Automation of the Far Ultraviolet Spectroscopic Explorer (FUSE)

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Abstract - As satellite program budgets become tighter, automation both in flight and on the ground has become crucial for maximizing the return on mission objectives. Automation can result in enhanced safety and more effective use of the vehicle while lowering costs throughout the operational phases of the mission. Often, programs can extend the useful life of a satellite through autonomous fault management and adaptability in handling failures of aging hardware.[1]

The Far Ultraviolet Spectroscopic Explorer (FUSE), an astronomy satellite mission developed and operated for NASA by the Johns Hopkins University (JHU) is designed to explore the origins of the universe. FUSE makes extensive use of automation on both the satellite and throughout the ground system. As the program moves into an extended mission phase, the FUSE team has enhanced automation further to reduce costs and improve scientific return.

This paper will concentrate on the automation of the Satellite Control Center (SCC) and the Instrument Data System (IDS) but will describe features of other major areas as they apply.

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1 INTRODUCTION

The Far Ultraviolet Spectroscopic Explorer (FUSE), a NASA *Origins* mission, is designed to investigate basic astrophysical processes related to the formation and development of the early Universe, as well as the origin and evolution of the galaxies, stars, and solar systems. FUSE complements the Hubble Space Telescope by extending observations to shorter ultraviolet wavelengths. This scientific program is performed via high-resolution (R=20,000) spectroscopy in the far ultraviolet (905-1187Å) wavelengths on a wide range of astronomical targets.

The FUSE satellite was placed into low-earth orbit on a Boeing Delta-II launched from Cape Canaveral on June 24, 1999. The mission orbit is circular with an altitude of 768 km, inclined at 25 degrees to the equator. FUSE is operated as a general-purpose observatory with proposals evaluated and selected by NASA.[1]

2 FUSE SATELLITE

The FUSE satellite consists of a spacecraft bus assembly, referred to in this paper as the spacecraft, and the science payload, a far ultraviolet telescope referred to as the instrument. The instrument is mounted on top of the spacecraft bus assembly and together they form a combined entity termed the FUSE satellite. The satellite is roughly 5.3 meters tall, 1.9 meters in diameter, and weighs approximately 1360 kg.

Figure 1: The FUSE Satellite During Launch Preparations

A picture of the FUSE being prepared for launch at Cape Canaveral launch site is shown in Figure 1.

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The Spacecraft

The spacecraft, developed by Orbital Sciences Corporation, consists of five basic subsystems: Attitude Control System (ACS), Power, Command and Data Handling (C&DH), Radio Frequency (RF), and Thermal.

The ACS provides autonomous 3-axis control of the satellite and maintains inertial pointing to < 2 degree (coarse pointing) and controls to < 0.5 arc second with the instrument fine error sensor. The ACS subsystem consists of two 3-axis Ring Laser Gyro Inertial Reference Units, two 3-axis magnetometers, two Coarse Sun Sensors, three dual winding magnetic torque bars, and four Reaction Wheel Assemblies. ACS control algorithms are implemented in flight software running on an 80386-flight computer.

The power system for FUSE contains the Power System Electronics, two redundant batteries, a dual panel solar array, and the spacecraft electrical harness. The Power System Electronics includes protection circuitry, battery state of charge control circuitry, and provides power to all satellite loads. During the mission, the solar array is articulated to the sun autonomously by the ACS subsystem.

The RF communications subsystem consists of two redundant S-band transponders and associated antenna diplexers, a 180-degree hybrid, and two omni-directional antennas. The RF subsystem provides command reception and delivery to the C&DH, and telemetry modulation and transmission to the ground. Command reception is fixed at 2000 bps while telemetry transmission can be at one of four commandable telemetry rates. These rates are 8 kbps, 16 kbps, 32 kbps, and 1024 kbps. Routine operations utilize the 1024 kbps rate to telemeter recorded housekeeping and science data.

The C&DH subsystem provides redundant hardware and the software necessary to receive, validate, and distribute satellite commands; collect, format, encode, and transmit to the ground telemetry data; maintain and distribute spacecraft time; store and execute time tagged commands; and provide on-board telemetry data storage. The C&DH subsystem is a packet driven system and adheres to the Consultative Committee on Space Data Systems (CCSDS) recommendation for Advanced Orbiting Systems.

The Thermal subsystem maintains components and interfaces within acceptable temperature ranges during all mission modes. The system provides conductive and radiative interfaces for the FUSE spacecraft housekeeping components. The Thermal subsystem design includes thermostatically controlled heaters, a thermal louver, temperature sensors, and thermal coatings and blankets.

The Instrument

The instrument is comprised of four co-aligned telescope mirrors; four Focal Plane Assemblies, each of which contains three science apertures; four spherical, aberration-corrected holographically-recorded diffraction gratings; and two micro-channel plate detectors with delay line anodes. A visible light Fine Error Sensor CCD camera supports sub-arc second pointing of FUSE.

The four-channel design was chosen to maximize the telescope collecting area and keep the gratings to a reasonable size while fitting within the limited constraints of the launch vehicle. It is a very robust design, since nearly the entire wavelength region is covered by more than one channel, and the important 1000 - 1100 Å region is covered by all four.

Light from each telescope passes through a selected aperture in the focal plane assembly. The apertures include a narrow (1.25 x 20 arc second) slit that guarantees the highest spectral resolution at the cost of some effective area. A wider (4 x 20 arc second) slit which passes essentially all the light from a stellar source and can be used for extended objects, and a large square (30 x 30 arc second) slit. After passing through the slits, photons pass into the spectrograph cavity, where the gratings disperse them.

Two primary mirrors are coated with silicon carbide (SiC) and two are aluminum over coated with lithium fluoride (LiF). Light from two channels, one SiC and one LiF, are dispersed onto separate areas on each of two detectors. The detectors are photon counting micro-channel plate detectors with double delay line anodes, and they have an active area of 179 x 10 mm.

The IDS contains two electronics modules, one being reserved as a spare, has not been powered on while in orbit. The central processing unit, a Motorola 68020 has 1 megabyte of random access memory and 48 megabytes of bulk memory. The IDS communicates with the spacecraft bus and other local processor via two MIL-STD-1553B databus connections. One is used for the spacecraft bus and another for the local IDS processors such as the Fine Error Sensors (FES) and the detectors. For collection of high rate photon (science) data, the IDS uses a high-speed RS-422 serial interface connection with the detectors.

The IDS flight software runs on the VRTSsa™ real time operating system. The IDS flight software is a combination of COTS products and custom code. The IDS flight software is responsible for all instrument operations including communications with the spacecraft bus during slews and fine pointing. Major tasks include 1553B databus interfaces, collection of science data, real time and stored commanding, thermal control, bulk memory scrubbing, and time synchronization with the spacecraft bus.

Because of the complexity of IDS-controlled science observation sequences and the fact they must occur autonomously and be robust to failures, the flight software does not simply operate by executing stored command sequences.[2] Instead the IDS software incorporates a commercial off the shelf (COTS) product, Spacecraft Command Language, that provides script interpretation, rule evaluation, and flight database functions.[2] These features were used to control instrument science observation activities and to implement instrument health and safety.[2]

Spacecraft Command Language

Spacecraft Command Language (SCL), a product of Interface and Control Systems, Inc., was chosen as the key component in three major aspects of the FUSE project. As mentioned, it runs as part of flight software onboard the FUSE Instrument Data System (IDS). It also is the core software component of the instrument test bed. The instrument test bed was used during the integration and test phase and is currently in use in testing and validating flight scripts. Finally, SCL is the core software of the FUSE Satellite Control Center. As part of these three major subsystems, SCL has played an important role in automation of FUSE.

SCL is a fifth generation language system designed as a command and control solution for embedded applications with a history of successful use in the aerospace industry. SCL has extended fourth generation language capabilities, i.e., a high level procedural programming language (scripting) component, a rapid application generation capability, and persistent data storage (database) component, with an artificial intelligence (AI) or knowledge management component. SCL is a rule-based expert system that provides the ability to develop a knowledge base (in the form of SCL scripts and rules) that can be used to automate satellite command and control.

SCL consists of three main components:

- A database residing in RAM (typically shared memory) that can hold data such as telemetry mnemonics (sensor, relay, and other types of spacecraft parameters), global variables, and command packets.
- The final component and the core of SCL is the SCL Real Time Engine (RTE). The RTE is responsible for evaluating rules and executing scripts.
- The data decommutation process, named "DataIO". DataIO is responsible for extracting packetized data and placing it in the SCL database. As part of the decommutation process, DataIO performs functions such as limit checking and engineering unit conversions. If necessary, DataIO notifies the RTE of changes to the SCL database items.

3 FUSE GROUND SYSTEM

A dedicated ground station located at the University of Puerto Rico, Mayaguez (UPRM), provides primary telemetry and command operations. The UPRM ground station is a Low-Earth Orbit Terminal (LEO-T) design developed by Honeywell Technology Solutions, Inc. of Columbia, Maryland. A second LEO-T at Wallops Flight Facility in Virginia and the Universal Space Network (USN) Hawaii station provide backup ground station support. In addition, NASA's Tracking and Data Relay Satellite System (TDRSS) provides emergency support. Each ground station interfaces with the FUSE Satellite Control Center (SCC) over leased Integrated Services Digital Network (ISDN) circuits.

All telemetry data is sent from the ground station to the SCC in a priority order with the real time data receiving highest priority. The stored satellite housekeeping and science data is forwarded to the SCC at lower priorities. Transmission of the science data to the SCC is initiated during a real time pass, and continues after a pass is completed. File transfer to the SCC continues post-pass until all data acquired by the ground station have been transferred.

The Low Earth Orbit Terminal

The system is designed for autonomous, low-cost operation. The UPRM LEO-T station is completely unmanned, and is operated by the operations team remotely from the SCC. LEO-T interactive operation is through a standard UNIX X-Window user interface. Control of the LEO-T is achieved through a combination of Unix shell scripts, and procedures written in EPOCH 2000™ Systems Test and Operations Language (STOL). STOL procedures used for normal and contingency operations were developed and validated by the operations team during the pre-launch mission phase. The LEO-T has been enhanced to support automation.

A LEO-T feature FUSE has exploited is the Store and Forward (SAF) commanding capability. This capability allows pre-generated commands to be time tagged and scheduled for uplink. The SAF command loads are prepared in the SCC and transferred to the LEO-T for up-link during a subsequent pass.

FUSE Satellite Control Center

The FUSE satellite is operated from a dedicated Satellite Control Center (SCC) located in the Bloomberg Center for Physics and Astronomy on the Homewood campus of JHU in Baltimore, Maryland. The FUSE SCC is a custom control center developed for the FUSE project by Interface & Control Systems, Inc. using commercially available hardware and a combination of COTS software products and custom code.

Figure 2: The FUSE Satellite Control Center

The basic SCC is a distributed computing environment. It consists of: 14 Sun workstations, a 360 gigabyte Redundant Array of Inexpensive Disks (RAID), 1 digital linear tape (DLT), 3 ISDN router modems, 2 global positioning system receivers (GPS), two CRT video projectors, and 3 printers including a Hewlett Packard Color LaserJet 5M. A picture of the SCC is shown in Figure 2.

While not fully CORBA compliant, the backbone of the SCC is a combination of Orbix, Orbix Talk, and Network Data Delivery System (NDDS). Orbix and Orbix Talk handle the slower inter-process communication and control while the higher speed data transfer for telemetry display on remote workstations is handled by NDDS.

The core of the SCC software is SCL in the same basic configuration as described above. In addition, there is software to perform command generation (cmdgen), extract packets from virtual channel data units (VCDU) or frames, to provide interface to the ground stations, perform frame accounting (VCDUGUI), archiving, trending, etc. More details on the development and structure of the SCC are given by Calk and Silva [4]. Details on the operation of the FUSE ground system are given by Calk and Silva [4]. Details on the operation of the overall FUSE mission are being presented at this meeting by Moos [5].

4 AUTOMATION

There are three primary requirements driving the automation of FUSE. The first and foremost, has been to maximize the mission objectives (science return). The second is to minimize impacts from anomalies that were inherent to the satellite design/construction or have occurred during the satellite's operation. The third is to prepare for operations under a reduced budget during an extended mission phase. Each of these will be discussed in detail below.

Maximizing Science

Due to the low-Earth orbit and contacts limited to one primary ground station, the FUSE satellite was designed for autonomous operations. The orbital period is approximately 101 minutes and with the one ground station there are typically only 7 contacts per day the longest about 12 minutes. This leaves FUSE out of contact for a continuous 12-hour period each day.

The design of the IDS had to account for both extended periods of autonomous operation and limited uplink opportunities. The IDS uses a combination of permanently resident SCL flight scripts and observation scripts. A single resident control script manages execution of up to 14 observation scripts. SCL variables and flags maintain the execution state for the observation. Once an observation has finished, the variables and flags are updated and the control script moves on to the next observation. The observation scripts are typically uploaded about 2 days in advance. For the extended mission, the maximum number of observation scripts has been increased to 24. This will allow enough observation scripts to be loaded to cover unattended weekends and holidays.

The creation of observation scripts starts with the mission planning team. The FUSE mission-planning team performs all long and short-term planning. Selected observation proposals are verified for accuracy and maintained in a master planning database. Long term planning is performed by software called SPIKE obtained from the Space Telescope Science Institute and modified to work for FUSE. Once a long-term plan has been developed it is used by software developed at JHU to produce a short-term schedule and ultimately a Mission Planning Schedule (MPS) file.

The MPS is the primary interface between the SCC and mission planning. The MPS is a schedule containing blocks, activities, events, and tables necessary to complete the exposures that make up a science observation.[3] A portion of an MPS is shown in Figure 3. The MPS is passed along to the SCC where it is ingested and converted into SCL flight observation scripts.

The conversion of the MPS into flight scripts is performed by custom software called Autogen. Each MPS record maps one to one (in most cases) to a template. Templates are SCL script code that contain the instructions to perform that particular event or activity. Templates may contain embedded keywords or tags. During processing, Autogen replaces each tag with appropriate data from an MPS record. Autogen assembles templates into a complete observation script based on records included in the MPS.

Planners, mission scientists and operations team personnel subject the Autogen produced observation scripts to an extensive review. After passing review, the observation scripts are compiled into a project that is scheduled for up-link. Projects are sets of compiled SCL scripts and rules and are up-linked in a manner similar to table loads and memory loads, i.e., they are segmented into pieces and sent as multiple commands. Once onboard, the pieces are extracted from the commands and reassembled.

Handling Anomalies

Handling anomalies in an automated way onboard can frequently contribute to an increase in science return. The FUSE IDS uses SCL extensively for onboard fault detection and correction.

FUSE is using SCL to detect and correct single event upsets (SEU) in one of its main instrument computers that control the ultraviolet detector. A SEU is memory corruption that occurs when a particle of radiation impacts computer memory causing a bit to change state potentially rendering the software code useless. Typically, SEUs occur when the spacecraft is traveling through areas of high radiation such as the South Atlantic Anomaly (SAA) where the Earth's radiation belt dips low enough that FUSE passes through it. A software watchdog monitors the critical detector code. A SEU in the critical portion of code causes a watchdog reset while an SEU in a non-critical portion of code results in the detector running on corrupt code. Since the detector code monitors and controls the high voltage power supply, this was placing the detector at risk.

FUSE experiences an SEU in the detector about once every 4 days. Aside from the risk, this was having an adverse impact on FUSE science efficiency. Obviously, any observation underway when a watchdog reset occurs would be aborted and lost. Each day FUSE enters a 12-hour "blackout" period where there are no contacts with the ground. Initially, the mission operations team handled recovery from watchdog resets manually so a reset during the "blackout" could result in the loss of up to a full day of science observations.

```
record_type      = MPSHDR
  create_date      = 2002:012:12:59:22
  start_time       = 2002:016:09:54:44
  end_time         = 2002:023:05:10:53
  orbit_start      = 8244
  orbit_end        = 8312
  lrp_name         = CYCLE3
  lrp_date         = 2002:336:00:00:00
  lrp_verify       = true
  gs_cont_file     = gsc_2002_015_08213.01
  orbit_vec_file   = fuse.tle
  sys_cond_file    = fsyscond_2000_256_06575.01
  mps_id_number    = 240
  initial_data_vol = 6.5
  alignment_file   = mps240.align
  last_align_beta  = 71.23125
  last_align_pole  = 138.05981
  last_beta        = 62.12523
  last_pole        = 128.13523
  active_fes       = FESA;

! --------------------------------------------

! TTAG observation in LWRS; FES exposure taken
! at end of observation
! with target at RFPT.

  record_type      = FUVOB
  block_num        = B001
  start_time       = 2002:016:09:54:44
  end_time         = 2002:016:15:14:11
  comment          = "FUV observation block"
  num_blk_elm      = 15;

  record_type      = ICSA
  structure_id     = B001A01
  start_time       = 2002:016:09:54:44
  duration         = 30
  orbit_start      = 8244
  comment          = "Config. Setup Activity"
  program_id       = P190
  target_id        = 01
  object_name      = PG0832+675
  obs_id           = 01
  req_obs_time     = 10000
  obs_case         = 1
  fes_case         = YES
  fps_case         = 0;
```

Figure 3: Sample MPS
The MPSHDR is an MPS header record, the FUVOB is a block record, and the ICSA is and activity record.

To minimize the risk and impact to science observations, SCL scripts and rules were developed to autonomously detect SEUs and take corrective action thereby minimizing the detector down time. This all takes place without any interaction from the ground.

There are two areas in computer memory where the detector software can run called upper and lower core. Each has its own error detection process that computes individual cyclic redundancy check (CRC) bytes. Normally, the detector code runs in the upper core while a copy of the detector code is maintained in the lower core as a backup. SCL rules have been developed to monitor the CRC byte in the upper core. A change to an invalid value in the CRC byte triggers a rule that in turn executes SCL scripts to verify the lower core CRC byte. If the lower core verifies, detector code execution is restarted in the lower core and a reload or recovery of the upper core is initiated. Once the upper core has been reloaded and verified, SCL switches the detector code execution to the upper core restoring its normal configuration. This autonomous code repair is typically performed within 2 to 3 minutes with virtually no impact to science data collection.

Should both the upper and lower core experience a corruption, SCL scripts initiate a reset of the detector that reloads both the upper and lower core software. All of this takes place with no intervention from the ground.

SCL is utilized in other areas for automation. The Fine Error Sensor (FES) is a star camera used to track targets for observation by FUSE. The FES gradually accumulates contaminants that result in "hot" pixels. These hot pixels will ultimately degrade its performance.

One way to recover some of the hot pixels is to perform an annealing operation where the pixel array is heated over a period of time to "bake out" contaminants. During initial annealing experiments, it was determined that the heater is apparently oversized for the job. Further complicating matters is the fact that there is no thermostat to control the heaters. This results in the heaters driving the temperature above the high temperature limit of the FES and triggering an automatic heater shut down that aborts the annealing sequence. Because FUSE is out of contact with the ground most of the time, it has been difficult to maintain the annealing temperature for the required duration.

SCL scripts and rules have been developed to act as a thermostat. The temperature of the pixel array is monitored by SCL rules. SCL autonomously cycles the heaters on and off to maintain an appropriate temperature range for the specified duration. Again, this is accomplished with no intervention from the ground.

Extended Mission Phase

The 2002 NASA Senior Science Review has recommended an extension of FUSE operation through fiscal year 2006. The primary goal for automation during the extended mission is to maintain all critical scientific capabilities of the satellite and produce the maximum amount of science possible on a reduce budget.

The extended mission "belt tightening" will necessitate a reduction in the mission operations staff. The FUSE program plans to minimize the impact by moving to autonomous "lights out" operations during nights, weekends, and holidays. To this end, the FUSE SCC software has been enhanced to support this mode of operation.

To minimize costs, SCC automation relies heavily on the use SCL expert system capabilities. Development and modification of custom software was limited to that necessary to support the implementation of SCL scripts and rules. The extended mission automation strategy is summarized below:

- Enhance the communication between the SCC and the LEO-T;
- Enhance SCC software and develop an SCL automation knowledge base, i.e., SCL scripts and rules to perform the core SCC automation;
- Enhance the SCC event message monitoring to include a paging notification system;
- Refine limit violation parameters and error message generation, both onboard and on the ground, to include only critical problems;
- Provide limited secure external access to the SCC so that operations team members can remotely assess status and the nature of problems with the satellite or ground system.

The SCC and LEO-T - Adding an additional socket connection to the LEO-T enhanced the SCC front-end interface software. The new socket supports the Remote User Client (RUC), a new capability developed on the LEO-T to support automation. The RUC socket supports two-way communications between the SCC and the LEO-T. Commands can be sent to the LEO-T in the form of STOL directives. The LEO-T responds with an acknowledgement. The LEO-T response is stored in the SCL database so that it can be monitored by rules in the SCL knowledge base.

The FUSE program has always made extensive use of the SAF Capabilities of the LEO-T (see *"The Low Earth Orbit Terminal"* section above for information on SAF). Downlink of event message buffers, playback of the solid-state recorders (SSR), and loading of the FUSE orbit vector are all managed through SAF files. FUSE automation expands the use of SAF.

The Satellite Control Center[*] - SCC software was modified to support implementation of SCL scripts and rules to run the control center during "lights out" operations. In general most automation is also operational during staffed operations but is monitored by the console operators. Certain operations such as project loads are still performed manually.

Modifications to the SCC software included a process called the Ground Station Pass Process (GSPassProc). Input to GSPassProc is a ground station schedule file that is created by the mission operations team planners using the COTS product Satellite Tool Kit (STK). The schedule file contains AOS and LOS times for each scheduled ground station. GSPassProc uses its input to update ground station pass information in the SCL database. The information maintained in the SCL database is used to trigger rules that set up for a pass, perform pass operations, and perform post pass operations. The following shows the information maintained by GSPassProc:

- A timer; counts down to AOS and once pass has started, counts up to LOS;
- The next ground station (UPRM, USN, Wallops, etc);
- A pass flag (indicates true between AOS and LOS).

Based on the information maintained by GSPassProc, rules in the SCC knowledge base run scripts to configure the SCC for the upcoming pass. The LEO-T configures itself based on schedule information loaded by the SCC planners. The SCC waits for telemetry to arrive. Telemetry is verified by monitoring critical telemetry items such as the sequence counter for the packet count mnemonic. Telemetry mnemonics generated by both the satellite and the LEO-T are monitored so that the root cause of any in receiving telemetry problems (LEO-T or SCC) can be determined and appropriate actions initiated. Once telemetry has been verified, rules trigger to configure the LEO-T for commanding.

The LEO-T supports three types of forward link sweeps, coherent, non-coherent, and CCSDS Command Link Control Word (CLCW) Sweep. Both coherent and non-coherent sweeps are open loop and terminate based on predetermined sweep duration. For these sweeps, there is no verification that the spacecraft receivers are locked. After the preset time expires, the LEO-T enters a "go for command" state. On the other hand, the CCSDS/CLCW sweep is closed loop. The CLCW is transmitted by the spacecraft and contains commanding status information. The CLCW is interrogated by the LEO-T to verify spacecraft receiver lock before terminating the sweep and entering the "go for command" state. FUSE uses the CCSDS/CLCW sweep.

To support "lights out" automation and improved reliability, the "go-for-command" evaluation is performed by SCC software and uses spacecraft receiver lock and automatic gain control telemetry. Once the SCC software has determined a "go-for-command" status, a LEO-T STOL procedure is called for execution via the RUC interface. This procedure terminates the forward sweep, enables forward link modulation, and connects the command socket to the control center. The LEO-T FOP (frame operating procedure) state is then switched to active and spacecraft commanding is possible. This method assures that no commands, either from the SCC or from a SAF file, are up-linked before the spacecraft receivers are locked.

[*] The author would like to acknowledge Christopher Silva the FUSE Mission Operations Team Lead for contributions to this section.

Once the LEO-T is in the "go-for-command" state, scheduled SAF files are executed. Commands are sent to the satellite to turn on the SSRs and begin down loading spacecraft event messages (virtual channel 5) and SSR data (virtual channels 1 through 4). Once the SCC has verified the SSR is on, retransmit commands generated during the previous pass (if any) are sent and the recorders are released so they can accept fresh data.

The LEO-T checks telemetry (both real time and recorded) for bad data and sends only correct complete frames to the SCC. Any bad or missing frames is reported to the SCC in the form of gap status packets. Each gap status message reports missing frame(s) by providing the sequence count of the last good frame followed by the sequence count for the next good frame received. In the SCC, the VCDU Graphical User Interface process (VCDUGUI) processes the gap status packets.

VCDUGUI has been modified to support automation and now has two modes, a manual mode and an automatic mode. In manual mode, VCDUGUI displays the gap information for each virtual channel as ranges of missing frames. During a pass, the console operators select from the list of missing frames to generate retransmit command(s). Once VCDUGUI constructs a command it is sent to the command generation software and up to the satellite.

In automatic mode, gap status information is assembled and written to a file. After a pass has completed, the SCC performs post-pass processing. Scripts read the gap status files and construct retransmit commands to be transmitted at the beginning of the next ground station pass.

The SCC also performs other post-pass processing. The latest data critical to the health and safety of the vehicle is pulled out of the SCL database and written to a file as ASCII text. The text is formatted to mimic the layout of actual real time console displays in the SCC. Event messages are also assembled and formatted for external access, and finally, the SCC is configured for the next pass.

Paging Notification System – The FUSE Autonomous Notification System (FANS) is the only entirely new piece of custom SCC software developed for extended mission automation. FANS works in conjunction with a commercial paging service that provides two-way email paging capabilities.

FANS operates only during "lights out" operations and is responsible for monitoring event messages and notifying on-call operations team members via the paging system. FANS monitors ground system messages continuously but messages generated by the satellite are batched and processed after the ground station pass has completed. FANS receives all event messages and for messages of appropriate severity, such as red limit violations, it will generate an email to the paging service. The actual event message text is included in the page, and, if necessary, multiple event messages are grouped together to reduce the number of pages sent. This series of event messages (and pages) is considered an "incident". To reduce nuisance pages, FANS tracks messages for each incident and will only send one page (or set of pages) for that incident.

FANS maintains several paging lists. The primary paging list is a list of on-call operations team members. Maintained as well are one or more lists for science personnel. The operations team list always has priority, as the operations team is responsible for the health and safety of the satellite. Once FANS has generated a page(s) for an incident, FANS will wait a predetermined amount of time for an acknowledgement. After time expires, a page will be generated to the next person on the operations team list. FANS will continue to produce pages to persons in the operations team list in a round robin fashion until an acknowledgement has been received. Acknowledgements can be issued via the pager, email, or by access to FANS administration features.

FANS generates an email to each person in the science operations team list or lists. The email can go to a paging service if desired. However, no acknowledgment is expected or required and only one email per person is generated. Science personnel messages are of a "heads up" nature since only health and safety anomalies require a response during off hours.

FANS provides an administration capability. This feature can be accessed via the web and provides for page acknowledgment, page list maintenance, and the ability to filter event messages. The filter feature allows pages to be disabled for specific event messages once the operations team has addressed the problem or has determined the problem can be deferred until normal business hours. Separate filtering is provided for the operations team and science operations team.

Limit Parameter Refinement - In preparation for automation, the operations team has spent a significant amount of time in refining limit violation parameters (red low, yellow low, yellow high, and red high) for all satellite telemetry mnemonics. There were numerous mnemonics that would go into the red limit range before going truly critical. In many cases a console operator would glance at a limit violation event message and determine its real significance. The routine ones would be monitored for a continued trend and in some cases could be ignored entirely. In order for autonomous operations to realistically keep the program within an extended mission budget, it is important that on-call operations team members only be notified for truly critical incidences while still maintaining the safety of the vehicle. Refinement of the error messages has been a key step in eliminating the false and nuisance page notifications.

Remote Access to the SCC - Once an on-call operations team member has been notified of a problem via FANS, the operations team member must be able to evaluate the severity of the problem from wherever the member may be located. This will be done with information available via the World Wide Web and through remote access to the SCC software.

All event messages are available via a password protected web page. The messages can be retrieved for any time period. The messages are displayed in time ordered sequence and are color coded in the same way they are displayed on the SCC consoles. An operations team member will use this tool to view the events that lead into an anomaly. Data critical to the health and safety of the satellite (formatted at the end of each pass) is also available for external viewing via any simple text editor.

A major requirement for any type of external access to the SCC is that it must be secure. The current plan is to use Virtual Private Network (VPN) hardware. VPN is a private data network that uses standard telecommunications infrastructure such phone line modem service, DSL, or cable modem service. Privacy is maintained through a tunneling and encryption protocol. Hardware at each end of the telecommunication connection performs all of the VPN security functions and is transparent to the user. As of this writing, potential VPN hardware is still being evaluated.

In the current design, a remote operations team member would use a personal computer with VPN hardware installed and X-windowing software to provide a window environment similar to the SCC workstations. Commanding of the vehicle will not be allowed from external connections. Rather it is to be used as a tool for evaluating the severity of the problem. Decisions are then made as to the appropriate personnel needed and whether off-hours SCC support is necessary.

5 CONCLUSIONS

FUSE is nearing the completion of its primary mission. During the mission the program has used automation to increase the science return and to streamline anomaly handling. As the program heads into the extended mission phase, FUSE is coping with a constricting budget by reducing costs of operation.

Extensive and autonomous onboard fault detection and correction, automated operation of the ground system, problem notification system, and external access to critical data for problem evaluation are key features in the FUSE automation effort. By increasing the levels of existing automation in these areas, FUSE will continue to provide a significant level of science while operating on a reduced budget.

The robust capabilities of the spacecraft, instrument data system, LEO-T ground station, and the expert system capabilities of SCL, have allowed automation to be implemented at a reduced cost by minimizing the development of custom code.

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7 BIOGRAPHY

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