The Space Technology 5 (ST-5) Mission Constellation Control System & Operations Approach

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Abstract—The Space Technology 5 mission is part of NASA's New Millennium Program and is designed to demonstrate new technologies in hardware, construction, and operations that will be used as a benchmark for future NASA missions that include microsatellites and constellations. The ST-5 mission will demonstrate the ability to collect science data from a coordinated constellation of three satellites that will be managed with automation in a ground system.[1]

The ST-5 spacecraft are planned for launch in late 2004. Once the spacecraft are activated, spacecraft experiments and automated ground system tools will be tested via control from the mission operations center at Goddard Space Flight Center (GSFC). Four (4) innovations will work cooperatively to enable a reduction in operations costs with automation for the ST-5 spacecraft and as a demonstration for future NASA constellation missions. First, the use of a common ground system for Spacecraft Integration and Test (I&T) as well as Operations. Second, the use of simulation tools to determine spacecraft parameters for autonomy. Third, the integration of a graphical planning engine to drive the autonomous systems without an intermediate manual step. And fourth, the ability for distributed operations via Web and pager access.

Four (4) tools have been successfully integrated to provide autonomy and virtual control. These tools include:

- The Advanced System for Integration and Spacecraft Test (ASIST) and Front End Data System (FEDS) are a real-time command and control system, which is used in component level integration, spacecraft level Integration and Test (I&T), and on-orbit operations. Extensive savings are being realized by using the same system to gather and retain knowledge, databases, procedures and expertise from I&T through Operations.

- Simulink will provide spacecraft subsystem models, which will provide the intelligence behind planning activities with the constellation. The power margins on each spacecraft are relatively low. Therefore, each timeline's power consumption will be verified on Simulink before it is transmitted to the spacecraft. Simulink can be used in conjunction with a command management system as a planning tool.

- ST-5 will use an autonomous network scheduling tool to manage ground contacts with multiple satellites. To demonstrate larger constellations, virtual satellites and a prioritization based on a larger constellation mission will be designed and implemented.

- The Spacecraft Emergency Response System (SERS) is a configurable and robust paging and workflow system based on Lotus COTS groupware. For ST-5, SERS two-way paging is being used to allow human-in-the-loop autonomy. SERS is also being used to autonomously generate pass summaries and anomaly reports to expedite information distribution and problem resolution.

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1. INTRODUCTION

As part of the New Millennium Program, ST-5 will aim to validate in Space the new technologies associated with microsatellite design and the near Earth's magnetosphere. ST-5 is a mission that will serve to demonstrate a highly functional spacecraft that is many times smaller, requires less power and requires that the spacecraft magnetic signature stay below the sensitivity level of the magnetometer. In addition, the mission will demonstrate

[1] 0-7803-7651-X/03/$17.00 © 2003 IEEE

the ability to use many spacecraft as one scientific observatory.

Due to the small size, the available area for solar arrays and the battery is relatively small; therefore, ST-5 operations will be limited by the available power and is a major concern. ST-5 operations will manage the power loads with mission planning tools on the ground and utilize the on-board load shedding capability as a fail-safe. During load shedding, all non-essential loads will be turned-off so that the solar array energy can be used to recharge the battery. The battery is also required to provide power in addition to the solar arrays during contacts with the spacecraft due to the transmitters operational requirements. The power management tool on the ground will verify the spacecraft power system's performance before a timeline is executed on board the spacecraft.

As a demonstration to fly many spacecraft to act as one observatory, ST-5 will launch 3 spacecraft into orbit simultaneously. Future larger missions are expecting to fly between 50 to 100 spacecraft and this creates a new challenge to operate a mission without increasing the size of the operations team in proportion to the number of satellites. With 25 to 50 spacecraft per ground stations, one of the primary concerns is the capability to dynamically change the ground station schedule. Other concerns include configuration management, trending for health and safety maintenance and mission planning to ensure that the operations of the constellation for science as well as the health status of each individual spacecraft.

Many believe that automation is necessary to operate a large constellation at a manageable cost. In addition, many believe that by maintaining resources from the design phase, integration and test and through operations can help reduce costs, schedule, and risks. ST-5 will demonstrate a new level of ground system automation by integrating four separate systems that are available commercially and have proven track records on other GSFC NASA missions. In addition, ST-5 will demonstrate a current GSFC practice of maintaining the same ground system and operations team from the integration and test phase through on-orbit operations.

Each ST-5 spacecraft and mission parameters are as follows:

- Mass: < 25 kg
- Size: 26.6 cm (H) x 50.8 cm (W)
- Solar array power at EOL: 18 W
- Planned orbit: Highly eccentric Geosynchronous Transfer Orbit (GTO) with perigee of 200 – 350 km and apogee of 34,500 – 38,000 km
- Space transport: Secondary payload
- On-orbit operations duration: 3 months
- Science instrument: Low mass, low power magnetometer
- New Millennium Program specific technologies to be flight validated:
    - Digital X-Band Transponder
    - Miniature Cold Gas Thruster
    - Lithium Ion Battery
    - CMOS Ultra-Low Power Radiation tolerant Logic (CULPRiT)
    - Variable Emissivity Thermal Coatings
    - Autonomous Ground Network Scheduling Software

2. Design Approach Taken to Provide Constellation Control and Operations

A major consideration for the ST-5 ground control system was how to implement a low cost system that would provide all the functionality needed to ensure the operations and safety of a constellation. To accomplish this task, it was decided to use a GSFC developed system that uses commercially available products and that has been proven on other NASA missions at GSFC which share common elements with the ST-5 spacecraft subsystems. However some of these ground system components do require modifications which are currently being implemented in a very streamlined period of time by closely working with the development teams.

The core of the control system is the Advanced System for Integration and Test (ASIST) and the Front End Data System (FEDS). Together these two components have been used on other missions to provide all of the telemetry and command functionality. However for them to work with the ST-5 project, it was necessary to increase their functionality to interface with multiple satellites so that multiple data streams can be processed and stored via a single system to best control the amount of hardware required to operate a constellation. It was also necessary to develop a new command routing interface that is capable of allowing multiple users to simultaneously send commands to different spacecraft via the same Front End. In addition to processing telemetry and commands, the FEDS was updated to store the multiple data streams based on the spacecraft identification codes. This then allows a single machine to decode, distribute, archive, and post process all of the data for the entire constellation.

Another benefit of the ASIST/FEDS architecture is that other projects at GSFC have been able to implement simple automation via procedures that are executed based on a pass plan. Thus it is necessary to have a reliable notification system to contact appropriate personnel in the event of a problem whether on the ground or on a spacecraft. For this functionality, it was decided to use the Spacecraft Emergency Response System (SERS) which already provided the ability to support multiple spacecraft. In addition to personnel notification, SERS also provides the user with automated report generation that can be viewed via the Internet.

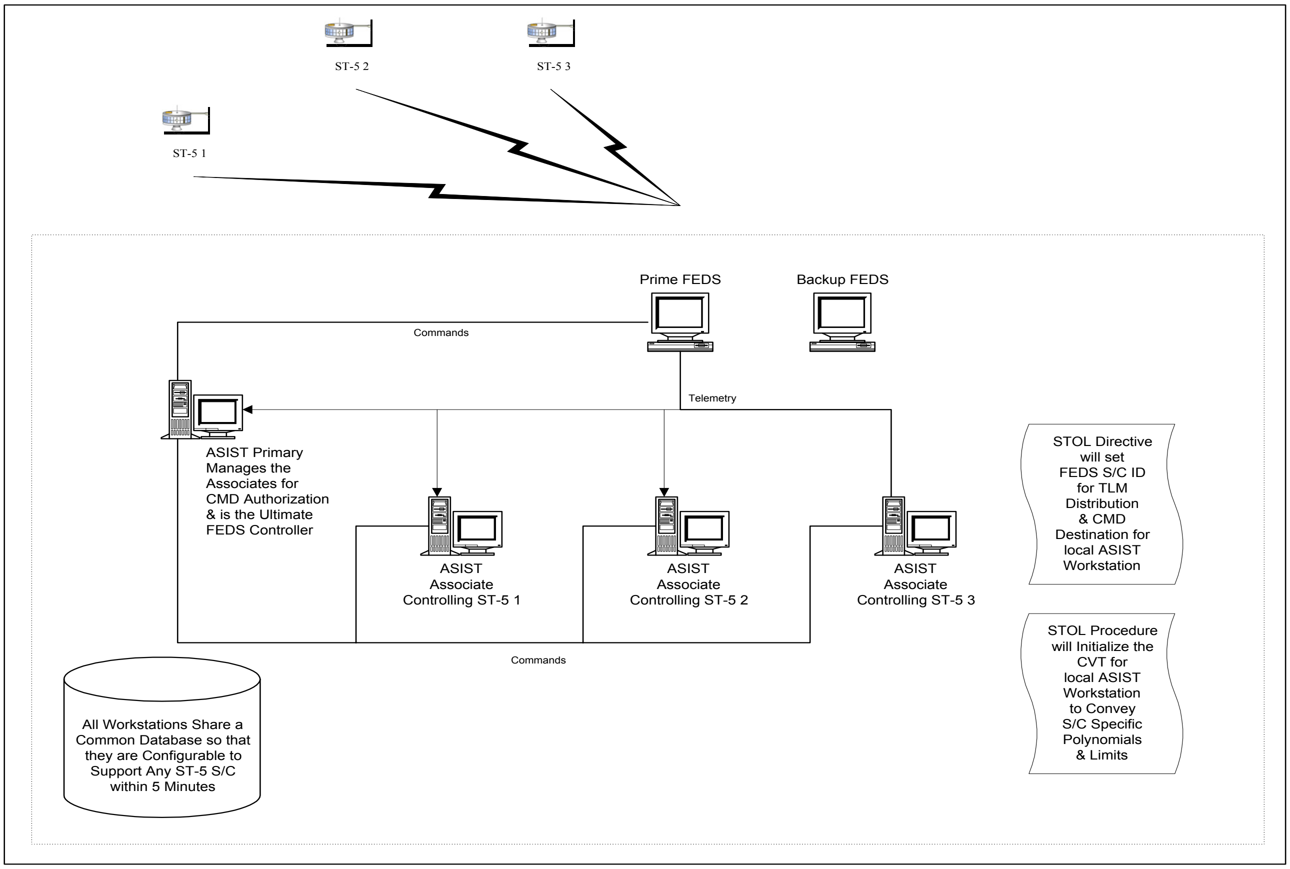

Figure 1: ST-5 ASIST/FEDS Implementation

However this still leaves the most complex part of the control system to be developed: intelligent mission planning for a constellation. Since the satellites of the ST-5 project are constrained by their power limitations, it was necessary to develop an accurate power model to ensure successful operations. To perform this task, Simulink was chosen and taken to the next level beyond the power subsystem in an attempt to create a more complete spacecraft simulator to drive operations. In addition to this simulator, a software package is under development to perform the tedious task of scheduling ground contacts with a constellation autonomously based on a number of conditions that are used to determine their priority.

3. Mission Planning as the Driver of Automated Activities

Software Spacecraft Power Model

Historically, software models have been used to "facilitate system design trade-offs, document and communicate the design configuration to the team, support subsystem and software developmental testing, support operator training, troubleshoot problems encountered during operations and to serve as a basis for future mission planning and design" [1]. If developed in tandem with the spacecraft design, the same tools can help reduce the cost and development time requirements. One more commonly used software modeling tool is Simulink which requires the MATLAB platform and are both offered by The MathWorks, Inc[1]. With these tools, one can develop a behavioral model to simulate the dynamic interactions between various subsystems in a simulated operational environment. The ST-5 power subsystem was modeled in Simulink to verify power margin and power consumption as a function of the orbital and operational scenarios in order to ensure that the spacecraft can operate at all points in the orbit throughout the 3 month mission life.

Now that these models have proven to be good tools to evaluate the designs under various conditions, these same software tools are starting to be considered for operational use, for example to troubleshoot problems during operations and to serve as a basis for mission planning. For power management in operations, the ST-5 power model will be used to ensure that the planned mission timelines will not cause the power system to enter a load shedding condition. With the help of three Worcester Polytechnic Institute

[1] MATLAB and Simulink are registered trademarks of The MathWorks, Inc.

(WPI) electrical engineering students, the ST-5 power model was examined and updated to make it more useful as an operational tool. One goal for the students was to update the model to provide feedback on orbital mechanics for sunlight/eclipse cycles and ground station availability. As a result, the students have demonstrated that the ST-5 power model is extremely flexible and can be readily modified to work more effectively with an operational approach. Figure 2 [2] shows potential operational outputs to the behavioral model which include the "eclipse regions (from operational scenarios), transmission periods, ground station visibility and the state of charge (SOC) of the battery" [2].

The plots shown in figure 2 illustrate 10 orbits in time along the x-axis and four related output items in the y-axis as follows:

1. The top plot illustrates the eclipse and sunlight periods. During the eclipse periods, only the essential loads are powered and the battery will begin to discharge.
2. The next plot indicates when the transmitter is on or off. In this scenario, the transmitter is powered immediately following an eclipse before the battery has a chance to recharge. As you can see, the transmitter electronics cause the battery SOC to drop quickly in the last plot.
3. The third plot illustrates the visibility of the Deep Space Network ground station sites (including link margins and ground antenna "look angles"). The first transmit is within Madrid's view, while the second is within Goldstone's view and so on.
4. The fourth plot illustrates the battery SOC which will be one of many indications of the power system's state of health.

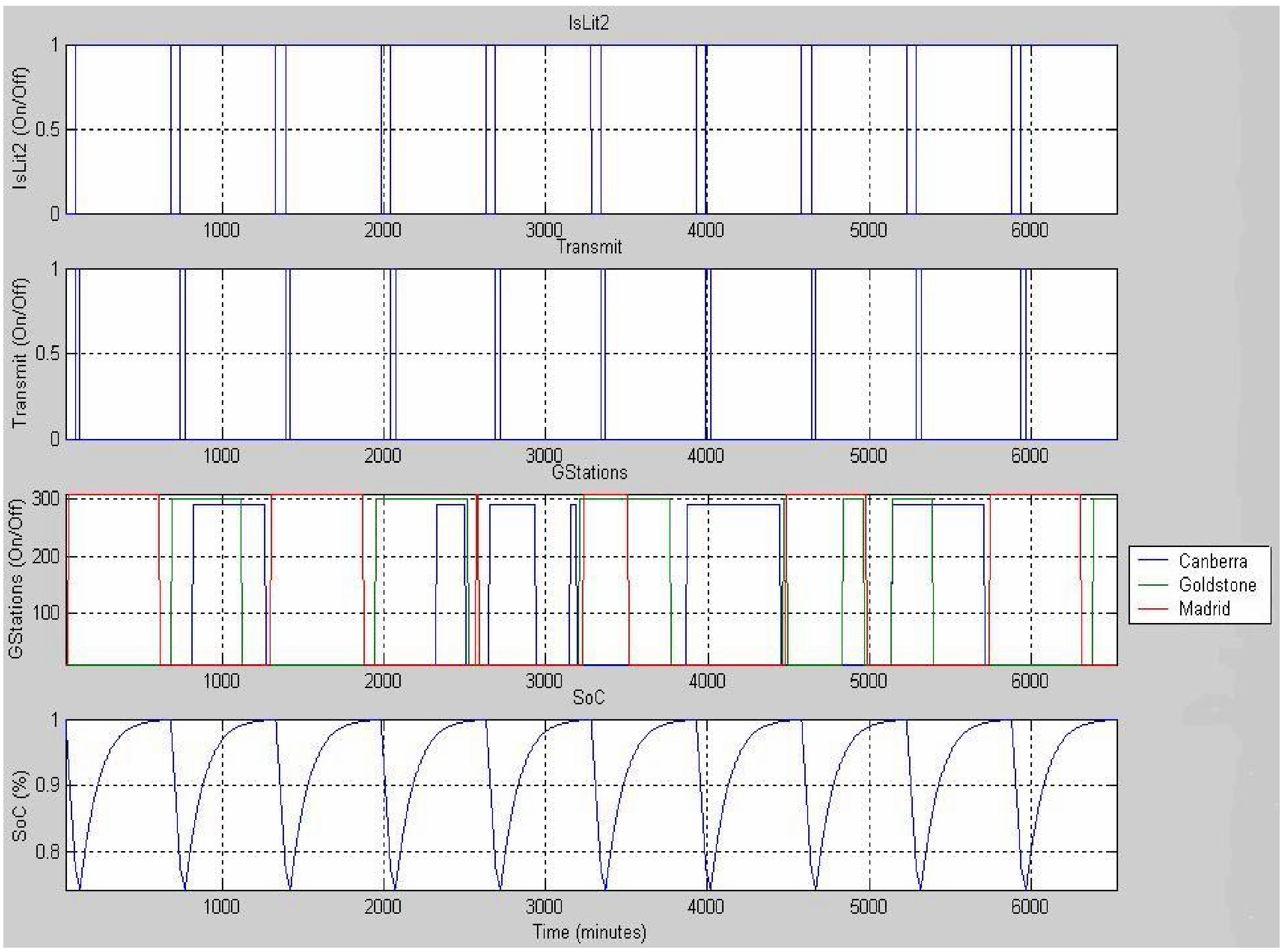

Figure 2: ST-5 Power Model Output

The data and calculations behind these plots will require a more detailed validation before being used in operations. However, the behavior of the model appears to be well represented.

During ST-5 on-orbit operations, the results of the Simulink model and actual on-orbit spacecraft data will be compared for final validation of the model. If the model and the spacecraft data compare extremely well, the Simulink model can also be used to determine the spacecraft's state of health and to investigate it under anomalous conditions. With even more updates such as programmed intelligence (ie. diagnose and repair), a command encode and telemetry decode interface, the system can correct an anomalous condition, but this is beyond the scope of the current research.

Ground Station Scheduling Tool

In addition to the ST-5 power model as a planning tool, a ground station scheduling tool will be demonstrated on ST-5. An orbit determination tool in conjunction with a scheduling tool can generate the pass support plan for each spacecraft and ground station. A suite of software tools, known as SatTrack[2], is planned to support ST-5 to demonstrate an automated scheduling system. SatTrack will create a pass timeline based on a number of constraints (not limited to), line of sight geometry, link margin based on spacecraft attitude and antenna pattern, slant range, Doppler and so on. Figure 3 is one graphical output from SatTrack which illustrates the track data from a large constellation.

The main challenge is the task of the scheduling tool to do conflict resolution by assigning priorities for pass supports. For 3 satellites in the case of ST-5, the tool should be able to work adequately. However, for larger constellations such as 50 to 100 satellites and a limited number of ground stations, orbit determination and scheduling will be a demanding task. Therefore, ST-5 will demonstrate a larger constellation by adding a number of virtual satellites and validate the software technology in a constellation operations environment. Verification of the autonomous scheduling functions will be analyzed by the amount of operator intervention that is required and the amount of data (real and virtual) that is collected.

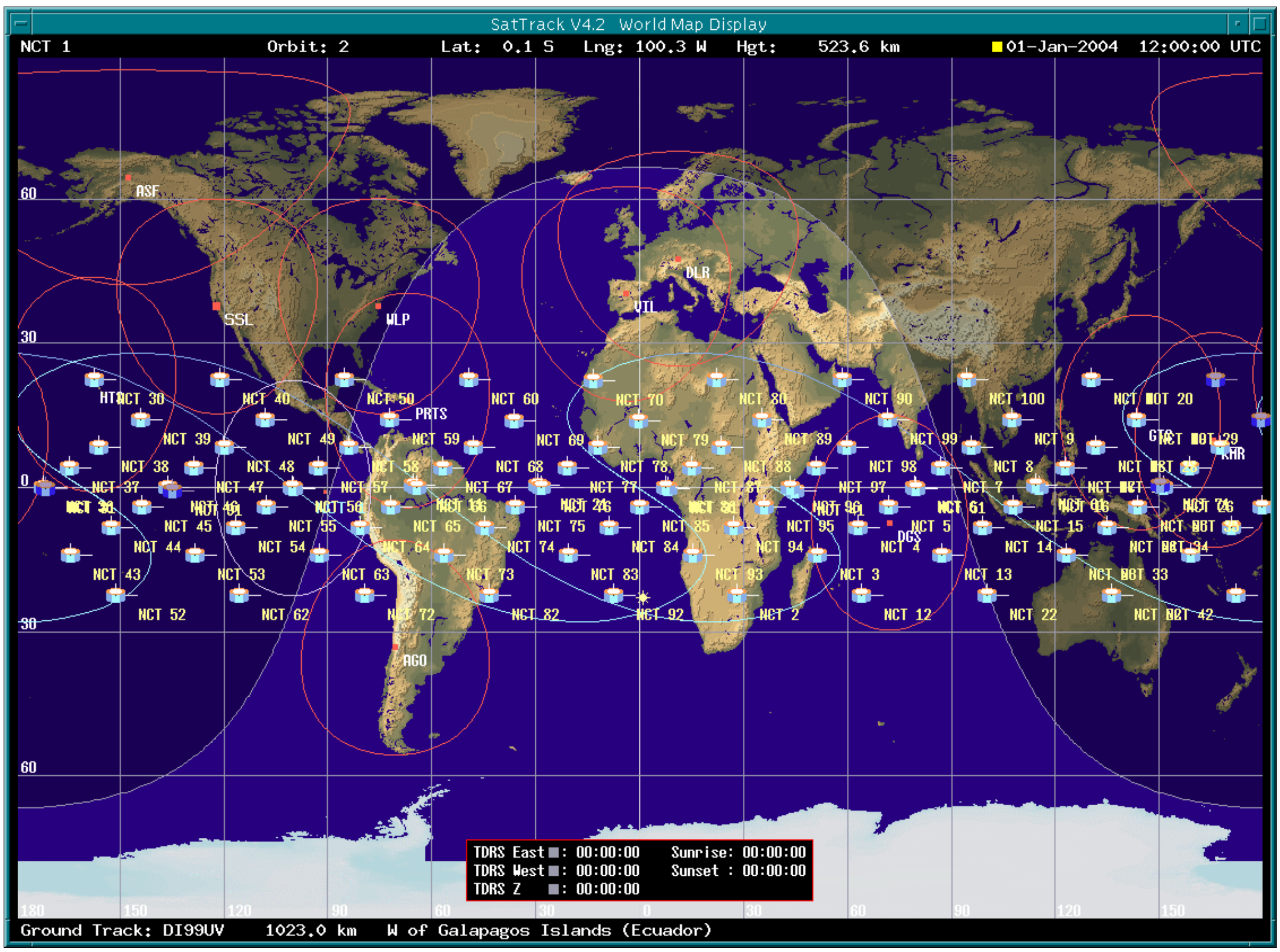

Figure 3 : SatTrack Sample Output

[2] SatTrack is a registered trademark of Bester Tracking Systems, Inc.

4. A Common Tool from Spacecraft Integration and Test (I&T) through Operations

The Advanced System for Integration and Spacecraft Test (ASIST) is a real-time command and control system, which was originally built to support spacecraft level Integration and Test (I&T). ASIST was not initially intended for use during mission operations; but has been developed to support ongoing mission operations for other spacecraft controlled out of the Goddard Space Flight Center (GSFC). Because ASIST was originally intended as a testing tool, it is very configurable and capable of handling additional operations requirements, such as interfacing with numerous different types of front-end data systems simultaneously. Test tools such as ASIST must provide their users with a high degree of control and internal access. Typical mission control systems shield operators from the level of detail used in testing, and prevent them from inadvertently taking certain actions.

Under the Medium-Class Explorer development effort, ASIST has evolved from its I&T specific application into a robust and reliable system capable of supporting both I&T and mission operations. Other benefits of ASIST include its distributed architecture and its capacity for automation through use of derived parameters and script execution. Every ASIST mission control system includes one ASIST Server, and any number of ASIST Clients. Thus, the data processing load can be distributed, and each operator can customize his/her ASIST workstation as needed. ASIST also has automation capabilities. ASIST handles automation during lights-out shifts for both the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) and Microwave Anisotropy Probe (MAP) missions, which were launched on March 25 of 2000 and June 30 of 2001 respectively. Operators have written Spacecraft Test and Operations Language (STOL) procedural scripts, which act upon spacecraft parameter values, and on values that are derived from multiple parameters.

ASIST provides the capability to define mission-unique derived parameters via its database, using a C-like language. The derived parameters may utilize all of the capabilities of the ground system available in telemetry processing. Derived parameters enable more powerful automation, health and safety monitoring, and reporting. The ASIST interface for definition of these derived parameters has significantly facilitated their use.

The use of ASIST has been very successful and has saved a substantial amount of time and cost by providing a single environment that meets the varied requirements of each phase of the mission life-cycle.

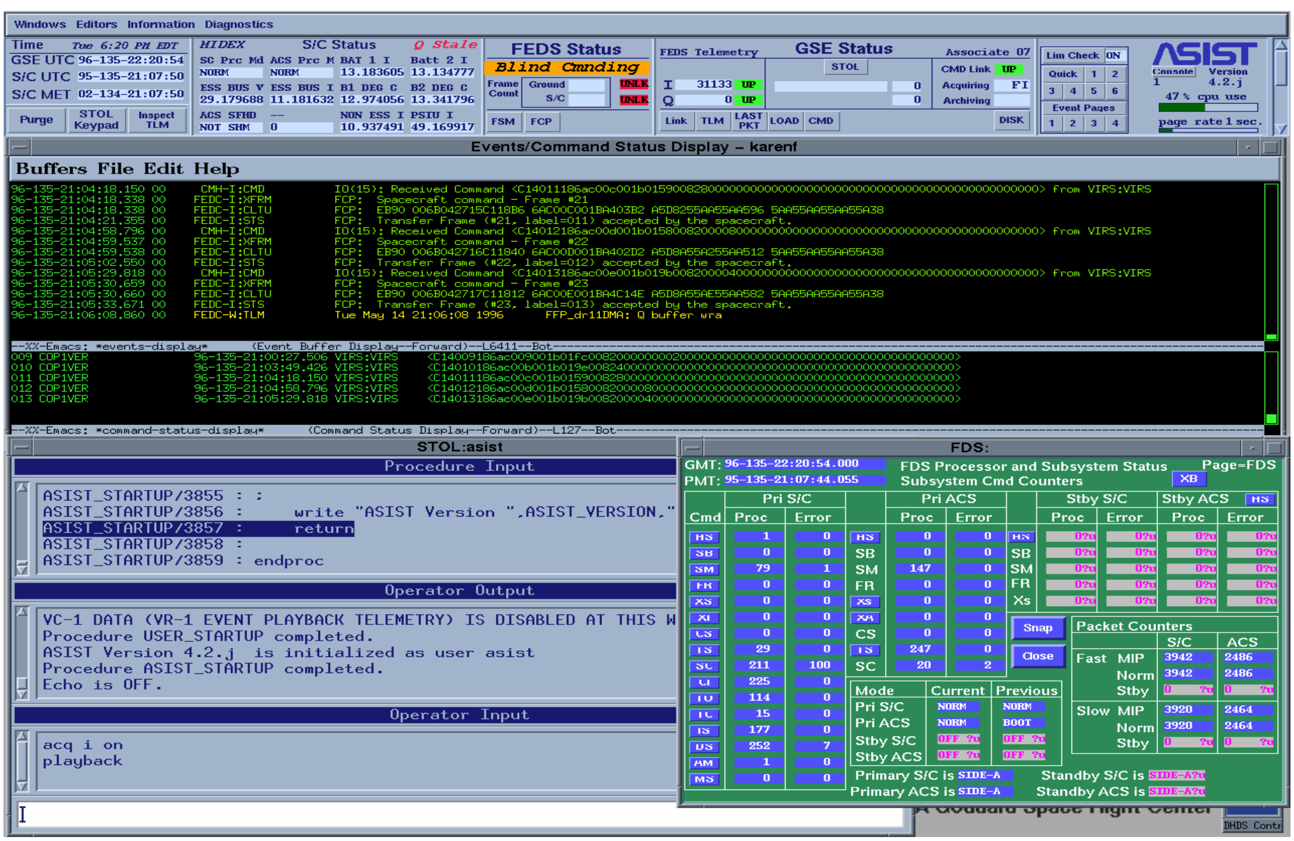

Figure 4: ASIST User Interface

5. RELIABLE NOTIFICATION OF ON-CALL PERSONNEL TO REDUCE THE RISK OF 'LIGHTS-OUT' OPS

The key to ensuring safety and reliability as advanced automation technologies are introduced is the ability to contact the operations team remotely in the event of an emergency. Spacecraft Emergency Response System (SERS) provides that capability. The SERS is a configurable paging and workflow system based on Lotus COTS groupware. The SERS is a modular alert system, which can receive a message from any ground component, and transmit it to a remote user via either Skytel 2-way pagers, email, or telephony. The latest SERS prototype executes in a miniature Web browser on a Palm Pilot screen within a Qualcomm telephone.

Because of its Lotus Workflow basis, the SERS is also being used to autonomously generate pass summary and anomaly reports. This eliminates the need for manual generation of reports and log entries, which will greatly expedite the problem resolution process. The SERS provides an on-line history of all events that occur during the lifetime of the spacecraft.

To mitigate the risk of lights-out operations and new technology insertion, the SERS uses 2-way paging and a pre-configured series of actions to ensure that when situations arise, the proper people are notified. Via the 2-way pagers, an on-call Flight Operations Team (FOT) member can acknowledge responsibility for a particular alert. If the primary person does not reply within a configurable amount of time, the SERS will then page the next person on the list, and so on.

The ST-5 Autonomous Mission Control System will achieve a high degree of reliability by not only monitoring the status of the spacecraft, but also by monitoring the status of the ground system components themselves. Remote FOT members can be kept informed of nominal automated functions, and will be immediately alerted to any unexpected or problematic situations.

6. CONCLUSIONS

The ST-5 mission plans to launch in late 2004 and is designed to demonstrate various new technologies. These technologies have been chosen to help provide direction for NASA's future missions in smaller and lower power spacecraft as well as to develop and operate a constellation. In the coming years, the ST-5 ground system hardware and personnel will work in both Integration and Test as well as the Operations Phases of the mission to best implement a constellation control system. We are confident that these operational tools will provide an excellent platform to enhance the ground system with automation and virtual control. The operations team will be better equipped with knowledge and equipment to operate and resolve any issues that may arise after launch.

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BIOGRAPHY

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