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A COMPUTER GRAPHICS SYSTEM FOR VISUALIZING SPACECRAFT IN ORBIT

Don E. Eyles
Charles Stark Draper Laboratory
Cambridge, Massachusetts

SUMMARY

To carry out unanticipated operations with resources already in space is part of the rationale for a permanently manned space station in Earth orbit. The astronauts aboard a space station will require an on-board, spatial display tool to assist the planning and rehearsal of upcoming operations. Such a tool can also help astronauts to monitor and control such operations as they occur, especially in cases where first-hand visibility is not possible. This paper describes a computer graphics "visualization system" designed for such an application and currently implemented as part of a ground-based simulation. The visualization system presents to the user the spatial information available in the spacecraft's computers by drawing a dynamic picture containing the planet Earth, the Sun, a star field, and up to two spacecraft. The point of view within the picture can be controlled by the user to obtain a number of specific visualization functions. The paper describes the elements of the display, the methods used to control the display's point of view, and some of the ways in which the system can be used.

INTRODUCTION

This paper describes a computer graphics display system designed to facilitate the visualization of spacecraft operations in Earth orbit.

The system was originally developed as a component of the Space Station Simulator project at the Charles Stark Draper Laboratory. The purpose of this simulator is to assess the flying qualities of space station configurations, and to provide a software framework within which to develop control-system concepts applicable to space stations. Computer graphics were added to the simulator to provide qualitative information about the progress of the simulation, and to allow for a man-in-the-loop capability. As time went on it became evident that the displays required by engineers working on the ground might also be valuable to astronauts working aboard a space station.

To be able to carry out unanticipated tasks with resources already in Earth orbit is part of the purpose of a permanently manned space station. Operations will be required which cannot be rehearsed by the astronauts using ground-based simulators because the need for them arose after the crew was launched into space. On-board capabilities must exist to allow the crew to plan such orbital operations and to train themselves to execute them. In addition, the space station crew must perform a sort of air-traffic-control function in keeping track of other spacecraft operating nearby, and must control not only the space station itself and its movable appendages, but also free-flying spacecraft associated with the space station, including spacewalking astronauts.

The display described in this paper, if attached to suitable mission and simulation software aboard a space station, can support both the on-board simulation capability and the real-time monitoring of operations. I shall speak of the visualization system as an on-board display instrument, with the understanding that its capabilities arose from, and are also applicable to, ground-based engineering simulation purposes.

The display is called a "visualization system" because it is a system designed to aid the user in visualizing a three-dimensional situation in space. In the terminology established for this conference, the visualization system fits in somewhere between a "spatial display" and a "spatial instrument." Like a spatial display, the system presents the user with an unembellished, undistorted image of a spatial situation. Like a spatial instrument, the system requires a degree of interaction with the user, who must control the point of view from which the image is drawn. Perhaps the best description of the visualization system is as a spatial instrument which can present a variety of spatial displays under the control of the user.

The existing implementation uses display equipment that produces "wire-frame" objects whose "hidden" parts are visible. Although in some cases wire frames may remain preferable, actual use aboard a space station will require flight-qualified display hardware capable of rendering solid objects with shading and shadowing.

I shall describe the elements of the scene created by the visualization system, discuss the means by which the point of view within the scene is controlled, and finally describe some of the specific ways in which the system can be used. A more detailed description of the visualization system is available in reference 1. A short published description with color illustrations is available in reference 2.

ELEMENTS

The principal elements of the display created by the visualization system are the planet Earth, the Sun, a field of stars, and one or two spacecraft. The planet Earth is drawn as a sphere made up of latitude and longitude grid lines and a map showing the outlines of major land masses and principal cities. Other Earth-fixed features such as circles indicating coverage from tracking sites can be added. The Earth is drawn from data expressed in a geodetic or Earth-fixed coordinate frame; that is, a frame of reference which moves with the Earth. The Sun is drawn, not to scale, as a yellow asterisk with 24 points. A star field of 123 stars is also drawn, and is valuable for two reasons. First, showing the stars in their correct astronomical positions provides a realistic star background for maneuvers being monitored or simulated, and allows maneuvers to be planned which may be dependent on the availability of specific navigational stars. Second, stars provide a motion cue when the point of view is rotating with respect to inertial space.

The visualization system also contains, in the present implementation, up to two spacecraft. One is often the space station. Each spacecraft may consist of a core and one or two movable appendages such as solar panels. For a spacecraft with thrusters, an exhaust plume is drawn when a jet is fired. Because the space station is not yet fully defined, and because other spacecraft may need to be represented, the visualization system allows spacecraft to be defined as an assemblage of simple cylindrical and plate elements. The visualization system also contains information such that a cylinder which is meant to represent an established type of module, for example a habitat module, can be given detail to make its appearance more realistic. In the case of an unusual or unknown spacecraft, simple cylinders and rectangular plates can be used to build up an image.

Additional minor elements of the visualization system include a gnomon, always drawn in the upper left corner of the square window occupied by the display, which indicates the orientation of the local-vertical, local-horizontal (LVLH), frame of reference pertaining to the principal spacecraft. The visualization system also has the capability of drawing a buoy, a yellow three-dimensional cross, which may be used to represent present a spacecraft of unknown configuration, or to mark a spot in space, as, for example, a nominal position to be returned to after a maneuver. There are some other minor embellishments which apply to specific ways in which the visualization system can be used, and these are discussed later.

Information Requirements

The Sun, stars, Earth, and spacecraft together form a sort of computerized orrery. The system is set into motion by computed transformations and positions which are used to locate each element in its proper relative position, either for the present time (for monitoring), or for some future time (for simulation). Besides initialization information specifying the configurations of the spacecraft that are to be drawn, the visualization system requires the following dynamic information from the simulation or mission software to which it is attached:

- Position of spacecraft center of mass.
- Position of spacecraft center of mass with respect to spacecraft structure.
- Position of spacecraft appendages.
- Attitude (orientation) of spacecraft.
- Jet firing information for spacecraft.
- Sun position.
- Transformation relating the Earth-fixed coordinate system to a reference inertial coordinate system.
- Transformation relating the spacecraft LVLH coordinate system, a frame which moves with the spacecraft and is defined in terms of its position and velocity, but not its attitude, to the reference system.
- Transformation relating the spacecraft "body" coordinate system, which is fixed with respect to the spacecraft's structure, to the LVLH frame.

New values for each quantity are required for each frame drawn by the visualization system.

For a given time, the relationships defined by this information form a scene which is representative of a real situation and not under the control of the user of the system. The point of view within the scene, however, can be controlled by the user to accomplish various specific visualization functions.

Control By the User

The point-of-view characteristics which are under the control of the user are the following:

- The coordinate system with respect to which the point of view will be defined.
- The origin, i.e., the object or point which is to occupy the center of the picture.
- The distance from the eye to the chosen origin.
- The line-of-sight vector, expressed in the chosen coordinate system, from the eye to the chosen origin.
- The angular field of view of the image presented.

In the present implementation all characteristics are dynamically under the control of the users as they use the display, with the exception of field of view, which is defined at initialization time. The user-controllable characteristics are input by means of an alphanumeric display and keystroke language based on the method used in the space shuttle. An analog dial and joystick may also be used in controlling point-of-view distance and direction. Although normally each characteristic is explicitly controlled, canned combinations can be provided so that certain favorite set-ups can be obtained with a minimum of keystrokes. Figure 1 shows the alphanumeric display page used to control the visualization system point of view.

The point of view coordinate system may be chosen from among the usual frames of references used in space applications. These include an inertial frame locked to the stars; an Earth-fixed frame which moves with the planet Earth; the LVLH frame which moves with the spacecraft, but is independent of its orientation; and a "body" frame which is locked to the spacecraft structure. When more than one spacecraft is included, the LVLH and body frames pertaining to each are available, although of course when the spacecraft are near each other their LVLH systems are not significantly different. All frames except the reference inertial are rotating coordinate systems. Additional coordinate systems can easily be added to the structure.

A second aspect of the point of view which is under the control of the user is the point upon which the display is centered. An early lesson in the design of the visualization system was that when the point of view is allowed to maneuver independently, it was easy to lose track of the object of interest. As a result, the point of view is normally centered on some chosen point. The choice of "origin" consists of the center of the Earth, the centers of mass, body coordinate system origin, or the crew station of either spacecraft, and the midpoint between the centers of mass of two spacecraft.

Having chosen an origin and a coordination system, the user must choose a line-of-sight vector. The line of sight is controlled by numerically specifying a unit vector expressed in terms of the chosen coordinate system, or by manipulating a joystick which is attached to the system. The line-of-sight distance, the distance between the "eye" and the chosen origin, may be controlled numerically or by means of an analog dial. Distances between zero and 500,000 km (continuous) are permitted in the present implementation. A negative distance may be specified, but the usefulness is limited because that puts the chosen origin behind the eye.

The point of view may be thought of as looking inward from a spot on a sphere. The sphere is stationary with respect to the chosen coordinate system, it is centered on the chosen origin, and its radius is the chosen distance. The point of view's position on the sphere is specified by the line-of-sight vector.

The angular field-of-view of the display is also under the control of the user, although in the present implementation in the space station simulator, the field of view must be chosen ahead of time and is not subject to real-time modification. Fields of view between 10° and 90° are allowed. The most usual choice is 40°. While this angle does not correspond to the actual angle subtended by the display window when looked at from the usual viewing distance, it does roughly correspond to the field of view of the normal photograph taken with a medium length lens, and is satisfactory to most users.

Ways of Using the Visualization System

The visualization system is a general system which can present the scene resulting from any combination of the available coordinate systems, origins, and lines of sight. The following are some of the specific ways in which the system can be utilized:

Chase plane views– The view that would be available from an imaginary chase plane flying alongside can be obtained by choosing the LVLH framework, an origin centered on the spacecraft of interest (or midway between two spacecraft of interest), and a line of sight and distance such as to achieve the desired view, whether from ahead, the side, behind, above, or below. Such a point of view can be useful when visualizing docking and berthing operations in which two spacecraft come together or separate. It can also be useful simply by presenting an "out of spacecraft" view of a single spacecraft, such that the spacecraft's location relative to the Earth in the background, its orientation, and the position of its movable appendages are simultaneously apparent. Figure 1 shows a chase plane view in which an OMV approaches a satellite to pick it up.

Pilot's-eye views– By selecting the body coordinate system of a given spacecraft, setting origin to "crew station," and choosing a distance of zero, the point of view can be placed in the driver's seat of any spacecraft, even an unmanned one for which an imaginary crew position is defined. Such views can serve a number of purposes, such as assessing what will be seen from the crew station window during a planned maneuver (including star availability and the problem of solar glare), presenting views that are not available in real life because there is no suitable window, and providing an on-board perspective for unmanned spacecraft which may be remotely controlled from the space station. If coupled to suitable simulation software, this point of view also allows the rehearsal of operations to be conducted by an astronaut using a Manned Maneuvering Unit, such as satellite capture. Figure 2 presents the view from a point behind the space station hatch to which the shuttle will dock. Such a view represents a "synthetic window" providing visibility in a case where spacecraft structure may preclude an actual window. (An illustration of the fact that the visualization system includes special cases equivalent to existing instruments is the fact that a pilot's eye view looking forward, perhaps with the horizon in view, corresponds to the stylized pattern presented by the attitudes reference instrument known as the 8-ball or artificial horizon.)

Whole-Earth views– The visualization system permits point-of-view distances large enough that the entire Earth is visible. Because at such distances the spacecraft appear as points of light, a capability called "rescale" is available which vastly expands each spacecraft (and shrinks the Earth), to produce a not-to-scale cartoon view in which both the position and orientation of the spacecraft are apparent. Such a point of view is useful for following a rendezvous operation in which the spacecraft may start out on opposite sides of the planet. For example, a whole-Earth view looking along the Y axis in LVLH coordinates shows the view normal to the orbital plane. Z-axis views in the Earth-fixed or inertial framework show the Earth from its polar axis. In the inertial case the Earth will be seen to rotate during 24 hr. Figure 3 shows a scene in which two spacecraft are viewed from a polar axis point of view.

Isolating a factor– Another way of using the visualization system allows the effect on a spacecraft of some single factor to be isolated. Such a capability might come into play when a new control system is to be tested on-board before being given control of the space station. The spacecraft is drawn twice at the same location and time. One image represents the spacecraft as it actually appears in real time, the other represents a simulated version of the same spacecraft as if it were controlled by the new control system under test. Divergences between the two images will illustrate performance differences attributable to the new system.

Roam capability– In most cases it is desirable to center the point of view on the object of greatest interest. The "roam" capability can be selected to remove that constraint and allow the point of view to maneuver independently within the framework established by selected coordinate system and origin. During a roam, the point-of-view orientation is controlled by a joystick and a dial can be used to creep forward or backward. When the joystick is deflected a reticle is drawn at the center of the screen to facilitate pointing at the object of interest. The reticle disappears several seconds after the joystick is released to afford an unobstructed view. The roam capability can be used to mimic a spacewalk, or EVA, by roaming within the spacecraft body coordinate frame. (However, control is geometric, and the orbital dynamics of an EVA are not simulated in this case.) The roam capability may be most important for inspecting the spacecraft's structure (as known to the computers) but, for example, the view from Boston or Los Angeles could be obtained by letting the point of view roam within the Earth-fixed frame.

The visualization system is not limited to the capabilities described. It can present any view that can be specified using the point-of-view variables under the control of the user. This can include points of view that are probably nonsensical. An example would be an Earth-centered view in the spacecraft body coordinate system. If the spacecraft is spun, the planet appears to gyrate in such a way that the spacecraft is kept in the same orientation.

CONCLUSION

The central strategies employed in designing the visualization system were, first, to use a picture to make available to the user the extensive information available in the space station's computer system; and second, rather than design a number of special-purpose instruments, to create a general display from which specific capabilities can be obtained by controlling the point of view in various ways.

It may be useful, in conclusion, to contrast the visualization system to concepts such as the "virtual cockpit" designed to assist the pilots of high-performance aircraft. While the virtual cockpit enhances the pilot's perceptual effectiveness, the "visualization system" enhances the crew's operational effectiveness.

The distinction follows from the dissimilar missions. The mission for which the virtual cockpit is designed may last only the few seconds it takes for a jet aircraft to carry out an attack. The pilot's success and survival depend on efficiency during this period. The virtual cockpit takes a single point of view and enhances its perceptions by introducing labels, speed posts, threat indicators the terrain itself, and so forth. The attack pilots might appreciate a view of themselves as seen by the target, but the exigencies of the combat situation require instead that they stay within themselves.

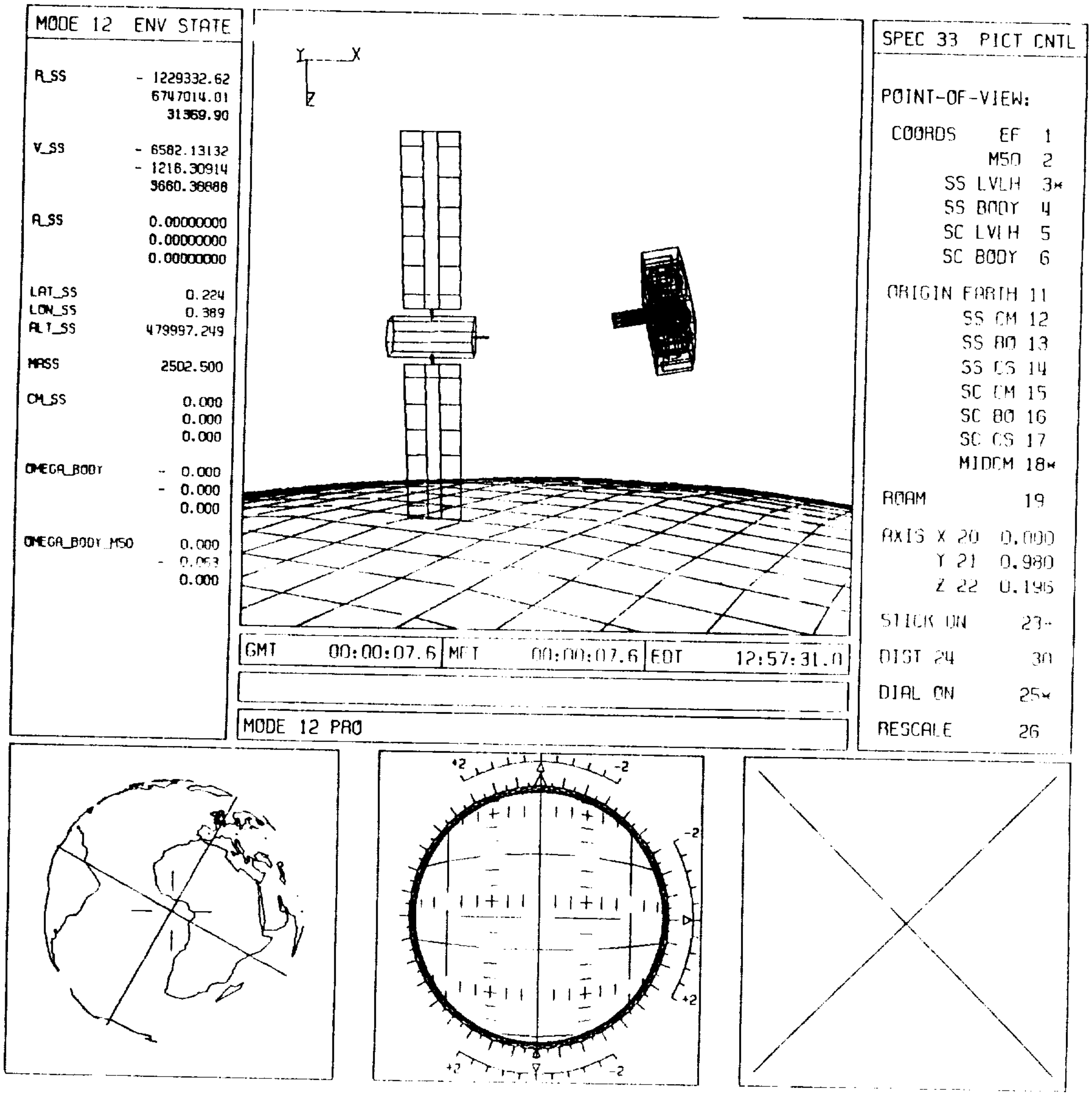
The visualization system is also designed to enhance the pilot's effectiveness, but in this case the mission may last months and, despite the high absolute velocities, the relative speeds are often closer to sailboats than to jets. On the other hand, space is a place with no up or down, or rather a variety of ups and downs, depending on the particular situation. The visualization system responds by providing a tool that is suitable for the on-board planning and rehearsing that will be part of a long mission, and which offers a way of visualizing operations as they appear in several shifting frames of reference.

Aboard a space station, the pilot is sitting at a console which may face in an arbitrary direction and may be without a window. Split-second reactions are seldom necessary. There are no weather problems. What is necessary is the ability to plan and then to monitor spatial operations which may be hard to see and hard to visualize. For this case, the ability to assume a God's-eye view and follow the orbits leading to rendezvous, to fly alongside in a phantom chase plane, to take the vantage point of an imaginary window in your own spacecraft, or the viewpoint of another, perhaps unmanned satellite, may prove to be useful.

REFERENCES

1. Eyles, Don : A computer graphics system for visualizing spacecraft in orbit, Charles Stark Draper Laboratory, R-2069, May 1988.

2. Eyles, Don: Space station thrillers unfold at Draper lab. Aerospace Amer., October 1986, 38.



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        SS BODY  4
        SC LVLH  5
        SC BODY  6

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        SS CM 12
        SS BO 13
        SS CS 14
        SC CM 15
        SC BO 16
        SC CS 17
        MIDCM 18*

ROAM          19

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     Y 21  0.980
     Z 22  0.196

STICK ON     23*

DIST 24       30

DIAL ON      25*

RESCALE      26
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Figure 1.– The complete space station simulator display. The visualization system forms the square window at upper center. The alphanumeric display page used to control the point of view is at upper right, simulation data are displayed at upper left, and special-purpose displays such as an orbit position indicator (OPI) and an attitude director indicator (ADI) are below. The visualization system shows an orbital maneuvering vehicle (OMV) nearing a satellite which it wishes to grapple, as it would be seen from an imaginary "chase-plane" flying beside them.

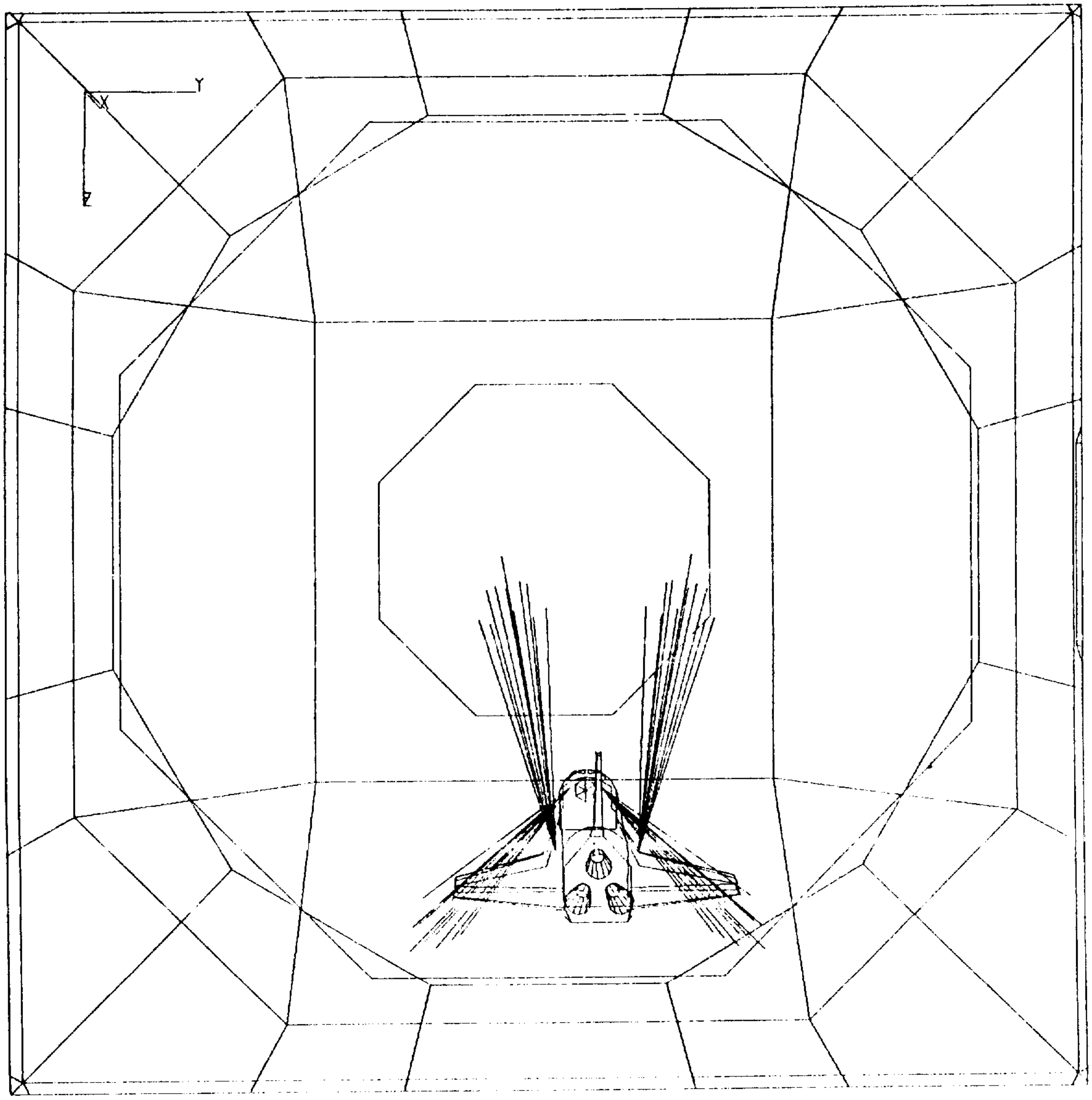

Figure 2.– In this view the point of view has been locked to the body coordinate system of the space station and located just inside the shuttle docking hatch, looking in a forward direction. At a distance of approximately 150 m a space shuttle fires maneuvering jets to reach an attitude for docking. Such a point of view can be used to assess window visibility for upcoming operations, or, as in this case, to provide a synthetic window where none exists.

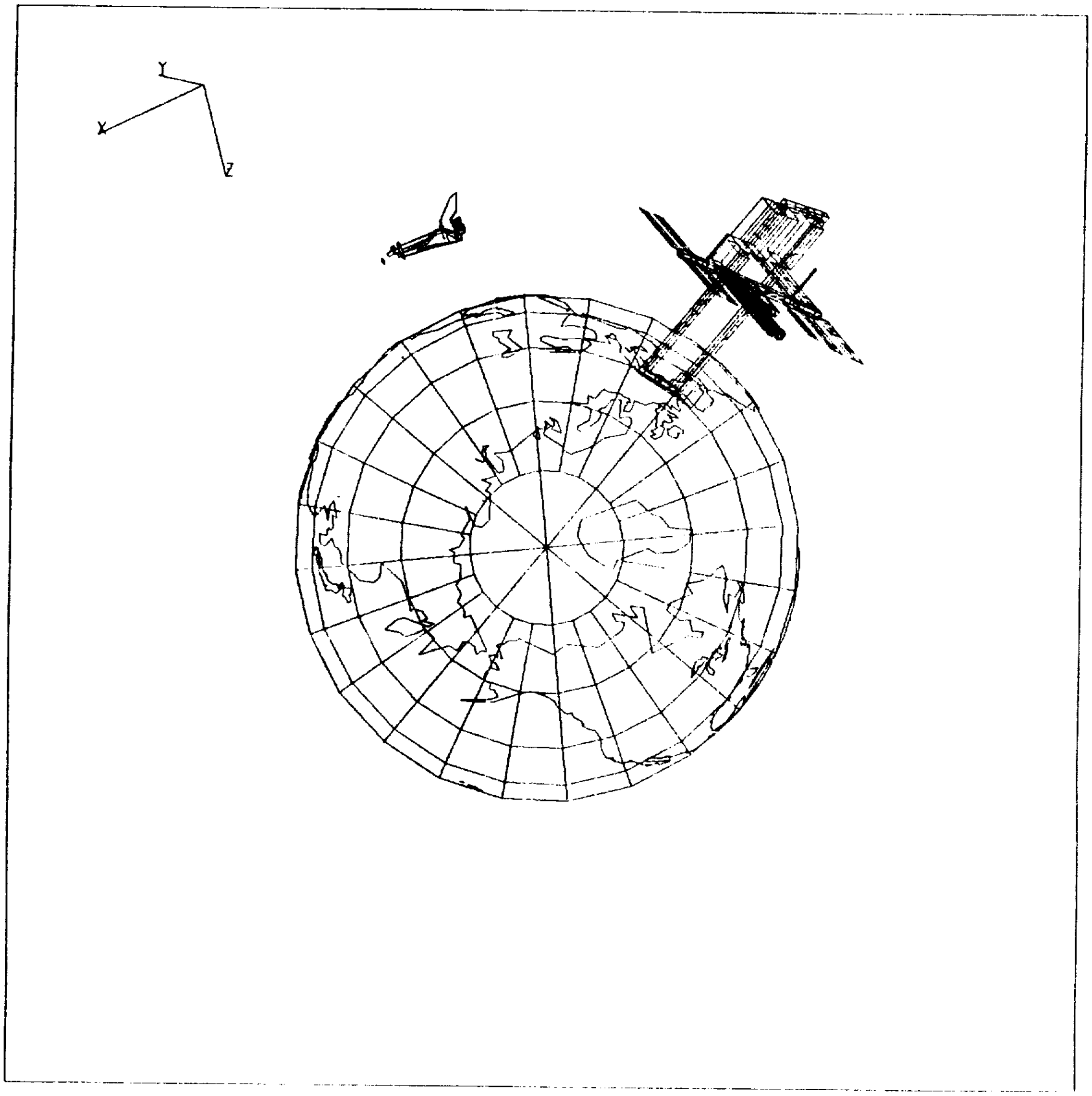

Figure 3.– In this view the point of view has been located 30,000 mi from the center of the Earth and directly above the north pole. Two spacecraft are shown, the dual-keel space station and a space shuttle. The RESCALE option has been selected and therefore the spacecraft sizes are exaggerated. Such a point of view allows the positions and attitudes of multiple spacecraft to be simultaneously visualized, as might be desirable during a rendezvous maneuver.