undertook the task of inserting electron density information as a component of space weather into a space virtual environment.

The purpose of our project was to build upon the space environment portrayal capabilities of the Virtual SpacePlane by providing a way to visualize the critical electron density levels a military spaceplane may encounter while conducting operations in a near-Earth orbit. Knowing the location of these areas of critical electron density can help spaceplane crewmembers plan missions so that the risk of electrical charge accumulation is minimized.

In the next section we present a brief background on space weather and the VSP user interface as well as the requirements and objectives for the display of electron
density information. Section three contains a discussion of the design, implementation, and results. Section four contains our conclusions and suggestions for further work.

2. BACKGROUND

In section 2.1 we discuss the components of space weather and the model we use for electron density modeling in the VSP. Section 2.2 contains a brief overview of the capabilities of the VSP user interface. Section 2.3 presents the requirements we used to guide our development of a space weather visualization capability.

2.1 Space Weather

The objective of our work was to visually indicate where the electron density exceeds a critical value. This visualization ability is important for several reasons. The most dangerous aspect of the space environment is the presence of charged particles arising from the solar wind, solar flares, galactic cosmic rays, and the Van Allen radiation belts. The Van Allen belts were discovered in 1958 and are formed by the interaction between the earth’s magnetosphere and charged particles from the sun. The point of contact between the solar wind and the Earth’s magnetic field is called the shock front. As the solar wind flows around the Earth’s magnetic field, it stretches out along the Earth’s magnetic field lines in a tail-like shape. Inside the shock front, the point of contact between the charged particles and the magnetic field lines is called the magnetopause, and the tail-like area behind the Earth (on the side of the Earth facing away from the sun) is called the magnetotail.

As the solar wind interacts with the magnetic field, some of the particles become trapped and concentrate between the field lines, these areas are called the Van Allen belts. The charged particles in the Van Allen belts, the cosmic rays, and the solar wind can all cause damage to spacecraft either by sputtering, inducing electrical charge in the spacecraft, and single event phenomena. Sputtering is the term used to describe the damage caused to a spacecraft by the impact of high speed particles on the spacecraft. Charging results when charge builds up on different parts of the spacecraft and then dissipates in the spacecraft. When space operations take place in low earth orbits, free electrons present in the space environment can collect on the surface of the space vehicle. In regions of high electron density, this can result in significant surface charging. Not all surfaces of the space vehicle will collect the same amount of charge. This difference in the amount of charge build up can result in a potential difference. During the time period of static charge build up, if the charge build up is large enough, sensors aboard the space vehicle may not function properly. When this difference becomes large enough, a static discharge can occur, resulting in significant damage to the sensitive components of the space vehicle. The severity of the damage depends upon the strength of the discharge, and what portions of the systems are involved during the discharge event. The term single-event phenomena is used to describe the damage caused to a spacecraft when charged particles disrupt the electronics of the spacecraft. Damage to a spacecraft from any of these three phenomena can include spurious electronic switching activity, vehicle thermal material breakdown, amplifier and solar cell degradation, optical sensor degradation, and actual physical damage to the space vehicle structure. Because of the potential for serious damage that can result from the interaction between the spacecraft and charged particles, a number of models have been developed to predict where an interaction can occur. Some example models are the International Reference Ionosphere (IRI) model, the Chiu model, the Parameterized Ionospheric Model, the Bent model, and the SLIM model. Although most of these models provide the output required to display the critical electron density values, the model selected for use was the Parameterized Ionospheric Model (PIM). PIM was selected because it can compute electron densities out to 25,000 kilometers. The galactic cosmic rays are essentially random events, so these models concentrate on predicting the location of charged particles that arise from solar flares or are trapped in the Van Allen belts.

The Parameterized Ionospheric Model was designed to get the input values it needs to run the model from the keyboard. The geophysical inputs the model uses to produce the electron density profiles are the year, the Julian date, the sun spot number, the Universal time, the \( F_{10.7} \) index, the magnetic activity index \( K_p \), and the \( y \) and \( z \) orientation of the interplanetary magnetic field. The \( F_{10.7} \) index provides solar radial flux at the 10.7 centimeter wavelength. Fluctuations in electron density within the ionosphere have been found to correlate to the flux of these solar particles at this wavelength. The \( K_p \) index is a measure of the variations in the horizontal component of geomagnetic field measured at the equator. These fluctuations occur due to injection of solar wind particles into the plasmasphere and cause increased electron density levels. The \( K_p \) index value is updated based on observations every three hours. PIM provides the ability in the input values to specify the number of samples taken of the modeled ionosphere. The number of samples is established by selecting the starting and ending latitude/longitude and the step size. For each latitude-longitude pair selected, the user specifies how many altitudes are calculated. After execution, PIM creates an output file containing all of
the electron density data. The first few lines of the output file contain the values of the input field values used to calculate the output such as day, time, and solar sunspot number. The first few lines are followed by the latitude and longitude information used to calculate the data points. Following this information is the number of altitudes specified for the calculation and a printout of those altitudes in kilometers. The format for the altitudes corresponds to the format for the electron densities for each altitude-longitude pair. Following this initial information is the electron density for each latitude-longitude pair. The electron densities are provided in electrons per centimeter cubed. The first number given is the electron density for the first altitude specified in the output file, with each subsequent electron density value being associated with the next altitude. This format continues until all the data for every latitude-longitude pair has been displayed.

2.2 VSP User Interface

The VSP user interface on the console consists of nine types of panels. The Control Panel contains the flight controls for the VSP in orbit and in the atmosphere. The Control Panel reconfigures automatically as the VSP moves between flight regimes. The Aero-Flight Panel contains the information and controls for atmospheric flight operations. The Space-Flight Panel contains information and controls for space flight operations. The Navigation Panel provides information about the location and orientation of the VSP with respect to the surface of the earth and about the location and type of ground-based entities. The Mission Panel contains information about the VSP's payload and the controls necessary to perform missions activities such as satellite deployment. The Target Panel contains information and controls applicable to target selection, identification, viewing, manipulation, and interception. The Trajectory Panel presents information about dynamic atmospheric pressure, kinetic and potential energy, and temperature for orbit entry and re-entry. The Virtual Environment Panel contains controls for various aspects of the virtual environment such as the rate of passage of time and the amount of ambient light. The Engineering Panel contains diagnostic and time critical information concerning the VSP system and consumables status. A special-purpose type of Navigation panel that was developed for the initial VSP is the Orbit panel. The Orbit panel contains information about orbit and location of the VSP, any current targets, and transfer orbits between any displayed orbits. The Orbit Panel provides a three dimensional and interactive means of determining spatial relationships with respect to an orbit, the target object, the target's orbit, and the earth. The orbits are displayed in reference to the Earth’s globe on the panel. The user can select the globe and rotate the earth about its center to view the VSP orbit or any orbit from any angle. The orbit display is updated to reflect changes to the VSP orbit, target orbit, or transfer orbits. On the panel, the VSP orbit is displayed as a green ellipse. If any segment of the orbit intersects the Earth or drops below a safe altitude the color of the segment changes to red. Because the Orbit panel is used for orbital re-planning we chose it to present the information about critical electron density values to the VSP pilot.

2.3 VSP Space Weather Visualization

Requirements

The requirements for visualization of the critical electron density values in the VSP were twofold, to provide an out-the-window in-context display of the magnetosphere boundary to the operator and to provide information useful for mission planning. When choosing the most appropriate method, one must take into account computational expense, graphical display expense, accuracy, and intuitive representation. The development of intuitive representations is best accomplished by heuristic evaluation. Since an MSP operator was not available, the heuristics had to be evaluated within the development team. The foundational requirement for the display of critical electron density value data in the VSP was that the display must account for the size and scale of the space environment while retaining an interactive display rendering rate. The current VSP operator's external view includes both heavenly bodies and man-made objects in the near-Earth space environment. Additionally, the critical electron density value visualization must not obscure other important information.

3. DESIGN, IMPLEMENTATION, AND RESULTS

Integration of PIM into the Virtual Space Plane design was accomplished by creating a SolarWind class and a PIM_INPUT class. The PIM_INPUT class encapsulates the PIM software. The PIM_INPUT class provides all the functionality required to execute the model and send the output to the VSP. The SolarWind class provides the upper level management facilities for the PIM_INPUT class and determines when PIM needs to be executed.

The PIM_INPUT class provides four functions: PIM input file creation, PIM execution, output parsing and data preparation, and determination of critical density values. The development of the input file format for PIM was straightforward. Most of the input values,
such as coordinate system type, number of data points, and output data format do not change from one run to the next so they are placed at the head of the file by simply writing to the file when it is initialized. Values such as sunspot number, date, time, and other values that change and affect the location of the critical electron density field are read in from a user created parameter file and then written to the PIM output file. Once the PIM input file was created, PIM is executed. After execution, the class creates an output file to hold the electron densities. The final function determines the bounding altitudes for the specified electron density by testing every latitude/longitude pair. For each latitude/longitude pair, the class determines the upper and lower limits for the critical values and calculates the minimum lower bound and the maximum upper bound. These values are then returned as the bounding altitudes for the specified electron density levels. The value used to determine critical electron density levels can be adjusted by the user at run time, which provides the VSP pilot with control over the level of exposure to high energy electrons that will be tolerated in any aspect of the mission.

Our first approach to critical electron density visualization was to construct isosurfaces of electron density using the Marching Cubes (MC) algorithm. To use MC, a critical electron density value is chosen to identify the isosurface to be visualized. To generate the isosurface, the PIM output was run through the MC algorithm, which yields a group of semitransparent triangle strips to be displayed. However, MC proved to be inadequate because discontinuities in the data due to solar wind behavior produced a non-intuitive representation with large holes and gaps and exhibited a generally elliptical shape. While these problems could have been addressed via MC algorithm improvements, we decided to take a different approach and explore what could be accomplished by using a different rendering primitive.

The second approach was motivated by the insight that the visualization did not need to be perfect since it need only indicate dangerous areas. Additionally, there is error in the underlying data and the astronauts will not generally even plan to come close to the boundary. As a result, some error on the safe side is acceptable to achieve a rapid rendering that is also intuitive to comprehend. Our second approach to computing the critical electron data visualization was to calculate both the minimum and maximum radii of the critical electron density values and to render two spheres whose radii centered on the earth. These two spheres represent the bounds on the upper and lower dangerous electron density values. Thus, we know that below the inner shell, we are always below the critical electron density value and above the outer shell we are not near a dangerous electron density value. Though there may be discontinuities in the region between those spheres, electron densities will generally be higher than our critical value and the safe zones usually have no connectivity to the area above or below the spheres. The resulting VSP display shows where the critical electron density values are dangerous and the altitudes where the electron density values are safe.

The bounding spheres are displayed as semitransparent surfaces, with different colors used to provide visual feedback to the operator of the VSP. The inner sphere is colored green, and the outer sphere colored yellow. When inside the inner shell the pilot sees almost exclusively green, indicating that the VSP is in a ‘safe’ region. Once we transition through the inner shell to the region between both shells, we see yellow at higher altitudes and green at lower altitudes. This “yellow over green” situation informs us that we are in the area of high critical electron density values. Finally, as the VSP transitions through the outer shell, the pilot primarily sees only the yellow shell beneath, informing the pilot where the dangerous region is and that the VSP is above it.

This visual feedback could conceivably be all that is necessary for a VSP operator to execute a mission. The feedback allows the pilot to be cognizant of the current status of the VSP with respect to the critical electron density values. However, the shell display provides little information about when a given orbit will intersect a dangerous region, if at all. To provide planning information to the pilot, we added information to the Orbit Panel to supplement the external view. The Orbit panel was selected to host the critical electron density value shell display because its functionality is to provide the VSP pilot with information to help in orbit re-planning by presenting data concerning the position of the VSP relative to the Earth and of the orbits of the other bodies of interest to the VSP operator. The display of critical electron density values shells are controlled via keyboard toggle so the information is only displayed when it is needed.

The challenge in representing the critical electron density values was to display on the panel the critical electron density values information while not obscuring the existing information. Two alternatives were considered, adding shells to the orbit panel as in the external view or indicating the altitudes of dangerous orbit along the orbital path. The second alternative was pursued, both due to its clarity and visibility from a distance (close inspection is required for determining orbit line-shell intersections). To add the information, we represent the section of the orbit in the dangerous electron densities as a yellow segment of our orbit. Since the orbit and the critical electron density values are calculated relative to the center of the earth we can
test a given segment's relationship to the critical region, by comparing earth centered radii to the radial values of the orbit at that segment. For display, the earth and orbits are scaled to fit within our panel. In the worst-case, there are at most four segments that can be colored yellow, along with eight intersecting points. The resulting orbit line displayed can vary between no intersections (totally unsafe and totally safe) up to all four segments. The resulting orbit display shows the operator of the VSP where potential exists for encountering the critical electron density values. This information allows the operator to take timely corrective action, such as selecting a new orbit. By supplementing the orbit information with the critical electron density values information, we were able to retain the existing warning criteria for earth intercept and low orbit that the orbit panel already portrayed.

4. CONCLUSIONS AND FUTURE WORK

In this paper we have described our approach to improving the mission re-planning capability of the VSP by portraying the locations where electron density values exceed a safe level. The portrayal has two components, one is a display within the virtual environment and the other is a display within the Orbit Panel of the VSP interface. These two displays allow the VSP operator to determine when the VSP is in a dangerous zone and to plan orbital maneuvers so that dangerous areas can be avoided.

An improvement that can be made to the electron density display would be to use a series of color values along the orbit line to indicate an intensity of electron density at several electron densities. Where currently, we use only a single electron density and single color, multiple colors could be used to define a gradation of intensity. This more complicated display would require more detailed parsing of the PIM data file to generate multiple critical regions.

5. REFERENCES


