Abstract

The ORBCOMM Flight Model (FM) 1&2 and MicroLab I spacecraft were flawlessly launched by a Pegasus® vehicle on April 3, 1995. Following sequential separation from the Pegasus third stage, the spacecraft deployed solar arrays and antenna assemblies, autonomously de-tumbled, and acquired sun-nadir attitude. Both ORBCOMM spacecraft connected automatically with a Gateway Earth Station (GES) about 8 hours after launch. Nominal early passes focused on post-launch housekeeping tasks. However, a series of anomalies developed: including loss of gateway uplink, gateway downlink transmitter oscillation, poor GPS position fixing, subscriber downlink transmitter lock-up, and several software problems. All these conditions were unique to the space environment or resulted from minor design changes or oversights. Eventually the spacecraft were recovered from their outages and the causes conclusively determined. Throughout this time, the spacecraft housekeeping subsystems continued to function nominally with a high degree of autonomy. Following maneuvers and testing, the satellites were delivered to ORBCOMM Global on August 3, 1995.

Introduction and Satellite Description

The Orbital Communications (ORBCOMM) satellite system offers non-voice, non-geostationary (NVNG) digital messaging services between remote or mobile users and customer locations worldwide. As shown in Figure 1, these services are provided via a constellation of small LEO satellites that simultaneously connect the users (called subscribers) to one of a number of gateway earth stations (GESs). The terrestrial network completes the connection between the GESs and the customer facilities. Satellite telemetry and command uses the same network facilities to connect the spacecraft to a central control center. The ORBCOMM network automatically connects the network through the appropriate GES to any satellites in view. This connection may carry user
communications and/or spacecraft telemetry on the backhaul TDMA downlinks to the GES. The GES uplink carries outbound customer packets and spacecraft command messages. The communications links to the remote/mobile subscribers operate simultaneously and in the same band as the gateway links.

Immediately following the 1995 initial launch, the network consisted of the FM1&2 satellites, three GES sites in the U.S. (including a dual site in Arizona) and the central network and satellite control center. A fourth U.S. GES and other upgrades have since come on-line as part of the transition to commercial service.

Each ORBCOMM satellite (Figure 2) consists of an aluminum-beryllium honeycomb ring and single equipment shelf holding the avionics, batteries, and cold-gas propulsion system. The antenna assembly (which also contains the magnetometer and gravity-gradient mass) folds in four pieces for stowage across the center of the equipment bay. Two ultra-thin solar arrays fold 90° from their zenith position to stow against the equipment shelf and across the “top” of the spacecraft body. Following launch, the deployed arrays are positioned in elevation by a single-axis drive and in azimuth by the spacecraft’s yaw motion. Attitude control uses a combination of magnetic torquers and weak gravity-gradient; a magnetometer and two staring horizon sensors determine attitude. The ACS propagates an orbit ephemeris based on information from the on-board GPS receiver; no other tracking is used.

For launch, the spacecraft simply stack on their matching fittings atop the Pegasus or Taurus® vehicle; each spacecraft can carry the weight and bending moment of seven others. This allows launch of an entire orbit plane with one vehicle. Alternatively, other payloads may be mixed with ORBCOMM spacecraft for polar or replenishment missions. The 1995 mission (Figure 3) launched ORBCOMM FM1&2 with MicroLab I, another MicroStar spacecraft derived from the ORBCOMM design.

The spacecraft’s avionics (Figure 4) comprise three serial busses radiating from a central flight computer. This computer handles telemetry, command, message storage and other message routing functions, and hosts the master health and maintenance (H&M) task. The first serial bus connects to the attitude control electronics (ACE) which autonomously runs all ACS functions and software, and the battery charge regulator (BCR).
Figure 3. Pegasus Launch Configuration.

The BCR is the heart of the peak-power-tracking power system and includes a main bus/battery charge 11-17 volt regulator, central 5-volt regulator, and an additional 5-volt "phoenix" regulator that powers the BCR itself. The second serial bus connects to the gateway transceiver, which handles up- and downlinks to the GES. The third bus connects the computer to the dual subscriber (downlink) transmitter (STX), and the seven-channel subscriber (uplink) receiver (SRX). An additional UHF beacon is also provided. Each major avionics unit contains a 68302 microprocessor. A slave processor in the flight computer provides additional serial links for the launch vehicle interface and test port.

Orbital Sciences Corporation (OSC) builds and launches the satellites under contract to ORBCOMM Global, L.P. ORBCOMM is an equity partnership of OSC and Teleglobe, Inc. OSC also provided the satellite control center and operated the satellites during initial operations and testing.

Launch Site Operations

The FM1&2 satellites shipped to the Vandenberg AFB launch integration site on the evening of March 2, 1995. The antenna assemblies and solar arrays were transported separately from the spacecraft bodies to minimize the stowage time of the densely-packed fiberglass/copper antenna elements. Upon arrival, the spacecraft immediately began a brief final test and integration flow (Figure 5). First, batteries were reconditioned, calibrated and charged. Abbreviated systems tests followed. Then the antennas were installed. Following RF communications checks, the solar arrays were installed and the electrical connections to the spacecraft confirmed. Connections from the array-mounted GPS antennas to the receiver were also verified. Then the antennas were carefully folded and packed in the narrow stowage trough.

The launch site operations were designed to hold the maximum antenna stowage time to about two weeks. Though no long-term deleterious stowage effects had been found, tests had shown that the antenna elements took a short-term "set" while in the tight confines of the trough. Therefore the stowage time was taken as a soft launch constraint. Following antenna stowage, the arrays were folded and attached to their redundant non-explosive deployment release. Then the two spacecraft were stacked in a horizontal position. A single lift and rollover operation mated the pair of spacecraft to the top of MicroLab I (Figure 6), which had just completed similar preparations and was already mated to Pegasus. The standard Pegasus integration and test flow was to prepare the vehicle and confirm the payload interfaces.

Launch site operations proceeded quite smoothly. Only two minor integration problems occurred: a minor software bug in the customized Pegasus telemetry initially caused communications problems. More seriously, the zero-force separation connector used between MicroLab and FM2 failed to fully engage after the spacecraft were mated. This forced the spacecraft to be demated, the connector adjusted, and the mate operation repeated. The connector has been relocated on future spacecraft to improve access in the launch configuration.

Battery enable plugs were installed prior to fairing installation. This turned on the spacecraft's 5-volt bus and forced continuous trickle-charge and spacecraft telemetry monitoring during the final days of Pegasus preparations. This condition also
required a mobile power supply during rollout from the integration facility to the flight line. Future Pegasus missions will permit installation of the plugs on the flight line to simplify payload operations.

**Launch, Deployment, and Initial Contact**

During final pre-launch operations, some key personnel were able to return to Virginia to support initial operations. Launch control room staff consisted of the vehicle engineers for the development, FM1, and FM2 spacecraft, the I&T manager, the program manager, and an ORBCOMM Global representative. Additional launch site personnel supported electrical and mechanical operations, flight assurance, etc. Spacecraft telemetry during launch was simple; the number of personnel was set to have expertise available in an anomaly.

Launch was scheduled for March 17 but fog prevented Pegasus carrier aircraft takeoff. A second attempt the following afternoon was aborted during captive carry flight when thermal protection material debonded from the Pegasus fairing. Both of these attempts had been scheduled for a late afternoon launch, resulting in daylight aircraft operations and an initial orbit with no eclipses for approximately two weeks. Launch preparations and countdown conveniently occurred during the normal working day.

All spacecraft telemetry during the aborted attempt was nominal. As expected, the spacecraft gradually cooled at altitude, and the lower battery temperatures increased their capacities. This resulted in additional trickle and topoff charging from the power supply on the aircraft. Landing loads on the return to base were not a concern.

However, the time required to remove and repair the fairing exceeded the two-week antenna stowage limit. Based on our recent experience handling the antennas and spacecraft, we decided that demating the spacecraft and subjecting the antenna assembly to another stowage cycle posed greater risk that the stowage effects. No asymmetric patterns or other side effect have been detected on orbit. However, this event highlighted the need to design a more "comfortable" antenna stowage and guarantee stowage times well beyond that needed for a nominal processing cycle.

The time to repair the fairing forced a switch to an early morning launch window to maintain the initial sunlit orbits. In addition to the annoyance of forcing early morning countdown operations, this placed the best daily series of passes in the late...
evening and overnight on the U.S. east coast during the first several weeks of operations. This was to later have a serious effect on team fatigue during troubleshooting.

On April 3, 1995, Pegasus launched successfully into an excellent 741 x 759 km orbit, inclined 70.03°. (Target was 739 x 743 km.) Telemetry via the Pegasus link indicated that the grazing solar incidence on FM1’s top panel began charging the batteries following fairing separation. Separations occurred at nominal times and attitudes according to the sequence shown in Figure 7.

The Arcade, New York GES successfully connected to both spacecraft approximately 8 hours after launch. Both spacecraft had autonomously acquired an upright attitude and killed residual tipoff rates from separation. One was already in ACS nadir-yaw mode. This is the best, and nominal operating, mode of the ACS where it both points the antenna at nadir and tracks the sun in yaw. The FM2 spacecraft was in “safe-hold” mode, where the attitude estimator is using horizon sensor data, but the yaw steering has not yet been initiated. Both these conditions indicated low tipoff rates, excellent ACS performance, or both. And one of the significant technical risks—autonomous ACS mode-switching—had worked flawlessly. In addition, all the spacecraft’s power systems, thermal control, and other subsystems were behaving nominally. And, best of all for the communications mission, this telemetry had been received on a 3° elevation pass.

Operations on the next four passes consisted of dumping “back-orbit” telemetry stored since launch, loading initial stored commands, and continuing to verify initial spacecraft operation. Launch telemetry also confirmed that deployments had been nominal; the spacecraft’s all-new array and antenna systems had worked as intended. All passes were fully staffed at this time. Meanwhile, the launch team slept and began to return east. ORBCOMM personnel began to evaluate the communications system, taking spectral scans of the uplink band using the SRX. This was a high priority mission because the level and nature of interference in the band is important to the system’s operations.

Anomalies and Recovery

On the sixth pass, FM2 failed to connect to the GES. FM1 connected normally to the same GES, seeming to rule out GES or network problems. This was the first of several, at times interlocking,
anomalies that clouded the early days of the ORBCOMM mission (Table 1). Though the table summarizes the most probable causes, the anomalies were resolved with a combination of traditional fault-tree approaches, testing on qual and engineering model hardware, analysis, creativity, and luck.

A good GES connection relies on proper GES software and modem configuration, working RF transmit and receive sections in the spacecraft transceiver, digital signal processing of the received uplink, and enough baseband processing to process the incoming messages and respond. The network commands the appropriate GES to send messages that begin the connection protocol when a spacecraft comes into view. The transmission occurs on the nominal uplink frequency but is pre-corrected for the anticipated doppler effect. The spacecraft's gateway transceiver is tuned to the nominal receive frequency, and has an effective frequency offset capability of less than 400 Hz. The transceiver's DSP-based demodulator constantly attempts to extract valid bits from the incoming signal and look for a packet preamble. The receiver DSP then demodulates the rest of the packet and passes it to the transceiver's 68302. It is then forwarded to the flight computer for routing by a network packet management task. This task also generates a return message that replies to the GES's attempted connection. That message passes to the gateway transceiver's 68302, which sends it to the transmit DSP for modulation. When received at the GES, the observed downlink frequency error is used to refine the uplink doppler pre-correction. Successful completion of the full exchange is called a "connection" and enables the flow of up and downlink commands, telemetry, and message traffic. Therefore such a connection uses the transceiver's RF functions, both DSPs, and the 68302 processors in both the transceiver and the flight computer.

Two simplified links also exist. The first, which originated as a test mode, bypasses certain network software. This approach, though reducing the amount of software required, does not guarantee delivery of packets like the full 'connect' protocol. The second provides a means for the gateway transceiver to reset all spacecraft microprocessors and reload the DSP code and parameter images in all the RF units. This master reset requires certain transceiver functions, but eliminates most of the other spacecraft hardware and software. FM1&2
Stage 3 Burnout Drop + 9 Min 14 Sec
FM1 Ejection S3B + 40 Sec
Stack 180° Reorient S3B + 50 Sec
FM2 Ejection S3B + 80 Sec
MicroLab Ejection S3B + 97 Sec

+ Velocity

Antenna Deploys S3B + 143 Sec
Folded Boom Deploys
Solar Panels Deploy S3B + 115 Sec

Gravity Gradient Acquisition Starts
Nominal Attitude Acquired
Start Drift Toward Station

Figure 7. Launch Sequence Diagram.

Table 1. Master Table of Anomalies.

<table>
<thead>
<tr>
<th>Anomaly</th>
<th>Cause</th>
<th>Constellation Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>FM2 Uplink Loss</td>
<td>Upset in GWRX DSP Resets Disabled</td>
<td>Improved Reset/Watchdog Strategy; Improved Ops</td>
</tr>
<tr>
<td>FM1 Subscriber Bus</td>
<td>Probable PROM SEL</td>
<td>Replaced PROMs; Additional Screening for SEE; Improved Bus Protocol</td>
</tr>
<tr>
<td>Gateway Oscillation</td>
<td>Coupling of STX Signal into Last HPA Stage When Undriven</td>
<td>Change Matching Circuit Between HPA Stages; Additional Testing/Analysis</td>
</tr>
<tr>
<td>Poor GPS Fixing</td>
<td>Interaction Between Variable Antenna Geometry and Satellite Tracking Algorithm</td>
<td>Use Fixed GPS Antenna; Correct Receiver Software Bugs</td>
</tr>
<tr>
<td>Miscellaneous Software Bugs</td>
<td>See Bug List</td>
<td>Incorporate Known Fixes</td>
</tr>
</tbody>
</table>

Early in the mission, the spacecraft used a broadcast telemetry mode so that telemetry was available even if they did not connect to a GES. Thus, basic FM2 telemetry was available despite its failure to connect. However, in addition to its failure to connect, FM2 stopped sending telemetry from its gateway transceiver. This prevented analysis of software status, tuning frequencies of the transmitter and receiver, uplink signal strengths, etc. Commands sent in the test mode described above failed operate any function that could be observed in telemetry. Nor did commanded resets of the gateway transceiver processor cure the problem. Later tests would show that no uplink packets had even reached the gateway transceiver’s 68302 processor. The spacecraft was likely to be lost unless the gateway transceiver could be reset or the master reset activated.
The situation of a non-responsive unit had been foreseen in the software design and mission plan. Each unit’s 68302 processor is polled by a health and maintenance software task on the flight computer. Units that fail to respond are normally automatically reset. However, late in the program, such automatic resets were disabled due to concerns about their effect during captive carry and launch. They had not yet been re-enabled when FM2 failed. This poll/response system only guarantees basic functioning of the 68302; it does not ensure proper operating task or operation of the DSPs in the SRX and gateway transceiver. This approach is being upgraded for FM3-36.

Therefore, stored command “watchdogs” to reset certain units on timeout were also planned. In particular, one such command will reset the gateway transceiver. This reinitializes its DSP and reloads all the parameters and software necessary for demodulation of the gateway uplink. However, these commands were not yet loaded into the spacecraft.

That left only the master reset (firecode) commands. However, this early in the mission, the two spacecraft had separated by only a small orbital arc. Thus, a firecode sent to FM2 would also affect FM1. With the future of the ORBCOMM project vested in FM1, we were extremely reluctant to completely reset it in an attempt to recover FM2. After about 10 days, limited resets were attempted while FM1 was below the GES horizon. However, these had the disadvantage of poor elevation angle, multipath, and time limits on the attempts. Gradually, the attempts moved higher in elevation as the spacecraft separated. The uplink was swept in frequency and various possible flaws in the modulation were countered. All attempts failed.

Both simple and exhaustive fault tree analyses were completed. However, the successful operation after launch, FM1’s use of the same GES and network assets and software, and lab testing on the qualification spacecraft eliminated most of the hypothesized failures. Those remaining included a sudden hardware failure in the gateway receiver, antenna, or reset circuitry; a mis-tuned receive synthesizer; or a receive DSP software fault, single-event upset, or latchup. Poor doppler correction on the “open-loop” uplink also could not be eliminated by ground testing, and FM1 had experienced a number of minor difficulties with other dirty-pipe commands. Other minor software bugs affecting FM1, the additional anomalies described below, and quirks in software operation triggered by unforseen side-effects of the actual SRX received spectrum contributed to the confusion.

The anomaly disrupted the operations plan, which had assumed a measured pace of testing over three months while the spacecraft drifted to their positions. Rather than the two operators, operations director, and supporting engineering planned, teams of engineers were added to the control center and pass planning to conduct the in-orbit recovery attempts. These engineers and others also conducted lab tests at other times of the day. People gathered outside the glass-walled control waiting for the latest news following a pass. Management and the program team were under extreme pressure due to the program’s visibility, importance to both ORBCOMM and OSC, and self-imposed dedication. The spacecraft team, already tired from the pre-launch schedule, attempted to adjust to working midnight passes on top of a day job. Efficiency and morale correspondingly suffered: crisp debugging skills eluded a team that recently had solved many obscure development problems quickly.

**Subscriber Bus Anomaly**

Approximately 12 days after launch, telemetry ceased from FM1’s STX and SRX. Reset commands to the units failed. The transmitter also failed to respond to observable frequency assignment commands. Cycling the 14-volt bus power at the BCR also had no effect. Again, fault tree, telemetry/timeline, and other classic analyses were employed to track down the problem. The primary clue was subtle changes in the SRX current consumption around the reset and power cycling events, as well as during the original anomaly.

The flight computer, STX, and SRX communicate on a physical bus that behaves, for telemetry, command and packet data, as a token ring. The flight computer generates a token message, appends its command or data messages, and sends them to the STX. The STX then can talk on the bus for a limited period before passing the token to the SRX, which in turn returns it to the flight computer. However, some of the network software in the flight computer commands SRX uplink channel modes directly, bypassing this token protocol. Following a reset, SRX current draw first increases as one channel’s DSP begins normal operation. However, a second small current increase could be
seen—possibly DSPs on the other channels being commanded into their operating modes from idle.

Lab tests confirmed the current levels corresponded to this normal behavior. A small software patch was developed and tested to route the token in reverse—to the SRX first. Uploading of this patch restored the SRX telemetry, confirming that the STX was losing the token. Likely faults remained a hardware failure or digital circuitry latchup. Lab tests also showed a sneak path from an unswitched 14 volt line that might have prevented complete removal of the 5-volt supply during a reset.

GPS Anomaly

Throughout the early operations the Trimble Navigation GPS receivers on both spacecraft would sometimes fail to provide navigation fixes for an extended time. During outages, the ACS propagates the emphemeris for its own use, but this propagated state degrades without periodic updates. Extensive testing showed that the outages could sometimes be ended by resetting the receiver. The exact behavior depended, but was not fully explained by, the combination of “hard” (reset line strobing) and “soft” (software commanded) resets used. Loading the GPS with a new emphemeris also helped. Additionally, on-orbit data also indicated a correlation with certain geometries and solar array steering modes.

While the GPS software accounts for GPS SVs being masked by the earth, it does not account for the additional blockage by the spacecraft as the solar arrays rotate. When the array-mounted GPS antennas tilt relative to local horizontal, SVs above the horizon can be obscured by the arrays. Even though enough other SVs are available, the receiver continues to track occulted SVs that are above the horizon through their signal “outage”. If more than two receiver channels are misallocated in this manner, the receiver cannot fix. Resets and emphemeris loads cause the receiver to look for new SVs that are currently showing adequate signals.

A simple test confirmed this theory. The solar arrays were commanded to a horizontal position and held there, so the GPS antennas faced zenith. The receiver was reset, and tracked SVs properly. A variant of this geometry-reset strategy provides an operational workaround.

Though the receiver software was tested in an orbital mode, the vendor did not fully understand the geometry effect. Conversely, the subtleties of the tracking algorithm were only fully understood by Trimble; spacecraft testing focused merely on the number of visible SVs. The ORBCOMM satellites now under construction feature body-mounted GPS antennas to avoid the varying geometry. (The array mounting on FM1&2 was a leftover from attempted GPS attitude determination, which did not work.) These spacecraft also use a more advanced Rockwell receiver. Finally, OSC has upgraded its GPS testing capability to allow full combined orbital and geometric signal simulation.

Recovery

The GPS problem also existed on FM2, but it could not be reset or loaded with new emphemerides. The on-board emphemeris gradually diverged from the actual one until an occasional GPS fix would correct it. When this divergence became great enough, the ACS yaw steering degraded. Eventually, solar array pointing became poor enough that deep battery cycles were needed to support the modest power loads on some orbits.

The ORBCOMM spacecraft are specifically designed to recover from a zero-power condition. This power-system feature, known as Phoenix mode, was tested extensively during development. Lacking any battery power, it first powers the BCR electronics from any solar array output there is. Additional power is crammed into the batteries at whatever rate is available, and essential loads are restored as the state of charge reaches predetermined levels. When nearly full panel output is available, this recovery can take less than half a daylight period on a single orbit.

On the morning of May 13, FM2 automatically connected to a GES. A telemetry dump indicated that the power system had passed through Phoenix mode and all avionics had reset. Watchdog commands were loaded and health and maintenance automatic resets enabled. Testing indicated no other hardware degradation. FM2 was back!

The healthy state of FM2 enabled us to prune the fault tree significantly. This narrowed the likely faults to a latchup or (more likely) SEU in the receiver DSP. Upsets in the data memory could have desensitized the receiver, or critical chip
operation could have been disrupted. While we were aware of this vulnerability—DSP operation was required even for a master reset—the lack of stored watchdog commands failed to protect us as planned. Further thinking about the reset design has lead to a much more robust approach for FM3-36.

A complete power cycle also seemed the best way to clear the subscriber transmitter fault on FM1. A stored command sequence was developed that would deliberately starve the spacecraft for power and deplete the batteries. On-orbit this proved surprisingly difficult to do—the spacecraft is quite effective at restoring a power balance in sunlight and exact time of battery exhaustion is difficult to predict. When power depletion finally coincided with eclipse on June 13, FM1 successfully passed through Phoenix mode and reconnected with the network automatically on the next pass. STX telemetry had already resumed. Following the normal recovery process, STX testing indicated no damage.

Again, the healthy hardware limited the number of possible causes of the outage. Analysis indicated that the most likely cause is a latchup in the STX controller’s PROM chip. This part has been removed in the newer design, and additional latchup protection features added. In addition to improved reset procedures, the upgraded power system on FM3-36 allows switching of the 5 and 14-volt power to each unit independently. This allows controllers to clear a latchup immediately without affecting overall spacecraft operation. Improved solid-state switching and several innovations in the wire harness design make this approach practical within the tight ORBCOMM mass constraints.

**FM2 Gateway Transmitter Oscillation**

In early June, routine SRX scans of FM2’s receive band showed an elevated noise floor. This slightly worsened over a period of days. Gateway transmitter “off” current (measured during non-transmitting slots in the downlink TDMA protocol) was also high. Furthermore the STX had to be on and operating at full power to trigger the behavior after the gateway transmitter was power-cycled.

The gateway transmitter uses a Class C high-power amplifier final stage. Its driver stage’s collector is nominally off, but is turned on by the transmitter DSP whenever a burst is being sent to the modulator. However, to save power, the final stage does not use a switch; power is always available at the collector.

With its tight power, mass, and volume constraints, transmit-receive band separation of only 7%, and in-band VHF backhaul links, the electrical isolation between antennas is critical. This applies to both transmitter-transmitter isolation (where the filters provide little help), and isolation between either transmitter and either receiver. Isolation between the subscriber transmit and gateway transmit antennas consistently measured about 23 dB across several flight and qualification assemblies. Most system-level communications testing used an antenna simulator containing attenuators to prevent radiation and mimic the isolation on each path. The flight and qualification spacecraft were also tested in a large anechoic chamber for proper transmission and isolation. None of these tests indicated an oscillation problem.

However, testing with spare STXs and gateway transceivers in the lab indicated that a reduction in isolation could eventually induce oscillation during the “off” period, but not always immediately. This effect depended on the particular gateway transmitter used. It also was strongly sensitive to the exact antenna isolation—a change of about 2 dB could take the setup from normal operation to guaranteed oscillation. This, coupled with the sensitivity to a particular amplifier, meant that FM1 was unlikely to experience the problem. Happily, after an initial degradation, the transistor did not appear to be damaged further.

For FM1&2, a workaround has been developed that involves using the minimum STX transmit power necessary for a locally good packet downlink error rate and switching it off when not connected to the network. For FM3-36, the redesigned antenna provides additional isolation and both HPA stages are switched off between downlink bursts. For testing, antenna simulator isolation has been set more conservatively.

**Software Anomalies**

Several software bugs were uncovered during operations. Most were minor and easily repaired. However, all served to obfuscate the troubleshooting on the major anomalies. The two
most significant were particularly related to the on-orbit operations.

A number of units were reset by the health and maintenance (H&M) task on the flight computer for no obvious reason. In all cases, the units appeared to be overdue in their responses to H&M polls. Thinking the units hung, H&M reset them. Though often apparently random, resets sometimes occurred in batches. Exhaustive timeline analysis showed a partial correlation with one of the two types of stored telemetry dumps. Certain patterns of ORBCOMM test traffic, the downlink TDMA assignments, and GPS receiver resets also seemed to have a poorly correlated effect.

The cause was flight computer processor peak loading. Resets occurred when the H&M task failed to listen to the returned message from a unit until after the timeout had expired. This behavior occurred during conditions of rapid telemetry dumping in a particular mode. (This rate was often above the level practical with revenue-generating traffic present.) Resets of the GPS, which caused an ephemeris loading operation, hogged resources. Communications traffic had a minor but finite effect on loading as well. System level tests, though more stressful of individual contributors to the loading, had not often exercised the particular combinations now causing problems, but many repetitions of the stressing load conditions were required to generate a reset. Numerous fixes were possible, but the simplest one was to increase the allowable timeout period. Since the peak loads were brief, no other problems arose.

The SRX 68302 processor also became momentarily overloaded at times. Generally this happened out of ground contact. The SRX and the system had both been tested for large single and broadband interferers thought to be representative of the flight spectral environment. However, certain characteristics of the actual uplink noise environments could more heavily load the active channel assignment task. Because these cases were unknown before FM1&2 collected detailed spectral data, and they are less stressful to the RF functions and channel availability, they were not tested.

Initial Operations

With the anomalies fixed, initial operations proceeded smoothly. A single operator could easily handle both spacecraft; planning, analysis and other support functions could be done on a daily basis without shift work. Telemetry logging, pass plan generation, orbit determination, and other software tools worked as planned. Many passes were declared to be "listen only" or simply not used as a contact.

Additional engineering support was used for maneuvers and on-orbit testing. Maneuvers began with a series of calibration firings to allow correction of thruster misalignments. This was simple on FM1, but the misalignment or deployed c.g. offset was much greater on FM2. Then maneuver commands are loaded that fire the thrusters at a selected point in the orbit if the attitude is within certain constraints. Thruster disturbances typically caused the ACS to lose sun-tracking and sometimes caused significant pitch and roll excursions. (Despite the mass penalty, FM3-36 use a three-thruster arrangement to simplify calibration burns and ground alignment, and reduce attitude disturbances).

Table 2 summarizes the on-orbit testing results. Power, ACS, and other housekeeping systems were mostly "tested" by analysis of routine telemetry. Communications links were exercised by a calibrated series of uplinks and careful measurement of downlink behavior. ORBCOMM Global also began extensive message traffic tests during this period.

Having successfully completed the planned on-orbit tests, the spacecraft were delivered to ORBCOMM Global on August 3, 1995.

Key Design Upgrades

Table 3 summarizes the most significant design changes from FM1&2 for FM3-36 now under construction. Most of these changes had been identified before launch as a result of the intense effort to integrate and qualify FM1&2. Some also reduce mass, enhance performance, or extend the satellite design life to 5 years from the original four.
Table 2. On-orbit Testing Summary.

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Tests/Objectives</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attitude Control</td>
<td>Pointing for communications &lt;br&gt; Auto. Acquisition/mode transitions &lt;br&gt; Fixed yaw for thrusting &lt;br&gt; Recovery following thrusting &lt;br&gt; Thruster control &lt;br&gt; Solar array pointing/feathering</td>
<td>All functions verified. Better nadir pointing (7°, 3σ vs 10° requirement) than expected. Yaw performance about 90% efficient vs. 95% goal</td>
</tr>
<tr>
<td>Power</td>
<td>Solar array output &lt;br&gt; Heater operation &lt;br&gt; Battery operation &lt;br&gt; Auto mode transitions &lt;br&gt; Load shedding &lt;br&gt; Phoenix mode recovery &lt;br&gt; Reset response &lt;br&gt; Eclipse transitions/management &lt;br&gt; Thermal and misc. telemetry</td>
<td>All functions verified. Solar array output about 8 W low due to excessive harness losses and other effects.</td>
</tr>
<tr>
<td>Flight Computer</td>
<td>Real time and stored commands &lt;br&gt; Telemetry gathering &lt;br&gt; Backorbit telemetry &lt;br&gt; Health &amp; Maintenance functions &lt;br&gt; Resets of other units</td>
<td>All functions verified. Some problem with H&amp;M timeouts.</td>
</tr>
<tr>
<td>GPS</td>
<td>Position and time fixes &lt;br&gt; Good, but infrequent at times due to geometry. &lt;br&gt; UTC/GPS time error on resets until initialized.</td>
<td></td>
</tr>
<tr>
<td>Gateway Link</td>
<td>Downlink performance &lt;br&gt; Uplink performance &lt;br&gt; Timing synchronization &lt;br&gt; Master reset operation</td>
<td>All functions verified. Signal strengths close to pre-launch expectations</td>
</tr>
<tr>
<td>Subscriber Uplink</td>
<td>Packet error rates in all modes &lt;br&gt; Mode selection &lt;br&gt; DCAAS (spectrum/channel assignment function)</td>
<td>All functions verified. Slightly high false-acquire rates. DCAAS sensitivity to certain noise patterns loads processor.</td>
</tr>
<tr>
<td>Subscriber Downlink</td>
<td>EIRP &lt;br&gt; Tuning &lt;br&gt; Power Control &lt;br&gt; All functions verified. EIRP close to pre-launch expectations.</td>
<td></td>
</tr>
<tr>
<td>UHF</td>
<td>EIRP &lt;br&gt; Frequency and Stability &lt;br&gt; Verified.</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Design Changes for FM3-36.

<table>
<thead>
<tr>
<th>Subsystem/Item</th>
<th>FM1&amp;2</th>
<th>FM3-36</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>VHF Antennas</td>
<td>Array of quad helices</td>
<td>Large quad helix</td>
<td>Performance, simplicity, requirements relief</td>
</tr>
<tr>
<td>Subscriber Receiver</td>
<td>Double-het/DSP</td>
<td>Direct conversion DSP</td>
<td>Mass, volume, performance</td>
</tr>
<tr>
<td>Subscriber Transmitter</td>
<td>Dual 20 watt</td>
<td>Single 40 watt, OCXO</td>
<td>Simpler antennas, better stability</td>
</tr>
<tr>
<td>Gateway Transceiver</td>
<td>8-bit processor</td>
<td>16-bit processor, OCXO</td>
<td>Better software distribution, stability</td>
</tr>
<tr>
<td>BCR</td>
<td>Original design</td>
<td>Upgraded switching</td>
<td>Better SEL protection, operational flexibility</td>
</tr>
<tr>
<td>Solar Arrays</td>
<td>Silicon</td>
<td>GaAs</td>
<td>Power, extra life</td>
</tr>
<tr>
<td>GPS</td>
<td>Trimble TANS</td>
<td>Rockwell MPE</td>
<td>Size, mass, power, performance</td>
</tr>
<tr>
<td>ACS</td>
<td>g-g/magnetic</td>
<td>Vertical wheel added</td>
<td>Improved yaw performance</td>
</tr>
<tr>
<td>Operating system</td>
<td>MPX/OSX</td>
<td>VxWorks</td>
<td>Improved development support, reliability</td>
</tr>
<tr>
<td>RCS</td>
<td>2 thrusters</td>
<td>3 thrusters</td>
<td>Relaxed alignment, longer burns</td>
</tr>
</tbody>
</table>

However, two additional key design upgrades resulted from the on-orbit experience. The first of these is a greatly improved reset/watchdog strategy. The reset approach uses four distinct levels of monitoring to recover portions of the spacecraft’s avionics function. These levels start from unit internal software self-monitoring and hardware watchdog and progress to a means for cycling power to the entire spacecraft. A function similar to FM1&2’s commanded reset is retained, but
woven into the more-comprehensive strategy. The design explicitly incorporates well-analyzed features at several of the levels to deal with single-event effects, which are difficult to test at the system level. The improved reset strategy has forced a straightforward but significant design change to most unit designs.

Improved piece-part choices, testing, and protection represent another general upgrade for the new spacecraft. ORBCOMM could not be built without using the latest DSPs, analog-to-digital converters, FPGAs, and other modern (frequently CMOS) parts. These parts often are newer than anyone’s “approved” list. A major effort was made to substitute parts which have inherently better radiation characteristics, or for which data was available. A substantial test program has characterized dozens of parts for total dose and single-event effects where this was not possible. In addition, the commercial part screening program used on FM1&2 has been enhanced. Finally, the unit designs have improved protection against damage from SEL current in critical parts.

Conclusions

ORBCOMM FM1&2 overcame initial operational difficulties and have now operated successfully for over a year. The all-new spacecraft successfully demonstrated highly autonomous acquisition, bus system performance, and simple operations. Performance of the complex communications system has matched that anticipated at launch.

Minor effects of the orbit and operational environment caused major anomalies. Critical conditions may be hard to foresee or simulate in test, but a good reset strategy can cure a lot of ills. The reset/watchdog strategy should be simple, comprehensive, and minimize disruption of revenue-producing services. Special attention is warranted for exceptions, such as non-conforming units (how is the watcher watched?), unusual modes (launch), or less-protected systems (gateway receive DSP). Modern parts will experience SEUs, and upsets will not wait until operations are ready for them.

Operations planning must assume that anomalies will occur during initial operation of any complex new spacecraft. Some portion of the engineering team should not be exhausted following launch.

Only anomalies that threaten further damage to the spacecraft need immediate attention. Otherwise, Kepler and Newton guarantee both the spacecraft and the sun will pass overhead tomorrow. Disconnect the troubleshooting and analysis from the operations and pass-taking as much as possible; engineering isn’t done best as shift work by those not used to it. An exhausted team is easily confused by the many false leads. Everyone from top management to the pizza delivery boy should assume that resolution will take many days or weeks, and plan their work, rest, briefing requirements, support needs, and attitudes accordingly. Prioritize problems and assign a unique troubleshooting team to each one. Finally, don’t give up—spacecraft are recovered after long outages.

Reference

1 Stoltz, Paul M., Krebs, Mark R., and Baltman, Richard, ORBCOMM Attitude Determination and Control, AIAA 96-3620.