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USING SFOC TO FLY THE MAGELLAN VENUS MAPPING MISSION

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ABSTRACT

Traditionally, Spacecraft Flight Operations at the Jet Propulsion Laboratory (JPL) have been performed by teams of Spacecraft experts utilizing ground software designed specifically for the current mission. The Jet Propulsion Laboratory set out to reduce the cost of spacecraft mission operations by designing ground data processing software that could be used by multiple spacecraft missions, either sequentially or concurrently. The Space Flight Operations Center (SFOC) System was developed to provide the ground data system capabilities needed to monitor several spacecraft simultaneously and provide enough flexibility to meet the specific needs of individual projects.

The Magellan Spacecraft Team utilizes the SFOC hardware and software designed for engineering telemetry analysis, both real-time and non-real-time. The flexibility of the SFOC System has allowed the Spacecraft Team to integrate their own tools with SFOC tools to perform the tasks required to operate a spacecraft mission. This paper describes how the Magellan Spacecraft Team is utilizing the SFOC System in conjunction with their own software tools to perform the required tasks of spacecraft event monitoring as well as engineering data analysis and trending.

Keywords: operations, ground data systems, telemetry processing, automation, Magellan.

1. SFOC INTRODUCTION

The Space Flight Operations Center (SFOC) is a collection of hardware and software subsystems working together in a multi-step process to provide mission control, telemetry processing, and storage services for a portion of the Jet Propulsion Laboratory's (JPL's) space flight missions (Ref. 1). SFOC receives spacecraft telemetry collected by the Deep Space Network (DSN) and performs frame synchronization and channelization of the telemetry. Once the telemetry is channelized, it is distributed to the user for real-time display and interpretation. This channelized telemetry is also archived to allow retrieval and analysis at a later date. All the basic tools necessary for a user to display real-time telemetry and retrieve archived data are provided by SFOC.

2. MAGELLAN

The Magellan Spacecraft is a National Aeronautics and Space Administration's (NASA) planetary mission designed to obtain high-resolution Synthetic Aperture Radar (SAR) images of Venus. Magellan was launched aboard the Space Shuttle Atlantis on May 4, 1989 and using the IUS, was placed in a type IV transfer orbit arriving at Venus on August 10, 1990. Magellan began SAR imaging of the Venusian surface on September 15, 1990 and to date has produced high-resolution imagery of over 99% of the planet's surface.

3. MAGELLAN and SFOC

SFOC was designed to be the first true multi-mission ground data system to operate at JPL. It supplies core ground data system capabilities with enough flexibility to adapt to specific mission needs in a timely and cost effective manner. The first user of SFOC was the Magellan mission. The Magellan flight team became involved early in SFOC development and helped to provide requirements, testing and feedback during the initial releases of each SFOC version. This led to the Magellan ground system configuration depicted in Figure 1. The first version of SFOC used by the Magellan spacecraft team was Version 6. This version was used to support some of the pre-launch spacecraft testing and spacecraft team training exercises. The next version, Version 7, was used to support launch and the majority of cruise operations. Magellan is currently using Version 13, which came on-line just prior to Venus orbit insertion. The latest versions of SFOC are being developed under the new Advanced Multi-Mission Operations System (AMMOS) program.

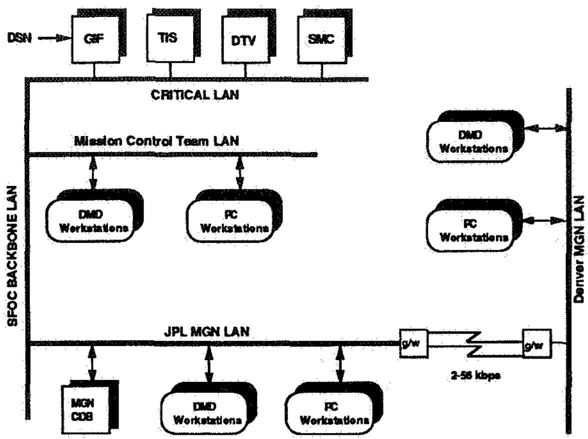

Figure 1 Magellan Ground Data System

4. SFOC REAL-TIME CAPABILITIES

SFOC provides the following real-time telemetry monitoring capabilities:

- Data Monitor and Display (DMD),
- Derived telemetry channels,
- Alarm limit maintenance and usage,
- Latest available data dump requests,
- Real-time memory readout verification.

4.1. Data Monitor and Display (DMD)

The Magellan spacecraft team uses the SFOC Data Monitor and Display (DMD) capability to monitor real-time telemetry via the spacecraft team workstations. Each subsystem has customized its DMD environment based on the characteristics of the individual subsystem and personnel. The DMD function allows engineers to define their own display screens or templates using the Template Definition Language (TDL). Although simplistic in capability, TDL provides the user with the tools required to create imaginative displays. The display types used by the Magellan spacecraft team include Fixed, List, Matrix, Message, Alarm and Plot pages.

Fixed Pages: These display types are designed by the subsystem engineers to logically group data in pictorial form which best suits their monitoring needs. The "fixed" indicates that the formats and data assignments cannot be modified in real-time. This page type is preferred by the Magellan spacecraft team for real-time data monitoring. An example of a Magellan power subsystem fixed display is depicted in Figure 2. The Magellan spacecraft team has designed and coded in excess of 100 fixed pages for flight use.

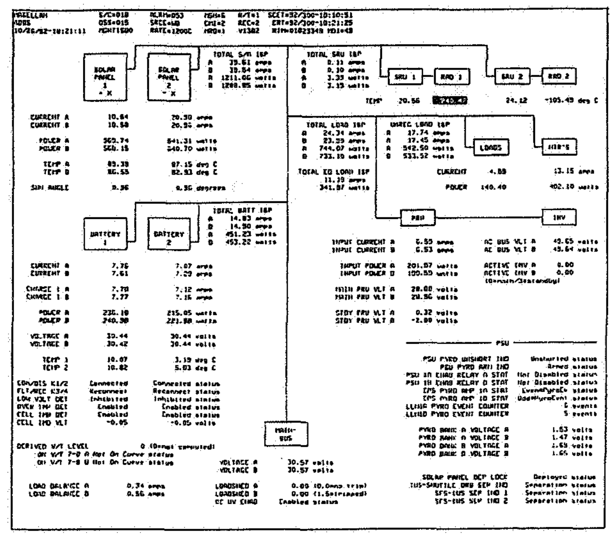

Figure 2 DMD Fixed Display

List/Matrix Pages: The data contents of list and matrix pages are designed to be modified in real-time simply by modifying a list of data channels. The data attributes to be displayed such as titles, values, time, units, etc are designed to be displayed on a single line for a list page and in a grid for matrix pages. This display type is useful when a subsystem wants to change data content on the fly.

Message Pages: The message page is designed to emulate a line printer on a video display. As new channel messages appear, they scroll down the screen. The format of the message page is user definable allowing the individual to display data attributes of interest. Message page output can also be routed to printers or data files.

Alarm Pages: This page type is designed to display channel information of telemetry channels which exceed a predefined threshold. The alarm page is structured like a list page. When a channel goes into alarm it is added to the alarm page and it maintains its position as data is updated.

Plots: For subsystems that monitor analog data, the capability to plot telemetry real-time has been extremely valuable. Plot types include Channel vs. Time, Channel vs. Channel and Minimum/Maximum plots. The DMD is capable of displaying 20 individual plot windows on a single workstation screen with up to four channel assignments per plot window. This allows up to 80 channels to be monitored graphically. The size of the plots, scales, labels and time ranges are all user definable.

Figure 3 shows a typical subsystem display configuration and contains fixed, list, alarm, and plot display types.

4.2. Derived Telemetry Channels

The DMD also provides the capability, via the Channel Conversion Language (CCL), to produce derived telemetry channels. Derived telemetry channels are measurements which are derived from information received in the main telemetry stream. The derived channels can be as simple as changing the units on a received value, to as complex as deriving the remaining propellant load on a spacecraft. In general, any data that is used for spacecraft analysis that can be generated from a snapshot of telemetry is a likely candidate for a derived channel. Just like the main telemetry channels, derived channels can be displayed, alarm checked, and plotted using the DMD. They can also be retrieved from the central database for non-real-time analysis or trending. The calculations of "Right Ascension and Declination" are simple but useful examples of derived channels developed by the Magellan spacecraft team. The algorithm for calculating the right ascension and declination utilizes the 4 quaternion elements telemetered from the spacecraft and is as follows:

$$c31 = 2\ x\ ((quat1\ x\ quat3) + (quat2\ x\ quat4))$$

$$c32 = 2\ x\ ((quat2\ x\ quat3) - (quat1\ x\ quat4))$$

$$c33 = quat4^2 + quat3^2 - quat2^2 - quat1^2$$

right ascension = *ATAN (c32,c31)*
declination = *ASIN (c33)*

The Magellan flight team has developed and implemented approximately 250 derived channels during mission operations.

4.3. Alarm Limit Maintenance and Usage

The capability exists within the DMD to check user-specified telemetry and inform the user when an unexpected value is encountered. This function is accomplished using DMD yellow and red alarms. The yellow alarms are set and monitored by subsystem engineers locally at each individual workstation and are generally used as caution alarms. It requires only subsystem lead approval to change yellow alarms. The red alarms are monitored on a system wide basis and usually indicate that an undesirable/take-action event has occurred. They are monitored round-the-clock by Magellan mission control team specialists. Red alarm values have been typically selected utilizing the following guidelines:

- Adherence to launch/deploy go/no-go criteria,
- Adherence to specified acceptance test limits,
- Adherence to S/C fault protection thresholds,
- Predicted values for mission phases,
- Nominal S/C values observed pre-launch.

To insure the correct level of review, Team Chief level approval is required to change a red alarm value.

4.4. Latest Available Data Dump Requests

Another feature of DMD used by the spacecraft team is Latest Available Data (LAD) dump requests. Maintained in the workstation is a buffer which contains the latest available data of all activated telemetry channels. The contents of the buffer may, at any time, be dumped to a printer or a file for further processing by spacecraft analysis tools. The Magellan spacecraft team used this capability to capture the state of the spacecraft following an anomaly which caused unexpected loss of downlink. One of the first actions performed after the anomaly occurred was a dump request of the LAD buffer. This LAD dump was immediately reviewed by the subsystem engineers for clues to the cause of the anomaly.

In addition to LAD dumps, the capability to perform channel parameter table dumps and coefficient dumps is also available. These capabilities can be used to determine channel information such as current alarm limits or polynomial coefficients.

4.5. Real-time memory readout Verification

There have been several instances during the mission where the spacecraft team has had to make flight software modifications or parameter changes that require real-time Memory ReadOut (MRO) verification. The majority of these software modifications are performed by a sequence of command groups. In general, memory verification of one command group is required before the next command group may be sent. This verification was usually required in a time-critical manner. To allow timely MRO verification, SFOC developed a tool to perform real-time MRO verification. This tool, named BCTOMRO, strips MRO data from the

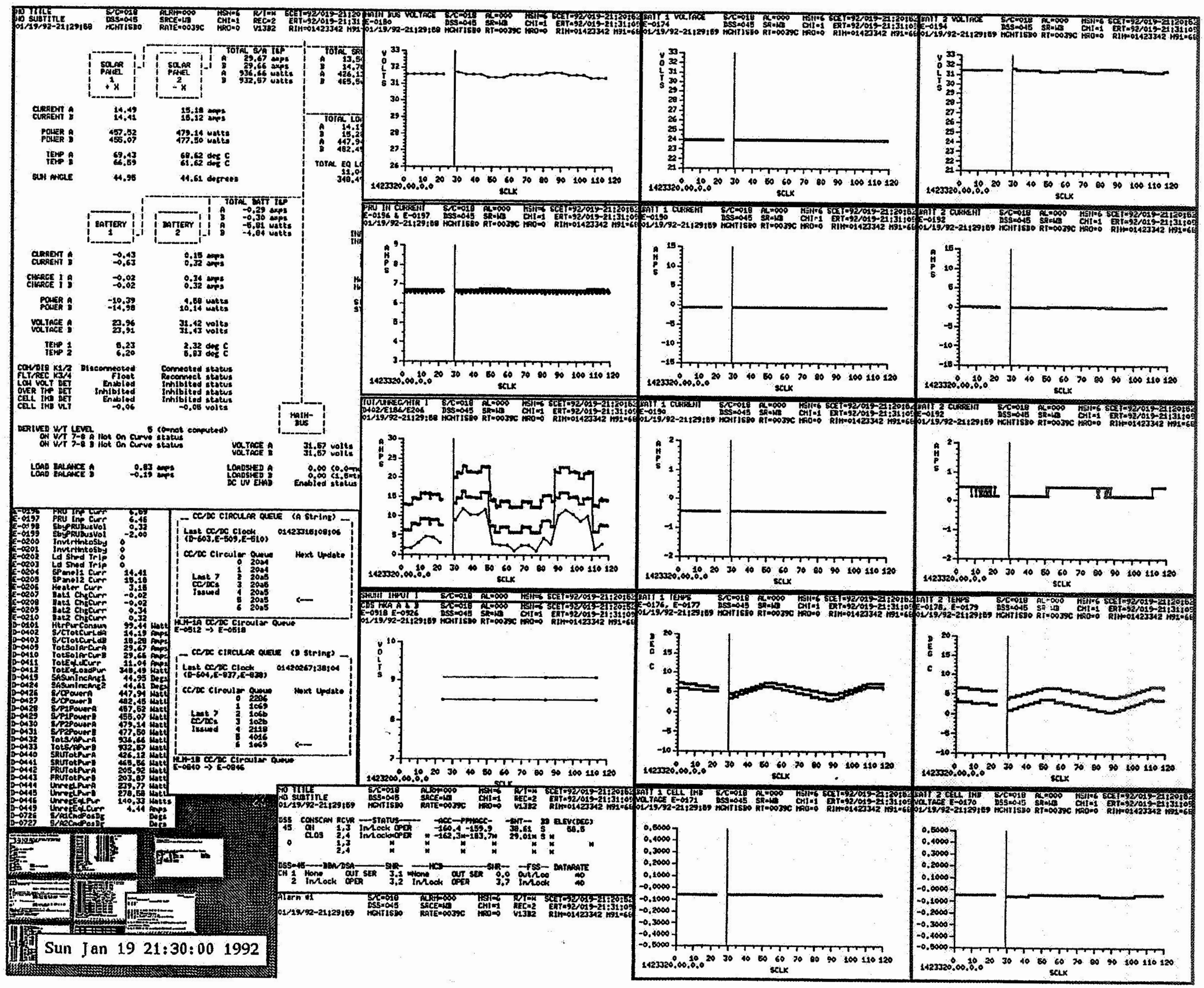

Figure 3 Typical Magellan Subsystem Display Configuration (Power Subsystem Battery Recondition Display)

SFOC telemetry stream and displays the data in real-time. BCTOMRO has allowed the spacecraft team to make the real-time MRO verifications of changes and continue commanding during time critical command windows.

5. NON-REAL-TIME DATA ANALYSIS

SFOC has provided several tools to aid in non-real-time analysis of spacecraft data. The spacecraft team uses these tools in combination with tools they developed to perform the following non-real-time functions:

- Telemetry recall from the central database,
- Automated analysis and trending,
- Telemetry state verification,
- MRO data recall from the central database,
- Analysis of spooler files.

5.1. Telemetry Recall from the Central Database

The most important SFOC tool developed for data analysis on the Magellan program has been the capability to query data from the Central DataBase (CDB). The Magellan CDB consists of 45 days of on-line storage of channelized spacecraft engineering telemetry, DSN monitor data and associated ancillary data channels. The query capability has been set up so that any engineer from a SFOC-provided workstation can extract data concerning the spacecraft or ground activities. The SFOC-provided tools used by the spacecraft team for querying the CDB include DMDETF, DMDQMOD, and DMDQUERY. These tools allow a user to produce "canned" queries that are used repetitively or "ad-hoc" queries that are built and submitted in minutes. The user selects the desired telemetry channels and the analysis interval. The data is returned in an ASCII Data Return File (DRF). This DRF can then be input to any one of numerous analysis programs or may be used as a stand-alone tool for data analysis.

5.2. Automated Analysis and Trending

Although the CDB query capability itself has been extremely useful, it became apparent that the Magellan spacecraft team analysts were performing a variety of repetitive queries and analysis during their daily and weekly routines. To make better use of an analyst's time these repetitive tasks have been automated using Unix-based scripts. This automation allows the analyst to perform additional mission analysis and anomaly resolution. The majority of the automation tools consists of scripts written in AWK, PERL, CSH, SH, etc, ... and some "C" code. The automated tasks were derived from manual tasks allocated to each subsystem in flight team procedures. The tasks were performed manually until they were well understood and then the engineers constructed a tool to carry out the task. It is important to note that the subsystem engineers performed their own coding since the spacecraft team did not have a dedicated software staff. One example of an automated script is the engineering telemetry long-term trending script. The first step in this script is to query the desired analog telemetry (temperatures, voltages, currents, etc.) over a specified interval, usually 24 hours. The script uses the resultant DRF to calculate the minimum, maximum, average and standard deviation for each telemetry channel over in the entire length of the file. These statistics are then appended, along with a time stamp, to a set of long-term channel trend files. There is a channel trend file for every telemetry channel of interest. The result is a set of long-term trend files that contain trending statistics for each 24 hour period from the beginning of the mission for each channel of interest. These trend files are formatted like DRFs which allows them to be plotted and analyzed using the same tools used to plot and analyze DRFs. Therefore, the trend files are used for analysis and are periodically plotted against long-term predictions using VMPLOT. An example would be to plot the actual long-term solar panel maximum current trend versus predicted solar panel current to quantify panel degradation over the life of the mission. The process outlined above has been fully automated with use of "perpetual" scripts. A "perpetual" script performs its task and then re-submits itself to run again at the next specified interval, without any operator intervention. For instance, once a day an automated script queries the desired channels to be trended and re-submits itself to run the next day. One other advantage of the automation scripts is their ability to run during early morning hours when system loading is low.

5.3. Telemetry State Verification

Originally Magellan did not have the capability to autonomously track spacecraft states. All critical component state tracking was accomplished by engineers from each subsystem manually recording their individual subsystem states in a spacecraft state table. However, soon after launch, the spacecraft team developed the ability to autonomously extract all spacecraft states that are telemetered. The spacecraft team created a Unix script entitled "Moose Query" which queries all Magellan telemetry and produces a summary report of all spacecraft states. Although this report is still compared manually to a table of expected spacecraft states, it greatly simplifies collection and recording of the approximately 1000 spacecraft states.

In addition to the state reports, moose query also produces plots of all analog data and tabular printouts of all status information over a user selectable time range. Since all spacecraft telemetry is either plotted or printed, this tool proved valuable during anomaly investigations. Following critical anomalies, a moose query would be submitted and the engineers would receive a copy of the output within hours for review. It should be noted that many anomalies were resolved by data from telemetry channels showing anomalous indications but were not immediately thought to be related to the anomaly.

5.4. MRO Data Recall from the Central Database

In addition to storing engineering telemetry, the CDB also has the capability to store MRO data for retrieval at a later date. The MRO query utility allows the engineer to retrieve memory readouts received from the spacecraft for any of the on-board computer memories. The user supplies the desired memory device, the start and end addresses, and the begin and end times of MRO collection. The MRO utility queries the CDB and returns an ASCII file identifying address and the memory contents at that address. This return file is utilized by the spacecraft team analysis programs, MEMANAL, VMPTRK, CHKSUM, and VMFLOAD to verify the contents of on-board memory and to verify flight software parameter values. Once the MRO is verified to be correct, the file is catalogued as the current updated ground memory mask. This mask is used as a baseline if an on-board computer memory ever needs to be reloaded. This process was used to reload AACS "Memory B" after an address bit failed in one memory bank shortly after Venus orbit insertion.

5.5. Analysis of Spooler Files

SFOC can also produce spooler files of telemetry data. These spooler files represent a collection or a stream of telemetry for a selected time period. The files are expanded to include all telemetry and ancillary information such as header data, monitor data, quality flags, etc. The processing of these spooler files is most easily done using a SFOC-provided utility called BROWSER. BROWSER allows an engineer to review spooler files and analyze the content for correctness. BROWSER has the capability to build templates that a) display data in a certain orientation, or b) filter through a spooler file displaying only the data that match predefined conditions. The capability to produce and analyze spooler files has proven useful for the Magellan flight team when troubleshooting problems with the telemetry stream. For example, the use of spooler files and BROWSER allowed spacecraft analysts to isolate and provide solutions to a radar telemetry spiral wrap anomaly. A "raw" spooler file and a "channelized" spooler of the same data were compared using BROWSER. From this analysis it was concluded that the ground decommutation process was working correctly and the problem was isolated to a timing problem within the radar, which has since been corrected. BROWSER was also used extensively to isolate the on-board tape recorder problems.

6. SUMMARY

SFOC has provided some extremely powerful analysis tools. The DMD provides enough flexibility to meet the dynamic real-time analysis needs of each individual subsystem and, although considered "Expert Friendly", it does not constrain the user as do many sophisticated graphical user interfaces. The capabilities and flexibility of the CDB query process have significantly contributed to the success of the Magellan mission. The versatility and flexibility of the SFOC tools and Unix have allowed the spacecraft team to build software and scripts "on top of" SFOC tools to provide automation and remove manual burdens from the analysts. Although the SFOC tools experienced some growing pains, the SFOC development staff has always responded well to problems and suggestions. Being involved in the development and use of SFOC has been a rewarding experience.

7. REFERENCES

1. Miller, D., Palkovic, L., Edwards, C., "Space Flight Operations Center User's Overview", July 1991, pages 1-6.

8. ACKNOWLEDGEMENT

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