GSMS AND SPACE VIEWS: ADVANCED SPACECRAFT MONITORING TOOLS

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ABSTRACT

The Graphical Spacecraft Monitoring System (GSMS) processes and translates real-time telemetry data from the Gamma Ray Observatory (GRO) spacecraft into high resolution 2-D and 3-D color displays showing the spacecraft's position relative to the Sun, Earth, Moon, and stars, its predicted orbit path, its attitude, instrument field of views, and other items of interest to the GRO Flight Operations Team (FOT). The GSMS development project is described and the approach being undertaken for implementing Space Views, the next version of GSMS, is presented. Space Views is an object-oriented graphical spacecraft monitoring system that will become a standard component of Goddard Space Flight Center's Transportable Payload Operations Control Center (TPOCC).

Key Words: Spacecraft monitoring, graphical, visualization, mission control

1. INTRODUCTION

Traditionally, the flight operations team (FOT), which is responsible for monitoring and maintaining the health and safety of a spacecraft, has performed its duties using alphanumeric text displays of telemetry data as its primary source of status information, augmented with graphical strip charts of a few select telemetry items. The operators must constantly interpret the data on their displays, building a mental picture of the spacecraft's condition. When a problem occurs, they must quickly determine the appropriate corrective action. Their ability to properly diagnose a problem depends, in part, on their ability to visualize the state of the spacecraft from the information on their displays. To assist the Gamma Ray Observatory (GRO) FOT with this visualization, the Graphical Spacecraft Monitoring System (GSMS) was developed. The GRO GSMS processes and translates real-time telemetry data into high-resolution 2-D and 3-D color displays that show the spacecraft's position and attitude relative to the Sun, Earth, Moon, and stars; its predicted orbit path; its instrument fields of view (FOVs); and other items of interest to the FOT.

As GRO GSMS has been found to be of high value to the FOT over the past 18 months, the next evolution of GSMS is now under development. Space Views will encompass all that GSMS is today, but will address making a generic graphical spacecraft monitoring system that can be easily tailored to support new spacecraft misions. An object-oriented approach is being used to achieve this goal. Space Views will also operate under X Window and Motif, in a client-server environment, providing network distributed displays across a mix of Unix-based workstations.

2. BACKGROUND

The Control Center Systems Branch (CCSB) at the Goddard Space Flight Center (GSFC) in Greenbelt, Maryland, is responsible for developing spacecraft control centers at GSFC. Current spacecraft missions supported by CCSB at GSFC include the International Cometary Explorer (ICE), Earth Radiation Budget Satellite (ERBS), Cosmic Background Explorer (COBE), Upper Atmosphere Research Satellite (UARS), Extreme Ultraviolet Explorer (EUVE), Solar Anomalous and Magnetospheric Particle Explorer (SAMPEX), and GRO. Each spacecraft mission has its own Payload

Operations Control Center (POCC), consisting of a Mission Operations Room (MOR) connected to, or containing, computer equipment hosting mission support systems.

From the MOR, the FOT provides round-the-clock support to its spacecraft. At scheduled times, the FOT makes a communication contact with the spacecraft that typically lasts about 20 minutes. During this contact, the FOT monitors telemetry data from the spacecraft on alphanumeric text displays that are color coded to show telemetry items with nominal values in green, marginal values in yellow, and out-of-tolerance values in red. The FOT relies on these color codes to help highlight potential problems with the spacecraft. The GRO MOR contains 12 display screens which must be monitored by 2 operators during each support period.

To further automate the POCCs and eliminate tedious, manual procedures for determining and monitoring spacecraft status, the CCSB directed CSC to develop the conceptual design for a graphical spacecraft monitoring system (GSMS). After concept approval, the CCSB tasked CSC under NASA's Research Technology, Objectives and Plans program to develop requirements and implement the system as a pilot project.

3. APPROACH AND REQUIREMENTS

The task of defining requirements for the GSMS was begun by creating a simple prototype, developing a few displays illustrating the capabilities of state-of-the-art computer graphics workstations. One display was a 3-D model of the GRO spacecraft that moved along its roll, pitch, and yaw axes in response to simulated data from a file. A second display simulated a video strip chart plotting several parameters at once in real time against separate left and right vertical scales, with a user-selectable time scale. A third display illustrated the GRO propulsion subsystem as an animated schematic diagram, showing the effects of a stuck valve by highlighting failed components in red, overlayed with alert messages. This simple prototype performed rudimentary display window management, allowing any display to be shown either full-screen or in a quarter-screen mode along with three other displays. The prototype also included basic popup menus for selecting display options with the mouse.

With the prototype completed, demonstrations were conducted for personnel from both current and upcoming spacecraft missions. Senior analysts from the GRO mission saw the potential benefits of the GSMS immediately and requested that it be developed into an operational system to support their FOT.

Working with GRO senior analysts, requirements for 11 basic displays were defined:

- Mercator map showing the orbit path of GRO, communication coverage of the Tracking and Data Relay Satellites (TDRSs), day/night terminator, and South Atlantic Anomaly (SAA) region of magnetic interference
- View of TDRS coverage of the Earth, as seen from the altitude of each TDRS
- View of GRO from its altitude, in its current position and attitude, shaded according to its orientation to the Sun
- View from the -X axis of the GRO spacecraft, with selectable FOV angles, showing reference frames for the bright object sensors (BOSs), fixed-head star trackers (FHSTs), and omnidirectional antennas
- View from the +X axis of the GRO spacecraft, with selectable FOV angles, showing reference frames for the fine Sun sensors (FSSs) and omnidirectional antennas
- BOS-1 and -2 FOVs showing shutter trip lines for closure due to the presence of the Sun, Earth, or Moon
- FHST-1 and -2 FOVs showing the position of the current selected guide star within the reference frame
- FSS-1 and -2 FOVs showing the position of the Sun within the reference frame
- Omnidirectional antenna-A and -B FOVs, with selectable FOV angles, showing reference frames for the BOSs, FHSTs, and FSSs
- High gain antenna (HGA) FOV showing the current position of a TDRS within the HGA communication coverage area

- Plot of HGA azimuth and elevation angle values versus predicted angle values

Also defined were displays that were combinations of the 11 basic displays, designed to maximize the use of available screen space to efficiently communicate spacecraft information to the operator. In total, 25 displays were defined for selection by the operator.

4. CHALLENGES AND SOLUTIONS

Development of GSMS for GRO was bound by the constraint that this system, as a pilot project, not impact the GRO POCC ground support system. New requirements could not be levied on the GRO POCC to facilitate integration of GSMS with the POCC nor change existing POCC interfaces to other supporting systems such as the Flight Dynamics Facility (FDF). This meant that accessing real-time telemetry in the GRO MOR had to be accomplished via a terminal interface to the GRO applications processor (AP), which received and processed telemetry for display in the MOR. GSMS also required access to predicted orbital data from the FDF. Because no direct electronic link existed between the GRO POCC and the FDF, the only way to access this data was by having the necessary files written onto 9-track tape and hand-carried to the GRO MOR. With these constraints in mind, a system architecture for GSMS was developed that, in effect, made GSMS a "read only" application within the MOR. Figure 1 shows the overall system configuration for GSMS.

Two workstations, a 386-class PC and a Silicon Graphics, Inc. (SGI) IRIS 4D/20 workstation, host the GSMS software. The GSMS software on the PC workstation is responsible for receiving telemetry data as a text display from the AP, extracting the data from the display buffer (synchronized with AP updates of the buffer), converting values where necessary into meaningful GSMS information, and transmitting the extracted telemetry data to the SGI workstation for conversion into GSMS displays. The PC workstation software also extracts FDF predicted orbital data from the Predicted Site Acquisition Table and sends it to the SGI workstation for conversion into predicted orbit paths for GRO.

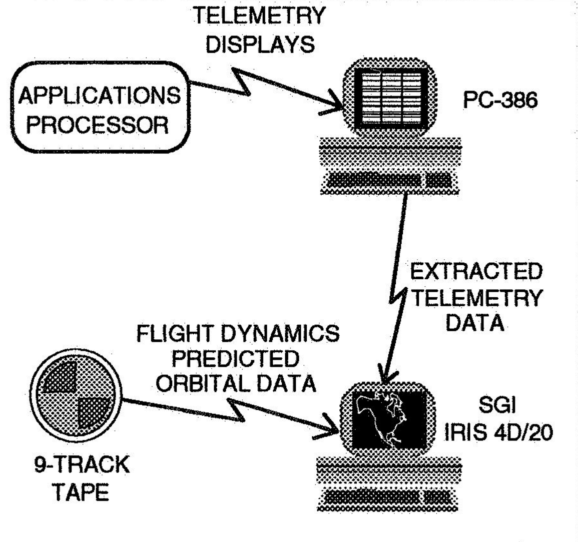

Figure 1. GRO GSMS System Configuration

The GSMS software on the SGI workstation is the core of GSMS, presenting the 25 defined 2-D and 3-D displays on a high-resolution color monitor and handling the user interface for selection of the displays to be shown, selection of the display options, and placement of the display when in the quarter-screen viewing mode.

The GSMS user interface was a challenge that had to solved early on in the design phase. A simple "point and click," mouse-driven user interface was desired so that the operators could quickly configure GSMS displays to their liking. Using the human factors principles of direct manipulation and immediate user feedback, a state-of-the-art user interface and window manager was developed. The GSMS user interface allows the operator to directly select any display desired from an iconic menu. As seen in Figure 2, each icon in the menu is actually a scaled image of a display. Using this iconic menu, the operator sees a preview of each available display, with its title appearing at the bottom of the menu.

The GSMS user interface features immediate visual feedback to the operator. When the operator invokes a popup menu of display options by pressing a mouse

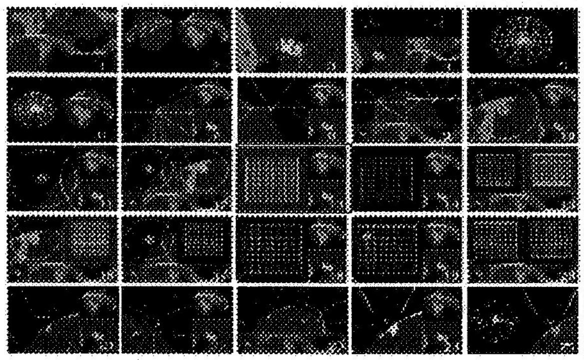

Figure 2. Iconic Display Selection Menu

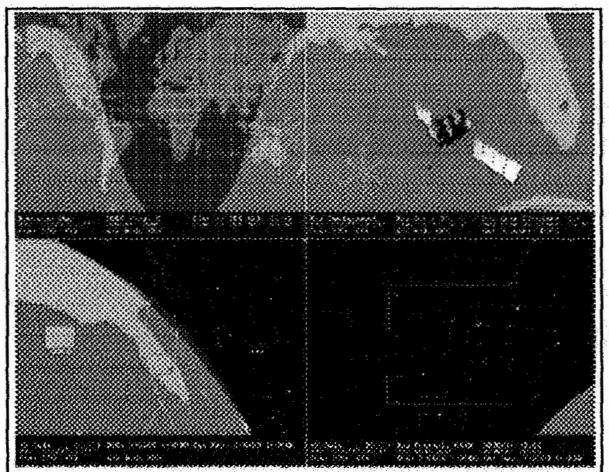

Figure 3. GSMS with (clockwise from upper left) Mercator Map, Sun Impingement, +X Axis, and -X Axis Displays

button, the effect of any selected option is immediately shown in the display, which continues to update even while the option menu is present. This allows the operator to see the effect of the option immediately and decide whether to accept it while the menu is still available for making choices and selections. Another feature of the GSMS user interface is its window management capability, which allows four displays to be viewed simultaneously in a quarter-screen mode, as shown in Figure 3, or a single display to be viewed full-screen, as shown in Figure 4.

Another challenge in developing GSMS was creating a 3-D model of the Earth that could be rendered quickly enough to maintain smooth animation in a display. GSMS implements its world map data base as a series of 3-D land mass tiles that, drawn edge to edge, render the Earth as a faceted sphere. Using clipping algorithms, GSMS culls out tiles that will not appear in a scene, saving rendering time. To further accelerate the process of depicting the Earth, GSMS simulates the ocean by drawing a simple blue disk behind the land masses.

Perhaps the biggest challenge in implementing GSMS was verifying the accuracy of the displays. Before GRO launch only limited simulated data was available, and was not sufficient enough to verify simultaneously the position and attitude of GRO relative to the positions of the Sun, Earth, and Moon. It was only possible to verify the computation of GRO's attitude and the Sun and Moon positions. This was accomplished using validated test cases furnished by the FDF and data from the U.S. Naval Observatory's ephemeris program. Immediately after launch, however, CSC and GRO spacecraft analysts were able to verify the GSMS displays by comparison to actual telemetry data.

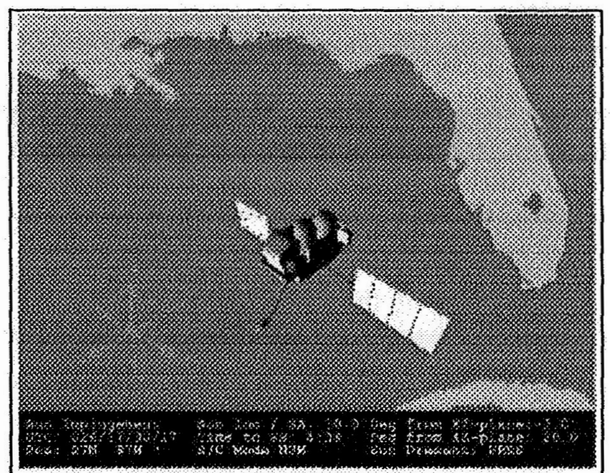

Figure 4. Full-Screen Sun Impingement Display

5. IMPLEMENTATION

Because of its powerful 2-D and 3-D color graphics display capabilities, a newly available (in 1989) SGI Personal IRIS 4D/20 workstation was chosen to implement GSMS on . As required by the CCSB, software for accessing telemetry data was implemented on a 386-class PC workstation, identical with those used in the GRO MOR. To promote system portability and reusability, all GSMS software was implemented using the C programming language.

In the first year of development, several tools and procedures were implemented to facilitate the implementation of the GSMS displays. The first of these was a tool for creating an accurate 3-D model of the GRO spacecraft, implemented using Control Automation's ModelMate CAD software. This tool enabled spacecraft components to be easily digitized from blueprints and processed into a format for efficient rendering by GSMS. To build a 3-D world data base for rendering the Earth as a solid model (instead of as a wireframe image), a 3-D graphical editor was developed that allows the user to interactively generate 3-D polygonal tiles of land masses from a basic latitude/longitude world map. Another tool was built to scale each GSMS display into an icon for use in the display selection menu.

The essential components of GSMS are the numerous algorithms that produce the displays. To compute the positions of the Sun, Moon, and stars, existing FDF algorithms were converted from Fortran to C. For developing FOV displays, a camera model capable of viewing angles as wide as 170 degrees was implemented. To simulate the FOVs of the star trackers, Sun sensors, bright object sensors, and other items of interest, this camera model was simply placed at the proper location on the spacecraft and pointed with a line-of-sight vector. Figure 5 shows GRO's high gain antenna FOV (the center circle in the view outlines the FOV of the antenna). Other significant algorithms developed include those for calculating GRO's position and predicted orbit path, day/night termination line (both at ground level and at GRO's altitude), and procedures for using multiple coordinate reference frames simultaneously (e.g., Earth-centered inertial, latitude/longitude, spacecraft body, high-gain antenna, and solar array panel).

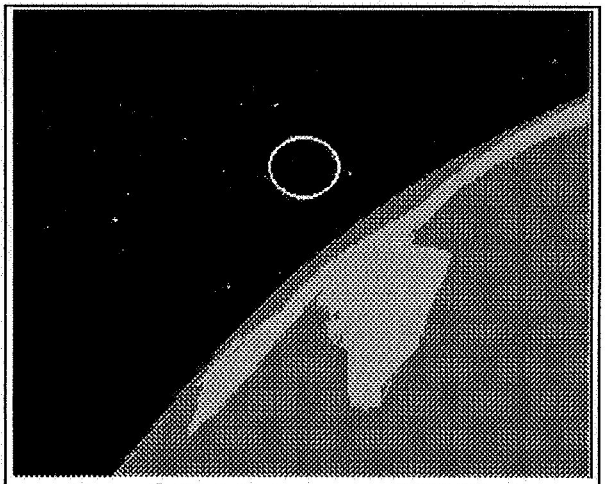
Figure 5. High Gain Antenna FOV Display

A system communication scheme synchronizes all of the separate GSMS processes. As each set of telemetry data is extracted by the PC workstation process, it is transmitted to the SGI workstation via an RS-232 serial line. Between the communicating processes on each workstation, an appropriate handshaking protocol helps ensure data integrity. On the SGI workstation, the executive communication process spawns a user interface process and a GSMS display management process. Communication between these three processes is coordinated through semaphores and shared memory. By using a double buffer technique, GSMS ensures that all telemetry data has been received before updating its displays.

6. RESULTS AND FEEDBACK

With GSMS operational, the GRO FOT began relying increasingly on the system to immediately see GRO's position and its orientation to the Sun. In monitoring GRO, knowing exactly when the spacecraft will enter or leave sunlight is important, because activity in the GRO power subsystem changes markedly then. With GSMS, FOT personnel can directly see GRO leaving or entering sunlight, and can also view a countdown clock showing the exact number of minutes and seconds to sunrise or sunset at the bottom of the display.

Whenever GRO maneuvers to a new attitude, a biweekly event, being able to see the maneuver as it occurs using GSMS is immensely reassuring to the GRO attitude analysts. They can easily verify that the highly critical roll, pitch, and yaw changes are being executed by GRO's attitude control subsystem exactly as planned. The consensus of GRO FOT personnel is that GSMS is a spacecraft monitoring tool without which they cannot operate efficiently. It has become invaluable in assisting them in rapidly understanding events that cannot be understood or explained through text displays alone.

7. SPACE VIEWS: THE NEXT GENERATION

With the enthusiam of the GRO FOT establishing GSMS as an unqualified success, the CCSB has now tasked CSC to port GSMS to the Transportable Payload Operations Control Center (TPOCC). TPOCC is a new ground support system architecture, based on Unix workstations connected via Ethernet and operating in a client/server relationship, with display and user interface processing performed using the X Window and Motif toolkits. This new version of GSMS for TPOCC, Space Views, uses object-oriented analysis and design techniques and the C++ programming language.

Whereas GSMS was specifically tailored to meet the requirements of the GRO FOT, Space Views is being designed to have a generic framework to which specific display components can be easily added and customized for a particular spacecraft. To achieve this goal, a decision was made to use object-oriented (OO) technology. With an OO approach, what is generic and what is mission specific falls out naturally from the OO analysis. The end goal is a tool kit full of objects from which Space Views displays can be built.

8. OBJECT-ORIENTED APPROACH

As has been frequently said, object-oriented programming (OOP) represents a new paradigm shift, a new way of organizing a solution to a problem. What makes the OO approach attractive are the improvements in system robustness, efficiency, and maintainability that it promises. But to achieve these promises, there is a learning curve that must be tackled through training.

Space Views developers initiated themselves into the world of OOP by attending two major conferences, SCOOP and OOPSLA, that focus on the entire life cycle of OOP. Based on the seminars at these conferences and a survey of books on OOP, a self teaching plan for OOP was developed as a large training budget did not exist. As the development team was already proficient in C programming, C++ was selected as the OOP language for implementing Space Views, the only other viable alternative being Smalltalk. The widespread availability of C++ support tools on a variety of platforms was also a factor in the decision to choose it for implementing Space Views. But before delving into C++ programming, it was necessary to put everyone into the OO way of viewing the world.

Endorsed by leading practioners of OOP was the Class, Responsibilities, and Collaborators (CRC) notecard method of object-oriented analysis (OOA). This was practiced on small sample problems in several highly interactive 2-hour sessions. The goal here was to get everyone to think like an object. At the same time, the leading books on OOP were acquired, but the ones having the best readability were An Introduction to Object-Oriented Programming by Timothy Budd, Object-Oriented Design by Grady Booch, and Object-Oriented Analysis (2nd Edition) and its companion, Object-Oriented Design by Peter Coad and Ed Yourdon. CSC has selected the Coad and Yourdon OOA tool program to document the Space Views OOA activity, and plans to use their OOD tool when it becomes available. An OOA Training video by Peter Coad has also been acquired and will be used to assist management personnel with understanding the Coad and Yourdon OOA methodology and notation.

After several weeks of OOA execercises, training was started on C++ through the C++ Primer (2nd Edition by Stanley Lippman, the PC-based, self paced, Teach Yourself C++ (2nd Edition) by Al Stevens and, of course, The C++ Programming Language (2nd Edition) by Bjarne Stroustrup. Another hurdle to overcome has been learning how to use X Window and implement displays as Motif widgets. Most of the learning has been through on-the-job trainng, working with TPOCC personnel already involved with these activities. Additional help has come from books, and from video courses on X and Motif available at GSFC. A prototype Space Views map display has already been built as a Motif widget, and rapid prototyping will continue to be used in parallel with the Space Views analysis and design activities.

Since Space Views has 3-D as well as 2-D displays, initially there was an issue of whether to use the PHIGS (an ANSI and ISO 3-D graphics programming standard) extension to X (PEX) graphics library/application program interface (API). PEX is an evolving standard and current vendor implementations of it exhibit, at least in our experience, inconsistant rendering behavior. Adopting use of PEX implied adding risk to the development of Space Views. Recently Silicon Graphics anounced GLX, the counterpart to PEX, that allows applications built with SGI's graphics language (GL), such as Space Views, to run under X. It is hoped that GLX will resolve this issue of implementing 3-D displays under X, since GL is now being made available to all major workstation vendors in an open architecture arrangement (OpenGL). Using GLX represents less risk than using PEX since the Space Views development team has several years of programming experience with GL, having implemented GSMS using GL, but only minimal experience with PEX, which was explored by implementing a small prototype application.

9. SUMMARY

GSMS proved that FOT personnel need direct visualization of spacecraft operations, a real-world view of events, and not just numbers updating on a screen. By the end of 1993, Space Views is expected to be in place supporting the SAMPEX mission, and ready to assist upcoming missions. At GSFC, Space Views will be the visualization tool for supporting the next generation of modern spacecraft. Space Views will use OOP to maximize efficiency, configurability, and reusability while minimizing future development and maintenance costs.