EXPERIMENTS IN AUTOMATED HEALTH ASSESSMENT AND NOTIFICATION FOR THE SAPPHIRE MICROSATELLITE

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ABSTRACT

As part of its space operations research program, Stanford University's Space Systems Development Laboratory (SSDL) is implementing an automated state of health assessment and notification system for spacecraft. On board the spacecraft, this system consists of software that filters telemetry to derive a health assessment and a periodic beacon that broadcasts this assessment to the Earth. Throughout the world, a network of low cost receiving stations receive the beacon signal and relay it to a central mission control center via the Internet. At the mission control center, a suite of software responds according to the value of the health assessment; appropriate responses may include operator notification, automatic groundstation rescheduling to accommodate new health operations, and intelligent retrieval of appropriate operational documentation.

Conceptually, this system acts as an automated mapping from spacecraft state to high-level operator response. It is being developed as a means to reduce the cost of space missions by drastically reducing the operator hours and communication bandwidth committed to nominal health monitoring. Validation of this system is being performed experimentally on the Stanford AudioPhonic PHotographic InfraRed Experiment (SAPPHIRE) microsatellite as operated through a real-world space operations system under development at Stanford University. This system includes a number of university-built microsatellites and groundstations. System level performance metrics will include cost of nominal monitoring, timeliness of anomaly notification, and quality of the health assessment.

This paper reviews the overall design of the health assessment system, detailing the unique aspects of the SAPPHIRE flight software and the Beacon Automated Contingency-in-Orbit Notification (BACON) receiving station. Results of initial, pre-launch system testing are also presented.

INTRODUCTION

Declining federal outlays for space projects and increased market pressures on commercial ventures are forcing space missions to find ways to reduce cost. Since mission operations can consume a significant portion of the overall budget – especially for long-term programs – special attention is being paid to lowering these costs. A commonly-held assumption in the space industry is that automation can lead to significant operational cost

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reductions without drastic cuts in mission performance. The Space Systems Development Laboratory at Stanford University is performing an experiment in automated health monitoring to assess these claims.

The core of this experiment is a health-indicating beacon, which essentially maps vehicle state to high-level operator response. The key elements of this "beacon monitoring" approach are: on-board health assessment, low-bandwidth signal transmission, low-cost automated receiving stations, and an "operator on call" response system. The beacon monitoring method aims to reduce cost in two ways: operator workload is reduced by performing routine health monitoring using automated systems; and communication requirements are reduced by migrating this automation to the spacecraft.

After reviewing the laboratory's satellite and operations architecture, this paper outlines the beacon monitoring approach undertaken by SSDL. Sections are devoted to flight software implementation and the design and development of the BACON automated receiving station. The final sections of the paper describe preliminary operational testing using the SAPPHIRE microsatellite and plans for future study.

THE SPACE SYSTEM DEVELOPMENT LABORATORY RESEARCH PROGRAM

SSDL was chartered in 1994 to provide world class education and research in all aspects of spacecraft design, technology, and operation. To achieve this goal, SSDL members enroll in a comprehensive academic program composed of coursework, project experience and research investigations. As one of their investigations, SSDL is actively involved in research in spacecraft operations and automation.

The Satellite Quick Research Testbed (SQUIRT) Microsatellite Program - The SSDL SQUIRT program [1] is a yearly project through which students design and fabricate a real spacecraft capable of servicing low mass, low power, state-of-the-art research payloads. By limiting the design scope of these satellites, the project is simple and short enough so that students can see a full project life cycle and are able to technically understand the entire system. Typical design guidelines for these projects include using a highly modular bus weighing approximately 25 pounds, a hexagonal form that is roughly 9 inches high by 16 inches in diameter, amateur radio communications frequencies, and commercial off-the-shelf components. Missions are limited to about one year of on-orbit operation. Since little money is available for operations, a highly automated mission control architecture is being developed.

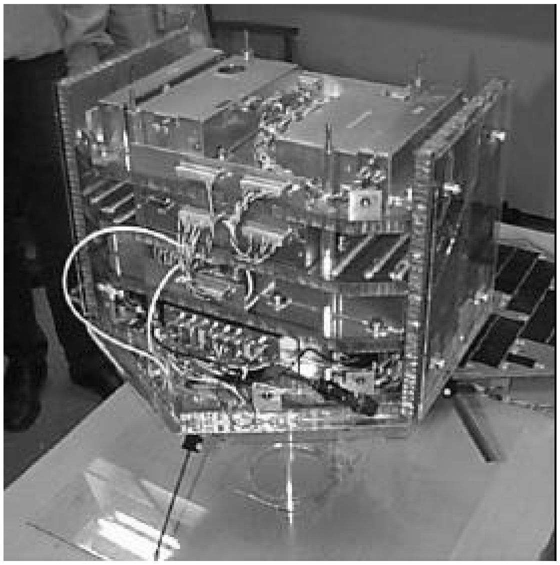

***Figure 1** – SAPPHIRE during assembly*

The Stanford Audiophonic Photographic Infrared Experiment (SAPPHIRE) Microsatellite – Shown in Figure 1, SAPPHIRE is the first SQUIRT spacecraft [2]. Its primary mission is to characterize the on-orbit performance of a new generation of infrared horizon detectors, in addition to flying two student instruments, a digital camera and a voice synthesizer. Student research interests are also driving experiments in nontraditional sensing and automated operations. SAPPHIRE is hexagonal, measuring 17" across its longest dimension and 13" high. It is primarily constructed of commercially available equipment: the communications subsystem consists of terrestrial amateur radio kits and terminal node controller enabling AX.25 communication in the

2m and 70cm bands; the vehicle CPU is a Motorola 68000 series microcontroller with 256k ROM and 1024k RAM; the aforementioned student payloads are modified off-the-shelf products. In addition, certain mission-critical elements are composed of or modified with some space-qualified elements, such as the space-rated 10-cell NiCad battery pack and radiation-hardened memory for the CPU. SAPPHIRE is being completed by a core of volunteers and research students, and is currently undergoing final preparations for launch. It will be launched as a secondary payload. Although it has not yet been launched, both SAPPHIRE and its fully-functional engineering prototype are available for operational testing and experimentation.

The Automated Space System Experimental Testbed (ASSET) System - The ASSET system [3] is a global space operations network under development within SSDL. The first goal of this system is to enable low-cost and highly accessible mission operations for SQUIRT microsatellites as well as other university and amateur spacecraft. The second goal of this system is to serve as a comprehensive, low inertia, flexible, real-world validation testbed for new automated operations technologies. Figure 2 shows a high level view of the ASSET mission architecture. The basic components include the user interface, a control center, ground stations, communications links, and the target spacecraft. During the current developmental phase, a highly centralized operations strategy is being pursued with nearly all mission management decision making executed in the control center. These tasks include experimental specification, resource allocation throughout the ground and space segment, anomaly management, contact planning, data formatting and distribution, and executive control.

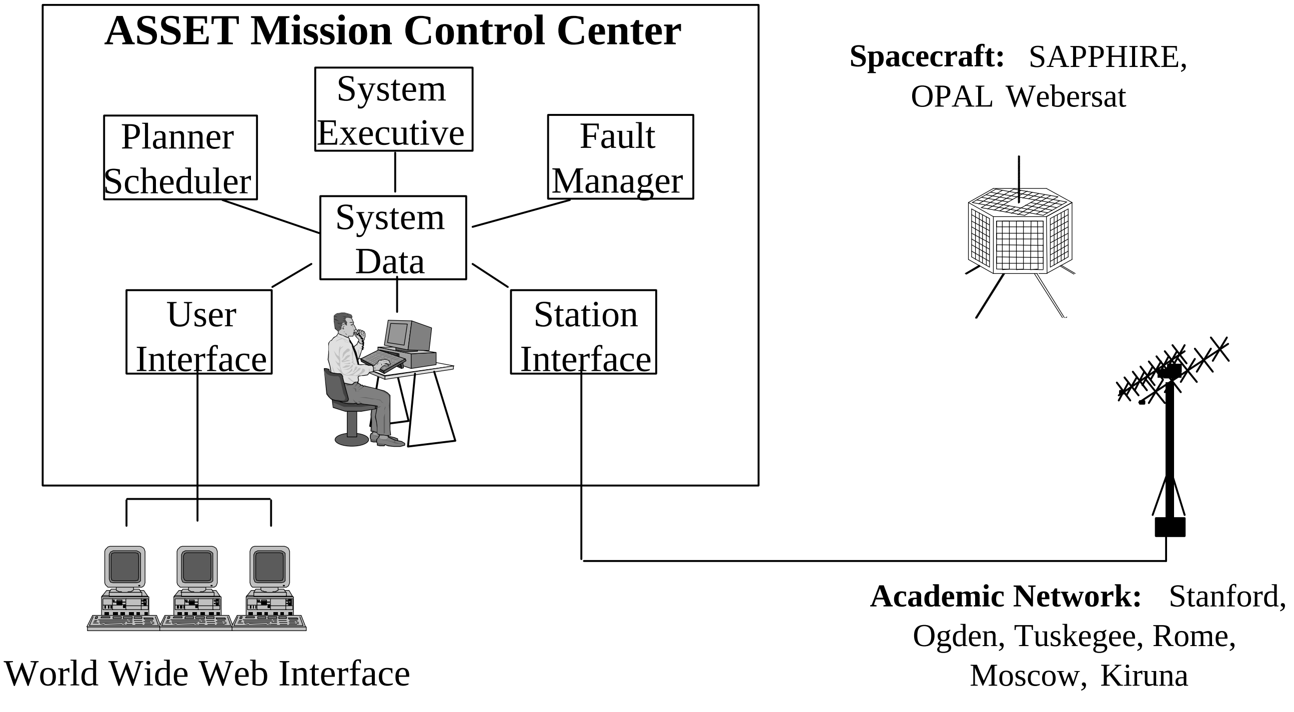

***Figure 2** - The ASSET Space System Architecture*

SAPPHIRE and all future SQUIRT satellites will be operated through ASSET. In addition, controllers for a number of other university and amateur satellites have expressed in becoming part of the system. As for ground stations, the Ogden and Stanford ground stations are the first two facilities to be included. Several other stations throughout North America and Europe have been identified for future integration.

BEACON-BASED HEALTH MANAGEMENT DESCRIPTION

A beacon-based health management concept was first presented in a U.S. Air Force study, Lifeline [4]. It is currently a flight experiment aboard NASA's Deep Space 1 [5] and is one of the key technologies for future NASA deep space missions [6]. This concept is being prototyped as a part of the SAPPHIRE mission [7]; its main features are summarized, below, and the new elements are further detailed. The signal flow for the SAPPHIRE implementation is presented in Figure 3.

SAPPHIRE Health Monitoring – SAPPHIRE will monitor its own sensors, comparing measured values with expected values in a state-dependent limit table. Certain measurands will be validated by aggregate analysis. For example, the vehicle's configuration prevents all solar panels from seeing the Sun at once; if solar panel measurements indicate that all panels are generating current, then there is good reason to believe that the current sensors are malfunctioning. These modest steps provide SAPPHIRE with an anomaly detection system far more mature than most spacecraft. Software implementation is described in a later section of this paper.

Depending on the seriousness of the limit violation, the spacecraft state is assessed to be one of four values. For example, when measurands are within limits, the spacecraft is judged to be *Normal*. Out-of-limits with moderate impact, such as an overheating camera, is considered an *Alert*. Out-of-limits that can rapidly jeopardize the mission elevates the health status to *Critical*. Finally, *Emergency* condition is defined to be an unexplained computer reset. Note that the rules by which measurands trigger the modes, and the limits for each, are defined by the operations team. This ensures that beacon modes are a mapping from spacecraft state to operator action.

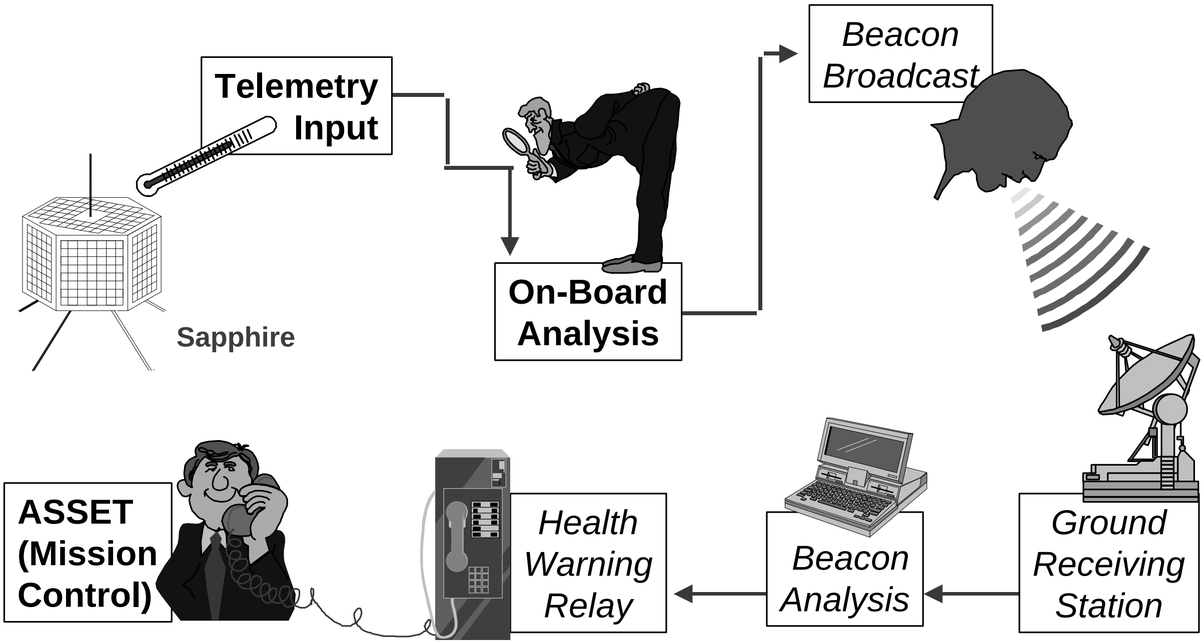

Figure 3 – *SAPPHIRE Health Beacon Signal Flow*

Health Beacon Transmission – The beacon is a pulse-modulation of the main transmitter carrier, with different pulse widths defined for a one bit and a zero bit. The total transmission time of the beacon message is less than one second. The message is broadcast whenever beacon operations are active, nominally at one minute intervals. Therefore, spacecraft health is continuously monitored and the health indication is available anytime the spacecraft is within range of a receiving station.

Receiving Station – SSDL has developed the prototype BACON receiving station, more fully described below. Based on a schedule provided by ASSET, it listens for SAPPHIRE transmissions. If a beacon signal is received, the pulse modulation is converted into bits and this information is time-tagged and sent via electronic mail to the ASSET mission control.

Mission Control Center – Once mission control receives a beacon monitoring update from a remote station, it logs this information and then takes appropriate action. Depending on the health assessment, there are varied responses, from storing the update in the system database to paging the operator on call and rescheduling the network to contact and recover a failed satellite.

IMPLEMENTATION – SAPPHIRE SOFTWARE

Modifications in flight software have given SAPPHIRE the ability to monitor itself, using a conventional limit-checking approach for health assessment. The table/beacon software is embedded in Sapphire's operating system. Called Chatterbox [8], it is a student-developed bulletin board system with a UNIX-like interface. This C-based platform is divided into hardware drivers and user interface modules. The modifications necessary to implement on-board health monitoring have been primarily in the creation of new data constructs, specifically limit-checking tables and virtual sensors.

Once every sample period (a commandable value, typically ten seconds), the operating system compares each of the designated sensors against high and low limits stored in a table; if the value exceeds the limits, then the system is instructed to perform a series of commands. These commands are built-in to the table and can be tailored to specific events. For example, an indication that a payload is too cold would result in a command to turn it on in order to generate heat. Such an event would also change the beacon message to *Alert*. If the battery voltage drops too low, however, it would trigger a sequence of commands to put the vehicle into a safe mode and send the *Critical* beacon message. Example table entries are shown in Table 1.

Channel	**Low**	**High**	**Command**	***Translation***
5	12.0 V	16.0 V	Jump to Table 8	*If battery voltage (channel 5) exceeds range, activate Safe Mode (table 8)*
1	-	50 mA	sensor set 32 step 1	*If solar panel 1 current (channel 1) is above threshold, increment the counter panels_in_sunlight (virtual channel 32)*
24	278 K	-	os pins set 2 1	*Turn on camera (pin 2) if the temperature (channel 24) is below 278 degrees Kelvin*
24	278 K	318 K	os beacon message 01	*Set beacon to "alert" if camera is out of temperature range*

***Table 1**: Sample SAPPHIRE Table Entries with Explanations*

As designed, the table system is extremely flexible; the software contains a series of pre-built tables to monitor major vehicle states, but these entries can be changed. The channels to examine, the low and high limits, and the triggered responses are all fully adjustable by ground command. Alarm thresholds can therefore be fine-tuned on-orbit to account for environmental degradation and other mid-mission changes.

Another important contribution of this flexible flight code is the ability to perform mode-based limit-checking. For example, there are different expectations for component temperatures and battery performance during sunlight and eclipse; the ability to tailor the alarm thresholds to specific modes allows for more accurate health monitoring. SAPPHIRE accommodates mode-dependent limit checking by enabling the operating system to add and delete table entries “on the fly” and by creating “virtual channels” containing abstracted information about the spacecraft. Such abstractions include the number of solar panels in sunlight and whether or not the vehicle is in eclipse. Again, these virtual channels can be customized after launch, based on the situations encountered during flight operations.

Another issue which the software must address is how to identify spurious state transitions. It is undesirable for a sensor value oscillating near an alarm threshold to trigger repeated transitions from one state to another. Such transitions may be the result of nothing more than sensor noise. To mitigate this problem, the SAPPHIRE code implements persistence counters. A sensor value must persist beyond the threshold for a certain number of cycles before it is considered to be out of limits; similarly, it must persist within the threshold boundaries to be normal again. Like the other elements of the table system, the persistence counter can be set for each entry. For clarity, the persistence values were not shown in Table 1.

IMPLEMENTATION – BEACON RECEIVING STATION

If a beacon receiving station is to be cost-effective, it was determined that total implementation costs had to be approximately an order of magnitude below a “standard” ground station. For communicating with SAPPHIRE, a standard station includes hardware for two-way communications (Mode-J), a TNC for packet radio, and one or two computers for tracking and data. Total cost for this setup is approximately $10,000.

These cost constraints impose severe limits on the kind of hardware that can be used for the station. Additional constrains are imposed by a need for automation and remote location. Instead of a fully tracking antenna, a much lower gain omni-directional antenna is used. The antenna connects to a computer-tunable commercial receiver able to detect an RF carrier and convert it to an audio signal. The audio signal is then fed to a standard sound card on a Pentium-based computer. The computer must be connected to the internet, so that the station can send and receive data from the ASSET mission control center.

At the heart of the station is a Windows95 program that monitors incoming data from the receiver. As the audio signals come in through the sound card, they are transformed to a frequency spectrum representation by use of a Fast Fourier Transform algorithm. Since the data rate (5 Hz) is much lower than the audio signal frequency (3 kHz) the signal comes across cleanly without any modulation. After accounting for the satellite’s transmit frequency and any Doppler shift, the software must simply look at the appropriate audio frequency, and determine whether enough power is present to represent a true signal.

Once the software knows that a signal is present, it is examined over time to determine the on-off pattern present. This pattern is then directly translated to a beacon code that has previously been defined in the information for the relevant satellite. The code, the time of receipt, the station ID, and the satellite ID are immediately e-mailed to mission control to be processed appropriately.

To monitor the skies effectively, the beacon receiving station depends on ASSET to provide it with a visibility schedule of the satellites in the system. It is as important for ASSET to know when a satellite was *not* heard, as it is to be told what code a satellite is broadcasting. The beacon station will also notify the system if the satellite was heard, but no sense could be made of the message. This could be due, for instance, to packet communications taking place between the satellite and the ground. Finally the station will treat itself as a “satellite” and send regular beacon messages to ASSET informing the system of its own state of health, and whether human interaction at the station is needed.

A prototype of the BACON station has been developed at SSDL. It has demonstrated capabilities to detect beacon signals from SAPPHIRE, convert beacon transmissions into information bits, and to forward this time-tagged information to ASSET via electronic mail. The BACON station is available for use in the preliminary operations testing, described in the following section.

PRELIMINARY TESTING

The beacon monitoring system of SAPPHIRE has been ground-tested. Not only have these tests demonstrated the ability of the system to function as expected, but useful data has been gathered concerning the cost savings from beacon operations. SAPPHIRE or its engineering prototype can be stacked in flight configuration and operated remotely at Stanford, using either the main SSDL ground station or the portable testing unit. Flight-like conditions can be simulated by restricting communications access to the vehicle to windows of opportunity reflective of a low-Earth orbit.

For these tests, two independent teams of SAPPHIRE operators were assembled. One team performed nominal operations, as if there were no health beacon and contacting the vehicle once per day. The second team relied on the BACON station to monitor the health beacon, contacting the vehicle only once per week. The test was conducted for one week of operations, during which time a third party created a "fault" by power cycling the vehicle. The purpose of this test was to measure the operator effort required to perform nominal health monitoring and the communications resources needed to identify the presence of an anomaly.

During this test, preliminary results indicate that the beacon-based health monitoring approach offers significant savings over the operator-intensive method. Not only did the automated approach indicate the presence of a "fault" using fewer man-hours and communication time, but the automated operations team was aware of the problem's existence hours before the nominal operations team!

CONCLUSIONS AND FUTURE WORK

The use of a low-power beacon and low-cost automated listening stations is a viable solution to the new challenges in spacecraft health management. Automation of limit detection and migration of this process to the spacecraft will significantly reduce the spacecraft-to-ground communication link and the time spent by operators on routine health management tasks. This beacon-based health management approach has been initially demonstrated in a ground test of the SAPPHIRE spacecraft using the ASSET operations architecture.

The preliminary tests described in this paper will be expanded to cover longer periods of operations and additional operating conditions. More "unknown" faults will be injected into the system; doubtlessly additional "true" anomalies will be discovered over the course of operations. Also, longer operational periods will help explore the potential long-term effects of automated monitoring, such as the absence of an exhaustive ground telemetry archive and the relative unfamiliarity operators have with vehicle nuances. Such effects are the subject of additional research within SSDL. Additionally, SSDL’s second satellite, OPAL, will be fitted with appropriate beacon software. This will allow testing of multi-satellite scenarios.

Ultimately, this health monitoring approach will be tested on-orbit during SAPPHIRE's flight. Until then, enhancements will be made to the ASSET system and to the BACON station, especially to accommodate Doppler shift and loss of signals. Other than some minor changes to the signal parameters, the SAPPHIRE software is frozen and ready for all future tests.

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