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OPERATIONAL COMPUTER GRAPHICS IN THE FLIGHT DYNAMICS ENVIRONMENT

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ABSTRACT

Over the past five years, the Flight Dynamics Division of the National Aeronautics and Space Administration's (NASA's) Goddard Space Flight Center has incorporated computer graphics technology into its operational environment. In an attempt to increase the effectiveness and productivity of the Division, computer graphics software systems have been developed that display spacecraft tracking and telemetry data in 2-d and 3-d graphic formats that are more comprehensible than the alphanumeric tables of the past. These systems vary in functionality from real-time mission monitoring systems, to mission planning utilities, to system development tools. This paper discusses the capabilities and architecture of these systems.

1. INTRODUCTION

Since the mid 1960s, Flight Dynamics Division personnel have been performing spacecraft orbit and attitude determination and a variety of mission planning, monitoring and analysis functions. These functions have often been based on the analysis of large volumes of numerical data. These data represent a wide variety and range of geometric values, some as easily interpretable as the position of the sun in a sun sensor's field-of-view, others as abstract as spacecraft attitude expressed in quaternions.

In the past, operators and analysts have been presented these data values via monochrome screens of alphanumeric tables. Today these displays are now 2-d and 3-d color graphic representations of the data. In an ongoing effort to increase the efficiency and effectiveness of this working environment, the Flight Dynamics Division has invested in an endeavor to utilize computer graphics technology as a means to present flight dynamics data in a more comprehensible format.

This paper discusses how graphics technology has been applied to the flight dynamics environment. Presented in detail are graphics software systems that are currently in use in the Flight Dynamics Operations Area. These systems have been separated into three distinct categories. The first, real-time mission monitoring systems, encompasses distributed processing software that receives and graphically displays real-time spacecraft telemetry data. These systems are used for ensuring the health and safety of a spacecraft and verifying the quality of experiment data. The second category, non-real-time planning tools, includes passive standalone software systems that are used for various mission planning and analysis activities. The final category, system development tools, contains high level subroutine packages used by Division programmers to create frequently incorporated graphical displays in a cost effective manner.

2. MISSION MONITORING SYSTEMS

The Flight Dynamics operations personnel are often required to interpret tracking and telemetry data as it is received on the ground. The interpretation of the data is necessary to ensure the integrity of experiment data, verify attitude maneuvers, and monitor the health and safety of a spacecraft. Computer graphics systems have been applied to four specific applications to assist analysts with this interpretation process. These applications are further discussed in this section.

2.1 TCOPS WORLD MAP

2.1.1 BACKGROUND

One of the most common real-time analysis problems faced by Flight Dynamics operation personnel is the determination of a spacecraft's position above the earth and whether that location is within communication range of ground or satellite-based antenna. To help visualize this problem, a world map display was incorporated into the Trajectory Computations and Orbital Products System (TCOPS), the Flight Dynamics Division's institutional orbit determination system.

2.1.2 CAPABILITIES

The underlying principal for the world map display is to generate a 2-d Cartesian projection of the earth then overlay orbit tracks of various spacecraft onto this projection. The orbit tracks are propagated and

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the current location of the spacecraft is updated as real-time position data is predicted analytically. Communication zones are drawn as a set of contours that take into account any interference that may be due to obstacles blocking either ground or space-based antenna. These obstacles are both tangible (e.g., mountains or buildings) and abstract (e.g., atmospheric interference). The world map display also includes electromagnetic radiation contours, a sunrise/sunset terminator line and sun icon. The system also predicts shadow constraints and possible communication obstruction due to solar interference (see Figure 1) [4].

2.1.3 ARCHITECTURE

The TCOPS world map incorporates a distributed processing approach (see Figure 2). Spacecraft orbit vectors are retrieved from spacecraft ephemeris files by a FORTRAN program (WMDRV) which is executed on a National Advanced Systems (NAS) 8063 mainframe computer under the MVS operating system. The orbit vectors are then transmitted over a bisynchronous 9600 baud communications line to an IBM PC/AT compatible workstation.

TCOPS WORLD MAP ARCHITECTURE

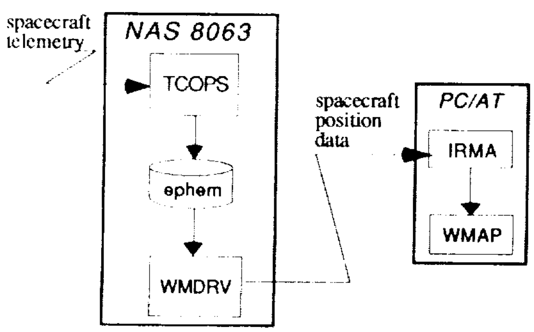

Figure 2.

The PC is configured with a Digital Communications Associates (DCA) IRMA communications board and an ATI Technologies, Inc. Enhanced Graphics Adapter (EGA) Wonder board (resolution of 640 X 350 pixels). This specific version of the EGA board is compatible with the closed circuit television (CCTV) system at the Goddard Space Flight Center, allowing the image to be transmitted to multiple control centers. A FORTRAN program (WMAP) on the PC, executed under DOS, then generates and continually updates the world map display using an orbit propagator to predict the location of the spacecraft [4]. All text and graphics are produced using the Media Cybernetics, Inc. HALO graphics package.

2.2 3-D MON

2.2.1 BACKGROUND

In contrast to the simplicity of the world map system and its related analytical support is the problem of verifying, in real-time, such items as: relative position and orientation of a spacecraft (and its appendages) to celestial bodies; objects and targets along an instrument's boresight; and solar lighting constraints.

To alleviate the time consuming and difficult task of determining such alignments by examining numbers, the Flight Dynamics/Space Transportation System 3-D Monitoring System (3-D Mon) was developed to display real-time spacecraft data with some degree of photographic realism. 3-D Mon presents a 3-d model representation of the Space Shuttle, its payloads and surrounding environment using near real-time Shuttle telemetry (received every two to five seconds) to compute the orbit and attitude of the models [8]. The system can also accept other satellite telemetry streams for spacecraft other than the Shuttle.

2.2.2 CAPABILITIES

The primary capability of the 3-D Mon system is to generate realistic 3-d images of the Shuttle, the Remote Manipulator System (RMS), and the Shuttle's payloads based on Shuttle telemetry data. These objects are shown at their relative sizes, orientations, and positions. All of these objects can be displayed as solid, flat shaded objects, with shading based on light sources located at the sun and/or viewpoint. The viewpoint light source prevents objects from appearing as silhouettes when the sun and viewpoint are positioned on opposite sides of the model. The objects also can be depicted in a wireframe representation if system performance needs to be increased or if a transparent object provides an improved analytical view [2]. The capability for Gouraud shading is currently being incorporated.

The next capability of 3-D Mon is to merge these spacecraft images with accurate representations of the surrounding environment. The earth is displayed in its accurately scaled size and position and is rotated appropriately. Land masses can be displayed as filled or outlined, with or without day/night shading. Interference zone contours and longitude/latitude lines also can be overlaid onto the earth's surface. Images of the celestial bodies (sun, moon, Mars, etc.) and other celestial objects (galaxies, quasars, etc.) are represented as 2-d icons or alphanumeric characters, respectively, at their relative positions. Celestial body positions are based on ephemeris files that precisely predict their location. The sun and moon icons also are displayed in their properly scaled size, with lunar phases (full moon, crescent moon, etc.) displayed upon request. Stars are rendered as groups of pixels whose sizes are varied proportionally to the brightness of the star. Vectors may be added that represent the direction of the sun, earth, targets, spacecraft velocity, etc. to provide a relative indication of motion with respect to the universe [2]. Figures 3 and 4 are images generated by the 3-D Mon system that merge both spacecraft and environmental data.

Interactive capabilities for analysts are also provided by the 3-D Mon system. An analyst can toggle any of the aforementioned system configurations, whether for system performance or analytical considerations. The analyst can specify the current view in a variety of ways, which include predefined views (RMS wrist camera view, rear Shuttle cockpit window view, communications satellite view, etc.) or a user-specified view where the user can select the viewpoint and point of interest. Analytical information is provided to the operator for any object selected interactively. Playback modes are provided for analysts to review previous scenarios in either a slow motion or frame-by-frame (data record-by-data record) mode [6].

2.2.3 ARCHITECTURE

To achieve the required image update rates, several key design concepts were incorporated in both hardware and software. The 3-D Mon system is a distributed processing system that consists of a FORTRAN program executed on a NAS 8063 computer under the MVS operating system and a set of C programs executed on a Silicon Graphics IRIS 4D/60 Turbo workstation under the UNIX System V operating system. (See Figure 5.) The mainframe program - the Data Acquisition and Transmission (DAT) program - acquires the spacecraft telemetry and environmental data and strips out or processes key parameters necessary to generate the graphics displays. The program then transmits these parameters to the IRIS workstation over an asynchronous 2400 baud line. The IRIS software receives the data from the mainframe computer and then generates the display using calls to IRIS Graphics Library routines. User interaction is conducted with either a mouse to control pop-up menus or a dial box to facilitate zooming, panning, rotating and trucking of the images [2].

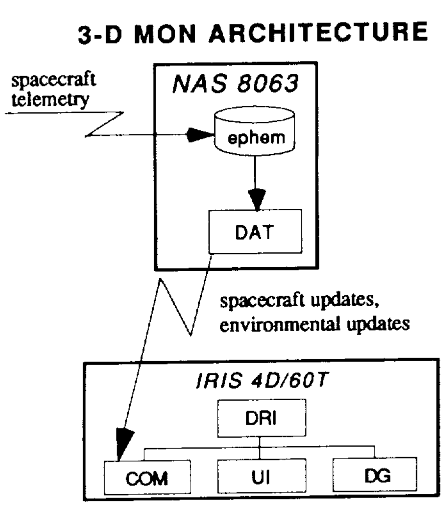

Figure 5.

The IRIS-resident software consists of three major subtasks that execute as concurrent UNIX processes - communications (COM), user interface (UI) and display generation (DG). These tasks are monitored by a parent task (DRI) and communicate with each other via UNIX pipes. The multitasking approach allows data receipt and display updating to occur simultaneously. This approach also allows the screen to be updated while a user interactively selects system options on a set of pop-up menus [2].

A simple 2-d version of 3-D Mon also exists at the Goddard Space Flight Center and is referred to as the 2-D Graphics Monitoring System (2DGMS). Modeled after another similar 2-d system in use at the Johnson Space Center, 2DGMS provides three predefined views along the Shuttle's x, y and z axes. This system has an architecture similar to the TCOPS world map system (residing on a PC/AT) and is executed simultaneously with 3-D Mon to provide additional visual support if needed.

2.3 PAYLOADS MM

2.3.1 BACKGROUND

Under NASA's Shuttle-Attached Payloads Program, government organizations and educational institutions can place scientific experiments in the cargo bay of the Space Shuttle [10]. Associated with these experiments are several constraints affecting the safety of the instrument and also the integrity of the data collected. Examples of such constraints are: no oxygen molecules can impact an instrument to avoid damage to its crystal lining; no data can be collected while the earth is occulting an instrument's field of view to avoid erroneous data values; and no ultraviolet light can enter an instrument's field of view to avoid damage to spectrometers [9]. The problem of monitoring all of these constraints simultaneously in real-time prompted the need for the Attached-Shuttle Payloads Mission Monitoring System (PAYLOADS MM).

2.3.2 CAPABILITIES

The PAYLOADS MM system generates six types of 2-d displays that depict the instrument environment. These displays are used to determine which objects, either real (sun, moon, etc.) or abstract (radiation regions, Shuttle velocity vector, etc.), are within the field of view of the instrument or are causing interference between an antenna and a communications satellite. Unlike the previously mentioned 3-D Mon system, photographic realism does not make a significant contribution to the analysis of such constraints, therefore 2-d rather than 3-d images are sufficient. Figures 6 and 7 present two types of displays generated by the PAYLOADS MM system.

Similar to the functionality of the 3-D Mon system, orbit and attitude of the Shuttle model are derived from near real-time Shuttle telemetry data. Additional payload telemetry streams are also captured and used for detailed information about the configuration of the instrument. The telemetry data are normally received at time intervals varying from two to 30 seconds [9]. Environmental data are retrieved from ephemeris files or computed by highly accurate analytical routines on an as needed basis.

The six types of displays can be cycled through, and simultaneously updated on up to six graphics devices. This capability allows all six displays to be viewed concurrently or one display to be configured in multiple ways. The dwell time for each display can be modified interactively or the display can be suppressed entirely from the cycle. Other interactive capabilities include: the selection of an object to obtain additional information on that object; the selection of multiple objects for computation of angular separation; and the ability to zoom in on the image based on a user-defined outline.

2.3.3 ARCHITECTURE

The first design of the PAYLOADS MM system, a mainframe based design, encountered serious performance problems due to the number of graphics devices used and the large amount of graphics processing needed for each device. To eliminate the performance problems, a distributed processing approach similar to the 3-D Mon and TCOPS systems was used (see Figure 8). Spacecraft and payload telemetry data are retrieved and processed by a FORTRAN computations program (COMP) executing on the NAS mainframe computer. Parameters necessary to generate the displays are then computed and written in real-time to an interface dataset (IDS). These parameters are then accessed by a communications program (COM) that transmits the data to an IBM PC/AT compatible workstation (configured with IRMA and EGA boards) using the same communications protocol incorporated in the TCOPS system. Up to eight sets of communications programs with corresponding PC workstations can be operating simultaneously (see [1]). Three FORTRAN subsystem programs reside on the workstations and are executed under the DOS operating system. The three programs - Initialization (INIT), User Interface (UI), and Display Manager (DM) - were designed as three separate executables to avoid memory limitations [7].

PAYLOADS MM ARCHITECTURE

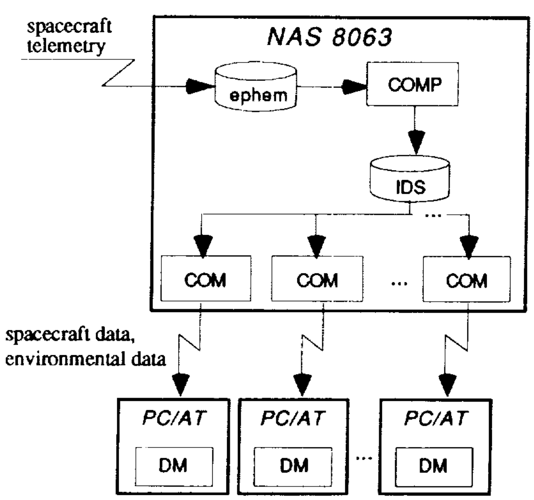

Figure 8.

The UI subsystem is first executed to allow users to initialize colors, image dwell times, etc. Next, the INIT subsystem is executed to graphically generate display skeletons that contain static textual and graphic information such as borders, coordinate grids and text legends. The display skeletons are saved to a Random Access Memory (RAM) drive for fast retrieval/access times. The DM subsystem is then invoked to process the most current data record sent from the mainframe and to control the generation of all displays. When a display is to be refreshed, the DM reads in the specific display skeleton and generates all the dynamic graphics and text onto the skeleton. The image is then displayed via a double buffering algorithm to provide an animation effect [7]. All graphics and text displays are generated using the Media Cybernetics, Inc. HALO graphics package. All user interface screens are developed using the West Chester Group Screen Generator Package.

As a result of this alternative architecture approach, remote usage of the system is now possible. Users who do not have access to a bisynchronous communications line directly connected to the NAS computer can run the DCA IRMA Remote software emulator package. This package emulates the IRMA hardware and communications protocol and converts the transmission to asynchronous messages that can be transmitted or received over a normal telephone line via HAYES V-series Smartmodem 9600 modems.

2.4 HUD

2.4.1 BACKGROUND

The Attitude Heads-Up Display (HUD) is a near real-time system that varies from those systems mentioned previously in this paper. Instead of using spacecraft data to produce images of the spacecraft in its surrounding environment, HUD attempts to allow analysts to see the spacecraft and its environment from the spacecraft navigator's perspective. This perspective decreases the difficulty of determining how a spacecraft is moving, what objects sensors are viewing and how the spacecraft's hardware is reacting during a maneuver. For example, data received from a sensor that is scanning the celestial sky are displayed in a window that corresponds to that sensor's field of view. Data received from an actuator are displayed in a format that indicates the level at which the actuator is operating and how safely it is functioning.

2.4.2 CAPABILITIES

The HUD system displays one graphics image that is updated every time a spacecraft telemetry record is received. Depending upon the spacecraft and its complement of sensors and actuators, the updates can be received as often as 1/8th of a second to every 10 seconds. The graphics image is configured similarly to the dashboard or heads-up display generated by aircraft flight simulators. (See Figure 9.)

Sensors that track solar system objects (sun sensors) and stars (fixed head star trackers) are shown as windows that display the object as it is viewed by the spacecraft in its appropriate location. Analysts can then see if the star trackers are locking in on a star. Thrusters are displayed as a series of lights aligned in the same configuration as they exist on the spacecraft. The lights are "turned on" when the thrusters are being fired. Sensors and actuators whose excessive operation can be hazardous to the spacecraft's health are displayed as various bars and potentiometers. The colors of the bars change as their operation reaches or exceeds safety levels. The color green indicates a safe level of operation; yellow indicates a warning that the level of operation is approaching the safety limit; and red indicates an unsafe level of operation. An attitude directional indicator, similar to those found in airplanes, shows the orientation of the spacecraft with respect to an inertially fixed coordinate system.

2.4.3 ARCHITECTURE

The HUD system is currently in a prototype phase. Eventually a distributed processing architecture similar to that used in the PAYLOADS MM system will be incorporated into the HUD system. To date, only the PC graphics program has been developed.

3. *MISSION PLANNING TOOLS*

Flight Dynamics Division analysts are responsible for determining various mission constraints and timelines as part of their premission planning activities. Often, this planning requires the study of environment and spacecraft parameters over a given period of time. In the past, this information has been generated in tabular form as records that are time incremented and contain the data as a series of numbers and flags. Although these data are highly accurate, the presentation format makes quick analysis of trends and time-oriented parameters difficult. To assist with these types of mission planning activities, two computer graphics applications have been developed and are described below.

3.1 MPGT

3.1.1 BACKGROUND

Prior to the launch of a satellite or a Shuttle- attached payload, the Flight Dynamics Division performs several analytical studies that are used to optimize the data collection time for a mission. These studies compute numerical values that contain such statistics as: the amount of Tracking Data and Relay Satellite System (TDRSS) contact time per orbit; the number of orbits per day that pass through a given radiation region; and the percentage of time in sunlight of a given orbit. As a utility to assist analysts with quick analysis of such details, the Mission Planning Graphical Tool (MPGT) was developed. MPGT also provides analysts with a means to produce a graphical picture of the overall spacecraft environment. From this information alternate orbit selections that may better fulfill the mission objectives can be more easily chosen for further investigation.

3.1.2 CAPABILITIES

MPGT produces 2-d and 3-d plots of the earth with spacecraft and environmental data presented as overlays. These overlays include: spacecraft orbit tracks, ground station antenna masks, TDRSS communication contours, interference zone contours, earth and spacecraft sunrise/set terminator lines, solar and lunar ephemeris, a star chart, and an ecliptic coordinate grid. Figures 10 and 11 are images generated by the MPGT system.

All overlays are designed to be mission generic. For instance, communication zone contours and spacecraft terminators are generated analytically dependent upon the altitude of the spacecraft. Interference zone contours are specified through text-edited data files that can be altered to reflect mission specific electromagnetic contamination regions. Up to six separate spacecraft orbit tracks can be specified via Keplerian or Cartesian state vectors. Time-oriented overlays (orbit tracks, sun terminators, etc.) are based on an interactively defined Greenwich Mean Time that is of specific importance to a given mission.

3.1.3 ARCHITECTURE

The system was designed as a standalone system for an IBM PC compatible workstation executing DOS. All graphics images are produced using the HALO device independent graphics package, eliminating graphics adapter hardware requirements.

3.2 SATVIEW

3.2.1 BACKGROUND

One of the Division's attitude responsibilities involves the planning of attitude maneuvers to achieve scientific instrument pointing objectives. Some spacecraft require several attitude constraints to be satisfied simultaneously. These may include instrument target availability, thermal restrictions and power requirements. As an aid to determine if such constraints will be satisfied, the Satellite Viewing system (SATVIEW) was developed as both an attitude maneuver planning aid and a quality assurance tool.

3.2.2 CAPABILITIES

Many of the SATVIEW system capabilities are similar to those found in the 3-D Mon system. Images of the earth, stars, moon, sun and other targets are generated in 3-d while the orientation of the spacecraft model is driven from attitude data that has been previously generated. The attitude and environmental data are provided to the system in greater than real-time. This allows a 90 minute maneuver to be viewed in several seconds. The user views this scenario from any of the spacecraft instrument or sensor field of views.

A second display mode of SATVIEW allows the user to look at the universe from outside the celestial sphere. The celestial sky is drawn as a sphere centered around the spacecraft coordinate system axes. The sun, moon, stars, and the earth's outline are drawn on the sphere while the spacecraft is represented by x, y, and z spacecraft body coordinate axes. Sensor and instrument field of view outlines are drawn on the sphere while attitude and environmental data are again provided in greater than real-time. The user can interactively alter the viewpoint to see the unfolding scenario anywhere outside the sphere. Figure 12 is a celestial sphere image generated by SATVIEW.

An additional feature of SATVIEW is interactive modification of the spacecraft attitude. The user can adjust the spacecraft axes such that a particular mission constraint or set of constraints are satisfied. The required attitude numbers are then returned to the user.

3.2.3 ARCHITECTURE

SATVIEW is a standalone system residing on an Silicon Graphics IRIS 4D/60T graphics workstation. All graphics images are produced by calls to the IRIS Graphics Library routines. Attitude data are produced by software on a NAS 8063 computer and downloaded to the IRIS workstation.

4. SOFTWARE DEVELOPMENT TOOLS

Due to the variance in capabilities, data formats, and dynamics between spacecraft, the Flight Dynamics Division is responsible for generating dynamic simulators, telemetry simulators, attitude ground support systems, and various mission planning tools that are specific to a given spacecraft. Since many of the displays incorporated into these systems vary from mission to mission only slightly in layout, but not in capability, software development tools have been created to increase programmer productivity. These tools are discussed in this section.

4.1 VEGAS

4.1.1 BACKGROUND

Of the numerical output generated by flight dynamics software systems, a large quantity is presented as displays of interactive alphanumeric tables or interactive X-Y plots. Some systems also display the output on world map plots. To reduce the resources required to reproduce source code that generates such complex display capabilities for each system, the Visual Environment for Graphics-oriented Analysis Systems (VEGAS) was developed. VEGAS consists of independent high level subroutine packages that produce x-y plots, text displays, and world maps (see [5]).

4.1.2 CAPABILITIES

The VEGAS X-Y Plot package provides capabilities for data to be displayed as scatter or line plots with Greenwich Mean Time axis label formats. An interactive environment is included that permits data modification, point flagging, curve fitting, zooming, panning and other orientation options. Curves can also be updated in real-time if desired [3]. These capabilities are invoked through high level FORTRAN subroutines.

The VEGAS Text Display package allows alphanumeric data to be displayed with different color and video attributes. User input is verified for type compatibility and range constraints [3]. Screen layouts are defined through text-edited template files. These files give an application programmer the ability to change the screen format without relinking the application.

The VEGAS World Map package was previously developed by another organization at GSFC. This package produces thirty world map continent projections and is invoked through a single FORTRAN subroutine. Routines are also provided for plotting contours on top of the projections.

4.1.3 ARCHITECTURE

Both the X-Y plot and World Map packages are built on top of the Template Graphics Software, Inc. machine and device independent graphics subroutine package TEMPLATE. This design allows these packages, and application software incorporating these packages to reside on the Division's IBM 4341 and DEC VAX computers. This design also allows displays produced by these packages to be generated on IBM 5080 and Tektronix 4100 series terminals.

Since TEMPLATE does not easily provide the character string capabilities needed for alphanumeric displays, the Text Display package was built on top of the IBM Graphics Access Method (GAM) package for IBM mainframe applications and on top of the DEC Screen Management Facility for VAX applications. The IBM version of the package supports the IBM 5080, 3250, and 3278 terminals. The DEC version supports VT series compatible terminals.

5. SUMMARY

The Flight Dynamics Division of Goddard Space Flight Center has committed itself to the use of computer graphics as an effective and efficient tool for comprehending mission related data. This commitment has only been accepted after various systems have proven their worth in the flight dynamics environment. From this commitment numerous graphics-oriented systems discussed in this paper were developed and have been or are currently being validated for operational use while more systems are being planned. And, as more graphics systems are created, more graphics development tools will be created, similar to those discussed in this paper, to reduce software development costs.

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REFERENCES

1. Brown, C., Franks, K., Bugenhagen, J., Mucci, D., Shirah, G., Weidow, D., "Attached Shuttle Payloads Broad Band X-ray Telescope Detailed Design Document," CSC/SD-88/6125, Computer Sciences Corporation, Greenbelt, Maryland, October 1988.

2. Chang, K., Garrahan, J., Langrehr, M., Pittarelli, E., and Tamkin, G., "Flight Dynamics/Space Transportation System 3-D Monitor System Release 2 System Description," CSC/SD-88/6066, Computer Sciences Corporation, Greenbelt, Maryland, August 1988.

3. Green, D., Pittarelli, E., Hendrick, R., Campos, M., Buhler, M., Durbeck, R., Jeletic, J., Shoan, W. , "Programmer's Guide to the VEGAS Graphics Utilities," CSC/SD-87/6018, Computer Sciences Corporation, Greenbelt, Maryland, December 1987.

4. Hardie, B., "System Description for the Trajectory Computation and Orbital Products System (TCOPS) User Interface," CSC/SD-88/6070, Computer Sciences Corporation, Greenbelt, Maryland, July 1988.

5. Jeletic, J., Shoan, W., "Flight Dynamics Graphics for the Space Station Era.," TEMPLATE User's Network Conference, Arlington, Virginia, March 1987.

6. Langrehr, M., Buchanan, L., Chang, K., Garrahan, J., Pittarelli, E., and Tamkin, G., "Flight Dynamics/Space Transportation System 3-D Monitor System Release 2 User's Guide," CSC/SD-88/6006, Computer Sciences Corporation, Greenbelt, Maryland, June 1988.

7. Shirah, G., "Solving a Real-Time Performance Problem of the Attached Shuttle Payloads Mission Monitoring System Through Prototyping," NASA/Goddard Space Flight Center, 552.2, Greenbelt, Maryland, December 1988.

8. Wallace, R., and Buchanan, L., "SPIF/FDF Interface Graphics Support System Requirements and Specifications," CSC/TR-85/6702, Computer Sciences Corporation, Greenbelt, Maryland, June 1985.

9. Weidow, D., "The Shuttle-Attached Payloads Operational Support System," NASA/Goddard Space Flight Center, 552.2, Greenbelt, Maryland, December 1986.

10. Wetmore, R., Anderson, C., and Coon, G., "Shuttle-Attached Payloads Operational System Requirements and Functional Specifications," CSC/TR-85/6001, Computer Sciences Corporation, Greenbelt, Maryland, May 1985.

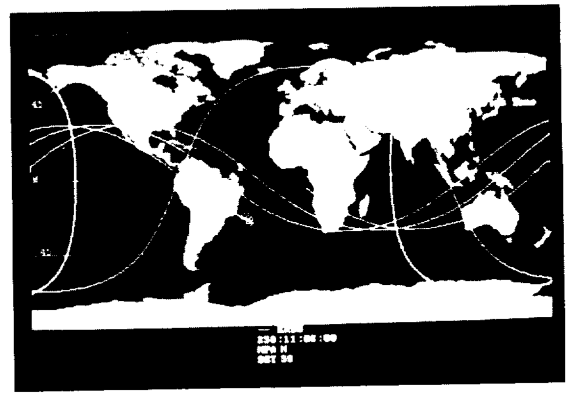

Figure 1. A Trajectory Computations and Orbital Products System world map plot displaying coverage of the Earth Radiation Budget Satellite (ERBS).

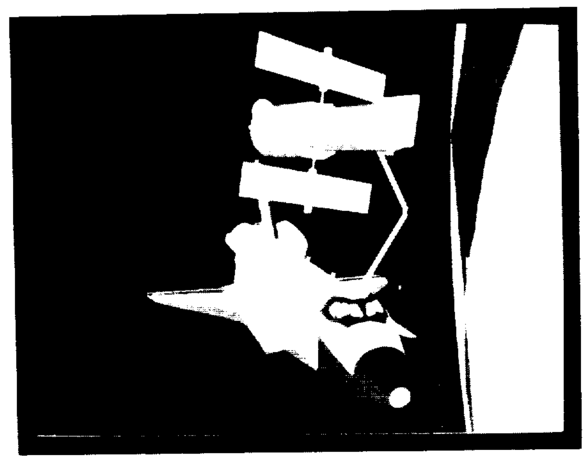

Figure 3. The deployment of the Hubble Space Telescope as displayed by the 3-D Mon system.

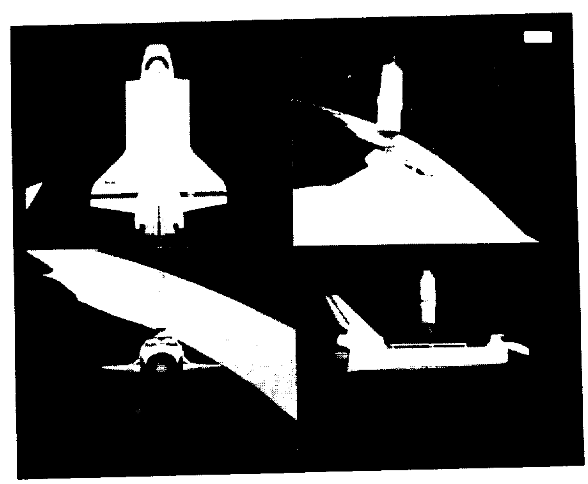

Figure 4. The deployment of a Tracking Data and Relay Satellite as displayed by the 3-D Mon system. The top right viewport displays a view from the rear cockpit window. The earth and sun position vectors and the Shuttle velocity vector are also displayed.

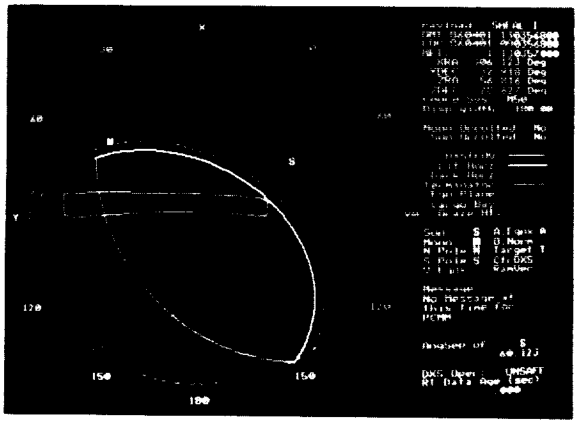

Figure 6. The PAYLOADS MM Celestial Sphere display illustrating the view along the Shuttle's -z axis including the position of the earth, the earth's atmosphere, celestial objects, and instrument field of view outline [1].

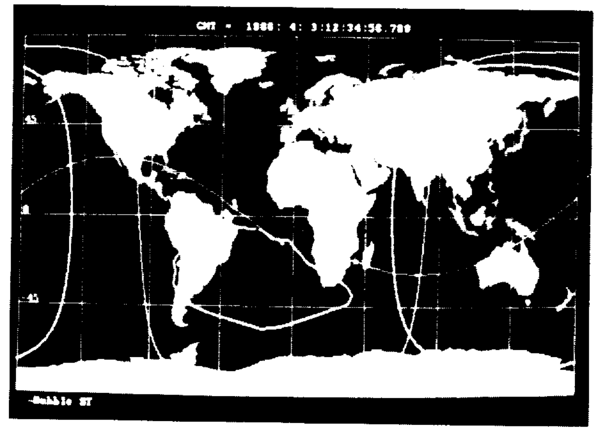

Figure 10. A 2-d world map plot produced by the Mission Planning Graphical Tool configured for orbit studies of the Hubble Space Telescope.

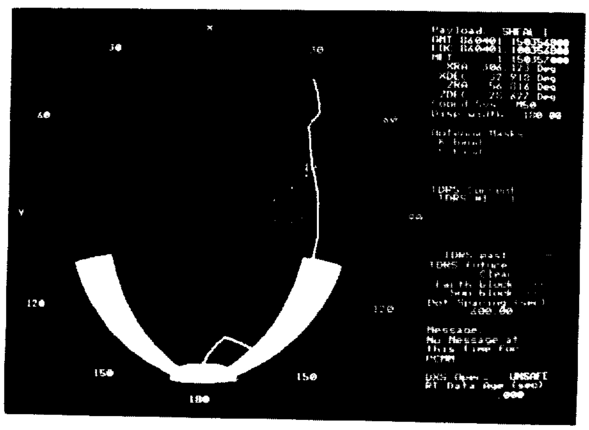

Figure 7. The PAYLOADS MM TDRS display illustrating the view along the Shuttle's -z axis including antenna masks and past, current and future positions of a TDRS [1].

Figure 11. A 3-d earth plot produced by the Mission Planning Graphical Tool configured for electromagnetic interference studies of the Hubble Space Telescope.

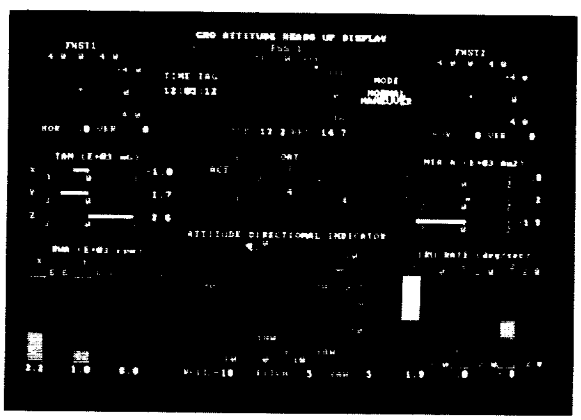

Figure 9. The Attitude Heads-Up display configured for the Gamma Ray Observatory satellite.

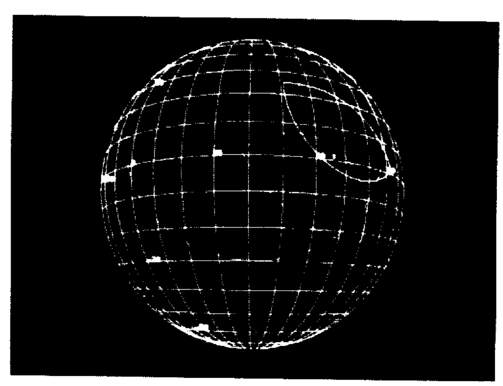

Figure 12. An interactive celestial sphere display produced by the SATVIEW utility.