AUTOMATING THE OPERATIONS OF THE ORBCOMM CONSTELLATION

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NOMENCLATURE

ACE	Attitude Control Electronics
BCR	Battery Charge Regulator
DOD	Depth of Discharge (Battery)
FM1,2	Flight Models 1,2 (1st 2 satellites launched)
GES	Gateway Earth Station
GPS	Global Positioning System
GWT	Gateway Transceiver
LEO	Low Earth Orbit
NOC	Network Operations Center
OSC	Orbital Sciences Corporation
SC	Subscriber Communicator
SRx	Susbcriber Receiver
STx	Susbcriber Transmitter
SVMS	Space Vehicle Management System
UHF	Ultra High Frequency
VHF	Very High Frequency

ABSTRACT

The ORBCOMM system is the world's first commercial LEO two-way data communications system. The ORBCOMM system, when fully deployed, will use a constellation of small satellites to provide users with low-cost near-continuous data relay and position determination services on a seamless worldwide basis. Due to the large number of spacecraft, and the need to keep operational costs low, automation will play a significant role in the operation of the ORBCOMM constellation. This paper discusses the principle operational functions needed to maintain the ORBCOMM satellites, and the design process for determining the degree of automation for each.

SYSTEM DESCRIPTION

Space Segment The first satellites of the ORBCOMM constellation were launched in April 1995. These first two satellites (FM1 and FM2), built and launched by Orbital Sciences Corporation (OSC), were launched at an altitude of 740 km, 70 degree inclination. After a thorough on-orbit checkout, they were placed into commercial service in February 1996. The remainder of the constellation will be deployed in four separate launches throughout 1997. Three launches of eight spacecraft each are scheduled for the second, third, and fourth quarters of 1997. These planes will be inclined at 45 degrees, with a target altitude of 775 km. One additional plane of two satellites will be launched at high inclination to provide better coverage at high latitudes. Eight ground spare satellites will be constructed as insurance against a launch failure; if the first three planes are successfully deployed, this fourth plane may be launched to augment the system coverage. Thus the system is expected to grow from two satellites in one orbit plane to as many as 36 satellites in six orbit planes over the next two years. The satellite design is discussed in more detail below.

Ground Segment The ground segment of the system consists of the Gateway Earth Stations (GESs), and the Network Operations Center (NOC). The US Gateway makes use of four redundant Gateway Earth Stations (GESs), located in Arizona, Washington, Georgia, and New York state. These are connected by dedicated landline to the NOC, located in Dulles, Virginia. The NOC houses the message switch and associated control elements, and the Space Vehicle Management System (SVMS), which controllers use to operate the satellites. Additional Gateways will be constructed around the world by international licensees beginning in 1997 to provide real-time service worldwide.

Subscriber Segment The interface to the users of the system is the Subscriber Communicator (SC), which consists of a VHF receiver, VHF transmitter, antenna, and data processing subassemblies. Subscriber Communicators currently in use for applications such as remote environmental monitoring weigh less than two pounds, and send and receive data by way of a serial port interface. Smaller SCs with displays and keypad data entry are also under development for personal messaging applications. SCs are capable of calculating their geographic position based on the measured Doppler shift of the satellite downlink signal and the transmitted satellite state vector.

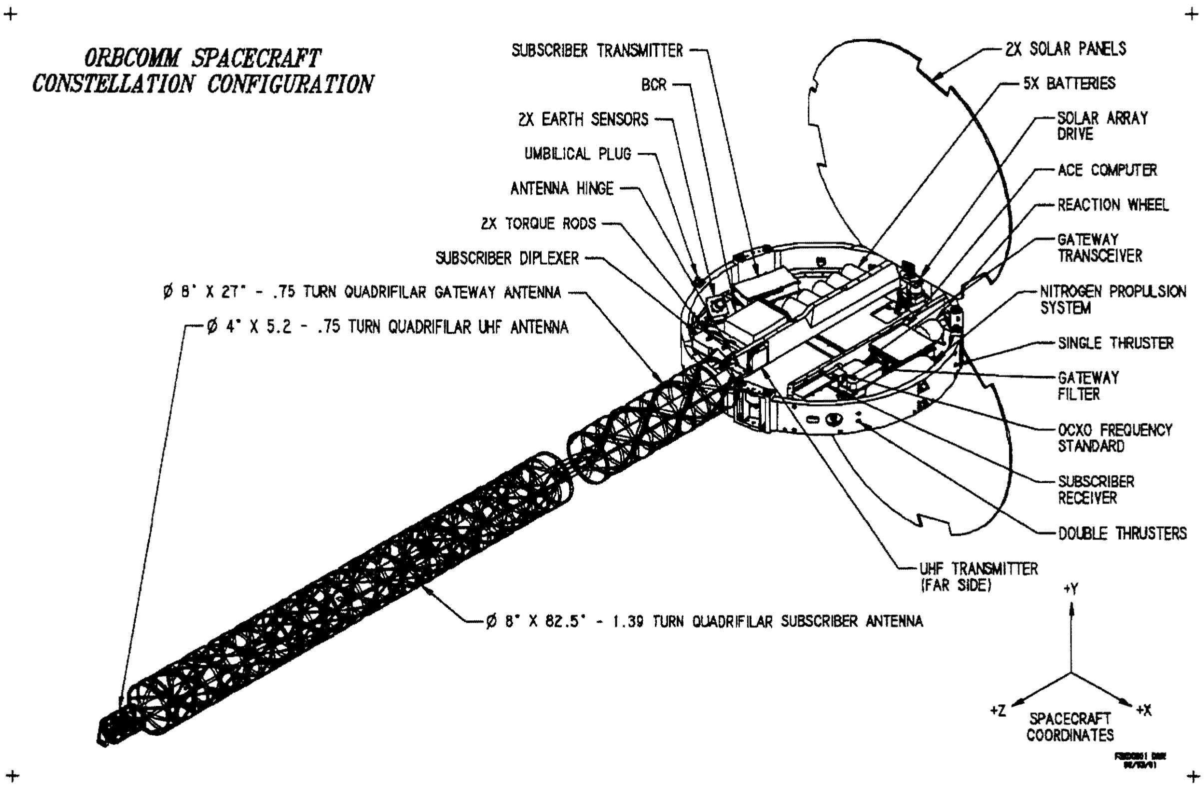

Figure 1 ORBCOMM Constellation Spacecraft

SATELLITE DESCRIPTION

Configuration

ORBCOMM is truly a small satellite, weighing 95 pounds and measuring 42 inches in diameter by 8 inches high in its undeployed state. After separation from the Pegasus XL launch vehicle, the antenna and solar arrays unfold to yield a deployed vehicle size of 14 feet long by 7 feet wide. The proportionally large antenna is necessary for efficient communication in the relatively low frequency VHF bands. The antenna points to nadir to while yaw steering and a solar array drive track the solar panels to the sun. The spacecraft electronics are mounted on one side of a flat payload shelf, which is covered by a thermal and EMI shielding material.

The avionics architecture, shown in Figure 2, is distributed, with each bus and payload functional unit having its own Motorola 68302 processor. In addition, each of the communications payload units contains one or more digital signal processors, bringing the total number of digital processors onboard to 17. The Flight Computer (FC), Subscriber Transmitter (STx), Subscriber Receiver (SRx), and the Gateway Transceiver (GWT), are arranged in a full duplex ring bus. The FC, Battery Charge Regulator (BCR), and Attitude Control Electronics (ACE) are connected by a separate token bus.

Satellite Bus

The satellite bus has a great deal of autonomy built in to the design. For nominal operations, the navigation, attitude control system and electric power systems are entirely autonomous. Each of these systems will be discussed below.

The power system includes two gallium arsenide solar arrays capable of producing over 200 W. Five nickel-hydrogen battery cells provide 10 Amp-hours of capacity on a nominal 14 volt bus. The BCR provides power regulation and full switching of virtually all loads. Solar array drive control, heater control, solar array peak power tracking, load management, and battery charge control are managed by the microprocessor dedicated to the BCR.

Navigation is provided by an onboard GPS receiver, which transmits position and velocity fixes every few seconds to the ACE. The ACE uses the information from the GPS receiver, along with earth horizon sensors, a magnetometer, and sun cosine detectors, to calculate the current state vector and attitude. Attitude is controlled using a tip mass on the end of the antenna boom, magnetic torquers, and a reaction wheel.

Command and data handling are controlled by the Flight Computer. The flight computer stores backorbit telemetry when the vehicle is not within view of a US GES, and dumps the data to the ground upon command. In addition, the flight computer manages immediate and stored commands, and performs health monitoring of the processors.

Communications payload

There are four components in the payload section of the satellite. The SRx has seven DSP-based receivers capable of detecting and demodulating transmissions from SCs on the ground. The receive band (148 - 149.9 MHz) must be shared with many terrestrial users, such as pagers and push-to-talk mobile voice systems. Therefore one of the receivers is always in use as a scanner, measuring the noise and interference power over the receive band. The SRx processes the in-band ambient power measurements and, given other constraints, such are regulatory limits, selects the channels for each SC to use for each transmission.

The STx provides a continuous downlink signal to the SCs. The SCs use this signal to detect the presence of a satellite, and then to receive authorized frequencies for transmission. The STx also broadcasts its position and velocity to the SCs to use in calculation their geographic position. The STx is agile in power level, data rate and frequency. Transmit power is continuously variable between 10 to 40 W by command of the 68302 processor. Data rate can be set to either 4800 baud or 9600 baud, and the transmitter can be commanded to any frequency between 137 to 138 MHz. This band must be shared with existing meteorological and radio astronomy users, and with future little LEO systems. Therefore, only eight channels at 25 kHz bandwidth and two channels at 15 kHz bandwidth will be used.

The GWT provides both the backhaul links for the subscriber traffic to the various Gateways on the ground and the command and control link for the bus and payload. The GWT operates at 57.6 kbps for both transmit and receive, with a time division multiplex system to allow connection to up to 16 different Gateways at one time. The GWT has one DSP for each of the transmit and receive sides.

The UHF transmitter broadcasts an unmodulated beacon at a constant 400.1 MHz. This will be used by some SCs for more precise measurement of satellite Doppler shift, resulting in more precise position determination.

MISSION OPERATIONS

The primary objective for operations in support of the ORBCOMM constellation is to maximize the availability of service to subscribers to provide the opportunity to generate revenue. The mission can be divided in to three operational goals. The first is to maximize the theoretical coverage of the constellation over primary market areas. This is accomplished by maintaining the orbit of each satellite according to the constellation design parameters. The second goal is to maintain a high level of availability for each satellite to eliminate gaps in coverage caused by satellites out of service. This is accomplished by quickly identifying and responding to faults and anomalous conditions. The third objective to maximize revenue opportunity is to extend the usable life of the each satellite by eliminating avoidable failures and managing the operation of life-limiting components, such as batteries.

A secondary operational requirement is to comply with negotiated frequency-sharing agreements whereby transmit power and bandwidth must be modified when in proximity to satellites which may experience harmful radio frequency interference due to ORBCOMM emissions.

DRIVERS FOR SYSTEM AUTOMATION

High availability

There are a number of planned applications of the ORBCOMM system that depend on near-realtime system availability, such as personal communications, search and rescue, and stolen

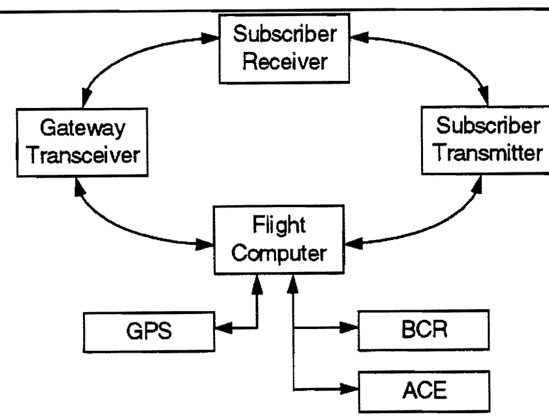

Figure 2 ORBCOMM Avionics Configuration

vehicle recovery. The maximum theoretical system availability when fully deployed is about 97 percent, with typical outage times of up a to 5 minutes several times per day. Outage time is a critical system parameter that is very sensitive to satellite failures; one satellite out of service can cause a significant increase in system outage times. The requirements for high availability of service are a significant driver to detect and respond to satellite anomalies before service is materially affected.

Mission Duration

Commercial service started in February of 1996. The constellation satellites are planned to be in service until the end of 2002. The length of this mission provides a significant payback period for investments made in system automation.

Number of satellites

The economy of scale that pertains to a large constellation of satellites is one of the principle drivers to automation. Many operations that are reasonably done manually with the current constellation of two vehicles would become overwhelming when applied to a constellation of 28 or 36.

Low cost

A prerequisite to ORBCOMM service becoming widely accepted is that it must be offered at low cost. The cost tradeoff of upfront investment in automation versus long-term operating costs is important in determining the optimal amount of system automation.

Lessons learned from FM1/2

The FM1/2 spacecraft were designed to be almost entirely autonomous. Many of the current tasks performed by operations and engineering support involve either investigation of anomalies or the implementation of operational workarounds to spacecraft anomalies. Therefore the approach taken for constellation is to apply a measure of automation to the process of detecting anomalies and of implementing operational workarounds.

METHODOLOGY FOR APPLYING AUTOMATION

Based on the system drivers discussed above, a set of criteria have been developed for determining whether a particular function should be automated, and if so, the partitioning of that function between the segments of the system. The operational paradigm which has been developed is to automate nearly all nominal, repetitive operations, to reserve human resources to solving anomalies. In general, if a function meets the following criteria, it is planned to be automated.

1. Time-critical fault detection and safing for anticipated anomalies.
2. Repetitive functions with a frequency of at least once per day.
3. Computationally intensive scheduling and analysis tasks.

In the next section, the approach to meeting each of the operational goals is described in a series of functional flows. For each of the discrete functions, the tradeoffs for making each of the tasks automated or manual is discussed.

MAINTAINING CONSTELLATION COVERAGE

The implementation of this requirement begins with the GPS receiver onboard the satellite generating navigational data and forwarding it both to the onboard navigator in the attitude control software, and to a telemetry buffer. The content of this buffer is periodically downlinked to the ground and fed in to a precision orbit determination program to generate an element set. The element set of each of the satellites is then used for two purposes. First, the scheduled satellite contact times are determined for each of the earth stations, and the determination is made of the optimal satellite contact and handoff times (as discussed in the next section). Second, the relative spacing of the planes to each other and the relative position of the satellites in each plane are evaluated and any required orbital maneuvers are planned.

This functional flow is outlined in Figure 3, along with the anticipated frequency of each operation. The collection and storage of GPS data of course is an automated function of the spacecraft. The downlinking of the telemetry data occurs at every pass over a US groundstation; this is planned to be automated. The precision orbit determination solution for the constellation is a one of the larger computational tasks in the operation of the constellation and although it will not be a daily function is strong candidate for automation. However, this is a difficult task to completely automate. This is because getting precision orbit determination software to converge on a good solution using real data often requires the expertise of an experienced mission analyst. Therefore most of the effort in automating this task will be put into developing a filter for the raw GPS data to eliminate bad data points and to evaluate the reasonableness and quality of the solution.

Orbit maintenance operations is expected to be a straightforward task of comparing the relative positions of the satellites in the orbit determining the direction for required orbital maneuvers, and the generation and transmission of a command load to each of the necessary satellites. While it is possible to completely automate this task, projections show that during mature operations, this task will need to be performed about once per week. Therefore, it does not seem worth automating this task.

Connection of Satellite to Gateway

When the ORBCOMM system is fully deployed, a new GES/satellite connection will be necessary about every five minutes. Because of the frequency of this operation, this process is almost entirely automated. First, the orbital element sets for all the satellites in the constellation are loaded into an orbit propagation tool which generates pass schedules for each satellite over each earth station. A realtime process in the GMS detects upcoming connection opportunities several minutes before the satellite approaches one of the earth stations. Several minutes before the scheduled contact, a command is sent autonomously from this process to the GES to begin move the antenna for acquisition. This command contains the ephemeris for the target satellite. The GES software contains a software to propagate the orbit and calculate the azimuth/elevation pointing commands. When the pass scheduling routine determines that the satellite should be rising, it issues a command to initiate a session with the satellite. This GES maintains connection to the satellite until it is handed over to another GES either autonomously or by manual command.

In the current system phase with only two satellites, only one satellite is in view of the continental US at any one time; therefore, the algorithm for satellite selection is relatively straightforward. During mature operations of the constellation, by contrast, as many as ten satellites may be within view of the four US GESs. The scheduling of connections between many satellites and earth stations will be a complex task which needs to take into account many factors, such as viewing analysis, ground station availability and constraints, and ground and satellite maintenance requirements. The complexity of this task requires the development of a sophisticated scheduler to balance all these constraints. The contact scheduling algorithm to handle this in an optimal fashion is under development. It is anticipated that not all constraints will be able to be satisfied, and some judgment will be required to assign priorities. For this reason, what is now an automated process running in realtime will become a manual process which is run periodically to generate the optimal pass schedules. However, it is anticipated that this scheduling will need to be performed about weekly, so the staff requirements are not expected to be excessive.

Maintaining satellite availability

Operationally, the objective of maintaining high satellite availability consists primarily of detecting and correcting satellite anomalies. Experience with the two operational satellites to date has been that

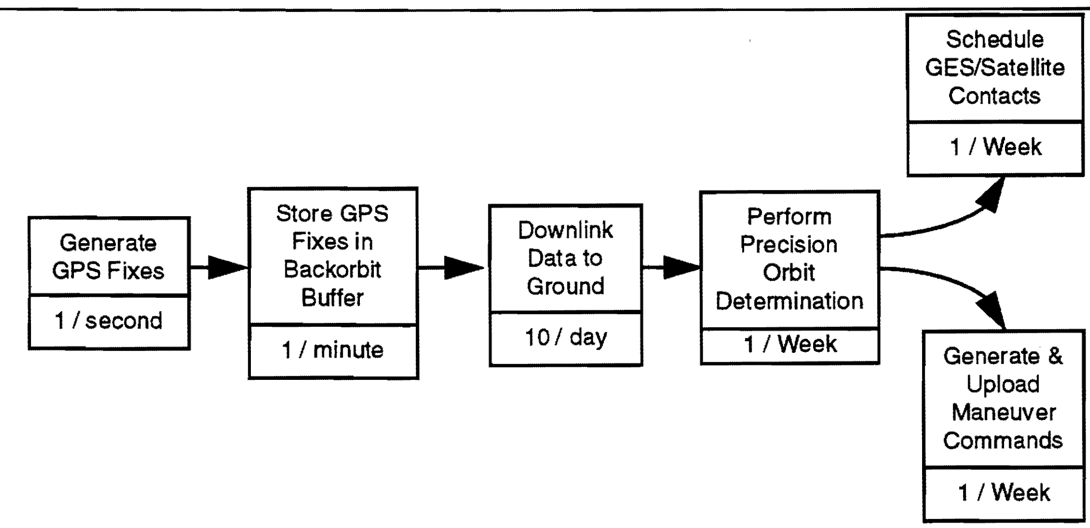

Figure 3. Operations to maintain constellation coverage and approximate task frequency

spacecraft anomalies are of two distinct types. The first type is due to single event effects on the digital processors and is generally manifested by sudden, obvious changes in the behavior and performance of the system. The second type of anomaly, generally due to faults in the analog electronic hardware, are typically slow in developing, more difficult to detect in the early stages. Single event effects are discussed in the next section, followed by analog anomalies.

Single event effects

The ORBCOMM satellites have a significant number of digital devices onboard including sixteen digital processors and ancillary devices such as RAM and EEPROM chips, and analog to digital converters. Most of these devices are susceptible to radiation-induced single event effects. The most common effect is the single event upset, or bit flip, which causes processors to behave unpredictably or cease functioning. This can be cleared by a hard or soft reset of the device. Less common is the single event latchup, when a bulk current flows in the part and it completely ceases functioning. This can only be cleared by power cycling the device.

The responsibility for detection and correction of single event effects has been allocated entirely to the spacecraft as an automated function. There are several reasons for this. First, most single event effects can be easily detected simply by monitoring the processor's nominal functioning. This can be done by watchdog circuits on the controller card or by programming processors to monitor each other's performance. Similarly, the action to correct the problem is also straightforward: either a reset or power cycle is required. Second, if the bit flip or latchup stops the functioning of a component on the command and control path, commanding from the ground to correct the problem may not be possible. The third reason to automate this function is to minimize the downtime of the satellite for each occurrence. Single event effects are more likely to occur over the poles and over the South Atlantic anomaly when the satellites will be not under control of the US Gateway. Significant service impacts could occur if upsets cannot be cleared until a command opportunity is available. Finally, a latchup event is less likely to cause failure of the part due to excessive thermal stress if the latchup is cleared quickly.

Analog anomaly detection

Faults and anomalies in analog components are much more challenging to detect using automated techniques than are digital upsets. Anomalies in analog components such as amplifiers, antennas, and regulators are typically manifested first by small yet detectable changes in the telemetry signature of one or more components, often with overall performance unaffected. If detected in the early stages, corrective action can be frequently be taken before the problem worsens to the point that damage becomes permanent or service is affected. Therefore the challenge in maintaining high satellite availability is to detect anomalies as soon as possible, and to initiate safing or corrective action before service is affected.

Anomaly detection can be modeled as a two step process. The first step is to define what the nominal performance of the system should be. The second step is to compare the current performance to the expected and notify controllers or engineering support. Each of these steps will be discussed in detail below, along with the rationale for the degree of automation selected for each step.

Nominal performance definition

The first step in the process of anomaly detection is to characterize the nominal performance of the system. To detect subtle warning signs of anomalies as they develop, the nominal behavior must be very tightly characterized. Defining what is normal system behavior is one of the most challenging tasks, due to the large number of telemetry points and the complexity of some of the systems. The approach described below to accomplish this relies on a combination of analytical and empirical techniques to define a baseline against which to measure vehicle performance.

Table 1 summarizes the range of techniques to be employed. For telemetry points which are expected to stay constant over the entire range of vehicle states, such as regulated bus voltage, simple static limits will be used which are derived manually from unit-level specifications and ground test data. For telemetry points that vary widely, but which have simple analytical relationships to other states of the system, expected values will be calculated in realtime using analytical models of parts of the system. Examples of this include calculating expected signal power levels for communications receivers based on transmitted power and link parameters, and calculation of expected current levels on an electric power bus based on the relay states.

For telemetry points which also vary widely, but are related to devices or subsystems that are too complex to model analytically, empirical device models will be generated based on statistical characterization of ground test or on-orbit data.

This technique will be used to calculate a narrow range of acceptable values for components such as battery voltage and transmitter current. The empirical models will be generated automatically and periodically updated as the components age or wear-in. A prototype version of this software has been developed by the satellite vendor.

Another approach planned for detecting anomalies that lends itself to automation is to compare the performance of satellites in an orbital plane to each other. This turns the large number of satellites to be monitored into an advantage, allowing each satellite to be compared to seven of its "peers". This is most suitable for high-level performance parameters such as attitude, array sun-pointing efficiency, and battery depth of discharge. For the parameters to be tested in this way, nominal performance is defined as the mean of the group, and satellites with performance that deviates significantly from the group will be subject to further analysis to determine if a fault is the cause. This is a process which also lends itself to automation.

Telemetry evaluation

For the fully deployed constellation, several thousand telemetry points need to be monitored on a nearly continuous basis to determine the health of all the satellites. The large volume of data to be processed necessitates that the monitoring be almost totally automated. The principle issue in designing the telemetry evaluation system is not whether it will be automated but in determining what segment of the system will be responsible for monitoring each telemetry point. Table 2 lists each of the segments of the system that will monitor telemetry and the types of telemetry evaluation functions allocated to each of them.

Onboard telemetry evaluation is used for realtime, continuous evaluation of critical telemetry points for which clear actions can be taken. This includes overcurrent conditions, high transmitter VSWR, low battery state of charge, and large attitude excursions.

The bulk of the telemetry evaluation is performed by the space vehicle management system (SVMS) software in performing an instantaneous vehicle-wide state of health check. Simple limit checks will be made on several hundred telemetry points for each vehicle. In addition, cross-correlation of telemetry from different systems will be done using the analytical models discussed in the previous section. These will be integrated with the SVMS to generate expected values to compare to many critical telemetry points.

The realtime component of satellite telemetry evaluation will be augmented by the Network Management System, which will use a network monitoring tool to monitor all elements of the ORBCOMM, including the satellites, gateway earth stations, and the message switch. The monitoring tool will be used essentially to augment the human controllers by detecting patterns of events that may span long periods of time. For example, it may be

Table 1. Techniques for Nominal Performance Definition

Source of performance definition	Applications	Examples
Static limits	System parameters which are not expected to vary significantly	Regulated voltages Attitude excursions
Analytical system model	Parameters which are expected to vary and for which simple constitutive relationships may be derived	Expected signal levels as function of transmit levels and orbit geometry Bus current as function of relay states
Empirical device model	Parameters which vary widely and for which analytical models are not feasible	Battery voltage as function of DOD and current Transmitter current draw as function of power setting and voltage
Peer comparison	High-level performance parameters	Sun-pointing efficiency of vehicle attitude and array gimbal position Message traffic throughput performance

Table 2. Functional Partitioning of Automated Telemetry Evaluation Process

Location	Data Available	Computing Resources	Response Time	Applications
Satellite	No knowledge of vehicle or system context	Very limited computing resources	Realtime 1-10 seconds	Load shedding at low DOD Single event effect recovery
SVMS	Full vehicle context available	Limited CPU resources	Semi-realtime 1 min to 10 hr.	Most simple limit checks Performance vs. models
MATLAB	Full historical database of vehicle & peers available	"Unlimited" computing resources	Offline evaluation 1 hour - 1 day	Performance vs. peers Long-term trending

programmed to determine if a limit was exceeded on an element more than n times over a time period t.

The final stage of telemetry evaluation is performed by the offline evaluation software. The obvious advantage of offline evaluation is that there are virtually no limits to the processing power, and the full database of all satellites is available. Offline processing consists of a set of analysis programs, implemented mostly in MATLAB, which compare the telemetry values to empirical and analytical models; perform trending analyses; generate comparisons among vehicles in a plane; and generate reports for engineering review.

Meeting Frequency Sharing Constraints

This aspect of operations is expected to be fully automated. Once the precision orbit determination has been performed for each satellite, mission analysis software will perform an interference analysis for each satellite to predict the instances when the ORBCOMM satellites may cause interference. The mission analysis software will generate the stored command loads to be uploaded to each satellite to reduce transmitter power and bandwidth during these periods.

MAXIMIZING SATELLITE LIFE

The one element of the satellite operation which directly affects satellite life is management of battery charge control. The factors affecting battery life which can be controlled are the depth of discharge, and the recharge ratio.

Battery depth of discharge

The relatively high power demands of the subscriber transmitter and the long eclipse times of low earth orbit require that the battery depth of discharge be tightly controlled to meet the five year mission duration. The principle driver for satellite power consumption is the subscriber transmitter. This transmitter is power agile, and can be commanded to transmit at between 10 and 40 W. High power settings are needed in only areas with higher demand for service, while over less populated areas or oceans it may be possible to lower the power output. Thus, significant reductions in orbital average power and battery depth of discharge are possible if the satellite power can be managed as a function of geographic location. This feature will be handled automatically onboard the satellite, with the attitude control system providing navigational information to the command handler, which will issue commands to alter the transmitter power setting depending on geographic location.

Recharge ratio

The second aspect of battery management which affects battery life is the recharge ratio, or the ratio of charge current to discharge current. To maximize battery life, it is important to keep this ratio between 1.04 and 1.06. The capacity can vary significantly over the life of the battery, and the amount of charge put into the battery must be adjusted accordingly. Maintaining the recharge ratio over the life of the satellite therefore requires continual adjustment of the battery full charge point. This will be determined automatically by the onboard battery charge control algorithm onboard the satellite based on feedback from the battery pressure sensors, thus assuring proper control of the recharge ratio without ground intervention. To verify that the recharge ratio is within limits, the telemetry postprocessing software in MATLAB will periodically calculate the recharge ratio and report out of limits conditions to engineering monitors.

CONCLUSION

There are many unique challenges to operating the ORBCOMM constellation. The number of satellites required to perform the mission and the compelling need to keep costs down in a commercial venture combine to make this system a good candidate for application of automated operational processes. With so much autonomy built in to the satellite design, the principal operational tasks of maintaining the constellation configuration and detecting and responding to anomalies have been described. Innovative techniques have been developed for increasing the amount of these functions which can be automated.