A NON-STANDARD PRODUCTION APPROACH TO SATELLITE CONSTELLATIONS

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Abstract

A non-standard approach solves several problems encountered in the production of commercial constellations consisting of relatively large numbers of spacecraft. In a commercial environment, market pressures drive the need for a rapid production schedule and highly reliable satellites. This dictates a departure from a conventional spacecraft production process.

The ORBCOMM spacecraft program has developed a singular approach to spacecraft production. This new approach consists of three major elements:

- On-line Production Process: On-line procedures guide the production process. The engineers input procedure modifications directly into the database that are then immediately accessible. The process incorporates on-line non-conformance reporting. Integrated quality assurance, configuration management, and assembly procedures reduce the turnaround time to process changes and anomalies. The data feeds directly into an on-line status database that automatically tracks progress.

- Automated Functional Testing: Automated functional test procedures, created during the development and qualification phases of the program, allow for repeatable and consistent testing for production units. The tests minimize operator involvement and real-time decision-making. They provide real-time limit checking and maximize automated data analysis, reducing test durations. Test results and status tie directly to the status database.

- Streamlined Testing: Rigorous box testing reduces the probability of unit failures during system integration and testing. After successful design verification, the production vehicles undergo drastically reduced system level environmental testing. The tests verify minimal functional requirements and screen workmanship problems.

The production and testing of the second generation constellation of commercial ORBCOMM satellites, consisting of more than thirty spacecraft, implement these elements.

Introduction

ORBCOMM is a satellite-based two-way near-real-time global communications system. The system consists of a space segment and a ground segment. The ground segment comprises a series of ground stations, called Gateways, and hand-held terminals capable of receiving and transmitting messages, called Subscriber Communicators. The space segment comprises several planes of spacecraft in low earth orbit. Two planes of two spacecraft each are in high inclination, polar orbits. Three planes of eight spacecraft each are in forty-five degree inclination orbits. The option also exists for one additional plane of eight spacecraft. Combined, these spacecraft make up a constellation that provides near global coverage.

Launched in early 1995, one plane of high inclination spacecraft is in operation at this time. The current challenge is to build, test, and launch twenty-six spacecraft quickly and efficiently, along with building and testing eight spare spacecraft. The drive to be "first to market" produces schedule pressures that translate into a complex analysis of schedule versus risk.

Schedule pressures dictate parallel efforts on several fronts. The manufacture of qualification hardware immediately follows development hardware. Flight hardware production starts before the completion of the qualification program.

Another example of parallel processing is in the test area. To mitigate the effects of the functional test development process, test development is decoupled from environmental testing. Environmental testing of the early spacecraft uses a hardware test that tests all hardware, but does not include high level functionality. In this way, the spacecraft assembly and environmental test process can continue in parallel with the functional test development.

Because of the relatively large number of spacecraft, it is essential to have an efficient and repeatable production and test process. These circumstances result in several challenges, including minimizing the amount of manual data analysis, and minimizing the chance of manufacturing variability, while also minimizing the processing time. The ORBCOMM spacecraft production and test process addresses these issues.

On-line Production Process

ORBCOMM is taking an automated, electronic approach to the entire production process. The development of all assembly and test procedures occurs in a relational database application that has been developed for this use. This approach allows the data associated with the execution of a procedure to be stored in a central location with the actual assembly or test procedure. The reporting of anomalies and non-conformance's relating to hardware fabrication and testing uses the same base application. Finally, a spacecraft status database allows this data to be sorted and queried efficiently. This relational database system is based on a network server that is accessed through personal computers. Figure 1 shows a schematic of the data structure along with the key interfaces.

On-Line Procedure System

The implementation of electronic on-line integration and test procedures offers several benefits in a production process. The ORBCOMM spacecraft approach includes the ability to retrieve the latest revision assembly or test procedure from a central server. This procedure, once released, may be performed multiple times for a single spacecraft or for multiple spacecraft. Unlike most systems in use today, the operator on the floor feeds the data generated during fabrication and test directly back to the central server. The resulting data is easy to sort or query.

To minimize the time required for the operator on the floor to perform the task and record any required data, the ORBCOMM program has developed a unique software application. A desktop relational database approach reduces the amount of computer literacy required to complete the task of data input. The software includes a user friendly front end with as much intuition as possible built into its interface. The system incorporates the following features:

- Access to latest revision procedures from a common interface
- Ability to sign off completed steps
- Password protected fields where necessary (QA fields, engineering signature fields, etc.)
- Real-time correction/modification (redline) of procedures by engineers on the floor (QA approval required before implementation)
- Redlines immediately available (electronically) for incorporation into the next revision
- Limited reference documents on-line
- Common interface to record all hardware and software related traceability information

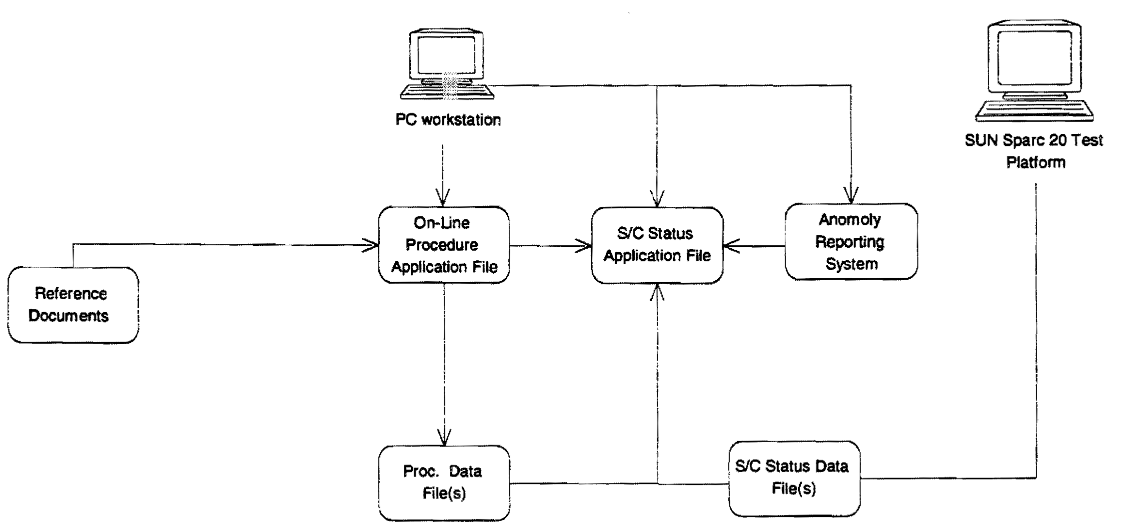

Figure 1 On-Line Production Process Schematic

The software application stores procedural information and the associated data in the same electronic location, but in completely different ways. All associated data is stored on a per spacecraft basis. The procedures themselves are stored independently so that they may be performed on any given spacecraft.

A planning organization writes and maintains procedures. After QA approval, redlines to a procedure are stored with that particular procedure. Before implementation on other spacecraft, the planning organization easily incorporates these redlines into the next procedure revision.

Various levels of security and user privilege exist in this application. Access to unreleased procedures is restricted to a planning organization, configuration management, and various engineering functions requiring review ability prior to release. Operators on the floor do not have access to unreleased procedures. Furthermore, procedures that have been released cannot be modified, only redlined.

Only critical areas requiring signature are password protected. Those areas include procedure release, QA verify/witness, and redlining. The operators performing the procedure may sign and record in all other areas without a password. This minimizes the amount of time spent on typing. The most common input mode for these procedures is clicking with a mouse button. Various drop down lists and combination boxes also minimize typing.

On-Line Anomaly Reporting

The production process incorporates an on-line anomaly reporting system. This central, on-line system allows real-time decision making based on the latest available information. The reporting system resides in the same location as the on-line procedure system and allows seamless entry from one application to the other. The same relational database employed in a run-time environment allows this to occur.

Anomalies encountered during integration and testing are reported directly from the procedure into the anomaly reporting system. Future revisions of both the on-line procedure application and the on-line anomaly system will allow instant data transfer from the procedure system to the anomaly system. This revision will eliminate the need to key in standard information (such as the vehicle serial number, the procedure being executed during failure, etc.).

The anomaly system incorporates the ability to classify incidents or anomalies. Classifications include hardware, software, and ground support equipment. Future versions of the system will incorporate priority identification and automatic email capability to reduce the amount of time required to identify and resolve schedule critical incidents.

Various dispositions exist, depending on the type of anomaly encountered. Since the anomaly report is available on-line, remote access and disposition is possible. To reduce the amount of time needed to resolve non-critical problems, floor engineers have the ability to approve various types of dispositions. More serious problems (non-compliances with respect to form, fit, or function) require higher levels of approval.

Similar to the on-line procedure application, ease of use and intuitive form design has been stressed in the development of the application. Various features have been and will continue to be included in the graphical interface of this application. One element of the automated non-compliance reporting system that will not be lost is the human factor. The ORBCOMM team has realized the importance of team member contribution and has elected to allow the human brain the final say on critical areas of integration and testing.

Spacecraft Status Information

Individual spacecraft performance and/or cumulative spacecraft performance is monitored real time using information from both the electronic integration and test procedures and from the on-line anomaly system. The status system uses the same run-time application that allows the procedure and anomaly systems to work. The status system provides information pertaining to the following:

- Procedure completion
- Test status
- Incident status
- "As built" configuration information
- Automatic transfer of test results, flags, comments, etc., from test scripts

One unique feature of the spacecraft status database is its ability to receive test status information from the spacecraft test station. Since the spacecraft test station operates on a UNIX platform, a way had to be developed to seamlessly transfer data from the UNIX platform to the PC server. Computer programs in C++ and Visual Basic® (by MicroSoft) transfer this data. Following the execution of a spacecraft test script (that portion of code which commands and receives data from the spacecraft during testing), the data is automatically transferred to the PC server without any interaction from the test operator. Once the data resides in the spacecraft database, various queries may be used to view or report this data.

Automated Functional Testing

Approach

The ORBCOMM production program uses automated functional testing. Automating functional testing for the production vehicles saves many hours during the production phase, however, it requires a commitment of schedule and resources early in the program development. The plan requires additional personnel and time to develop automated scripts. These people are different from the design engineers who would otherwise write the procedures and test the spacecraft later in the program—a process typical in a low production rate spacecraft program.

Functional test development, as with many aspects of the program, is divided into parallel paths. The initial test development, shown in Figure 2, is divided into individual box or subsystem tests. Test development to support the first release of software begins upon receipt of the first boxes. The purpose of the first series of tests is to support the system level environmental testing. The first release of flight software is only required to exercise hardware functionality—enough to get through environments and begin spacecraft assembly. Hardware functionality includes exercising power relays, the solar array drive motor, and the attitude control system sensors, along with the manual control of actuators. Later flight code releases include attitude control algorithms and higher level command capability.

The early parallel development has several benefits. Isolating the box test development also isolates debugging of the spacecraft test equipment assembly. Each subsystem or box requires a different subset of the Spacecraft Test Equipment (STE). In addition, decoupling subsystem test development allows each cognizant engineer to work on a single subsystem without interaction with or interference from other subsystems. For example, the power subsystem does not have to service attitude control requests for actuator control.

Automated Spacecraft Test Equipment

Design of the Spacecraft Test Equipment (STE) is critical to the spacecraft production flow. The STE must test the hardware in a safe manner, provide consistency between tests on different spacecraft, provide consistency between different runs of the same test, and reduce operator work load. A total of ten STE sets will be in operation to support all the spacecraft assembly teams, the qualification spacecraft, troubleshooting, and launch site operations.
Figure 3 shows a functional sketch of the STE.

The ORBCOMM program will fabricate a total of ten spacecraft test equipment (STE) rack sets. The

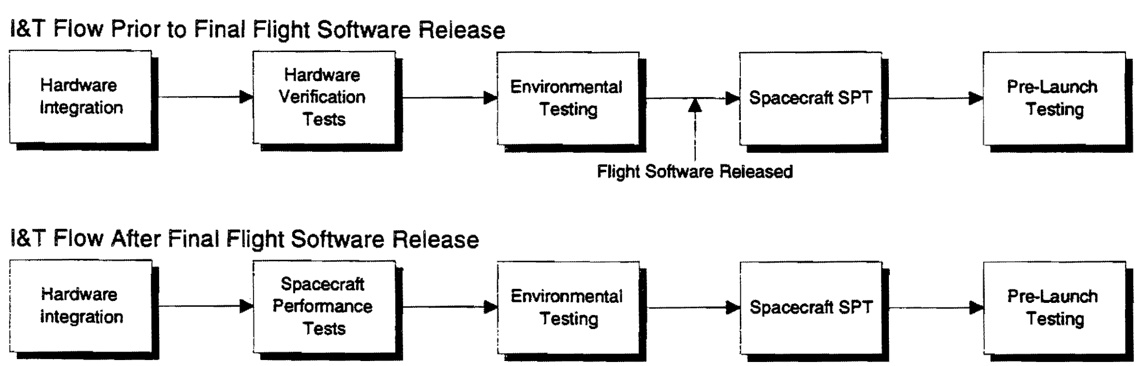

Figure 2 Early and Late Production Test Flows

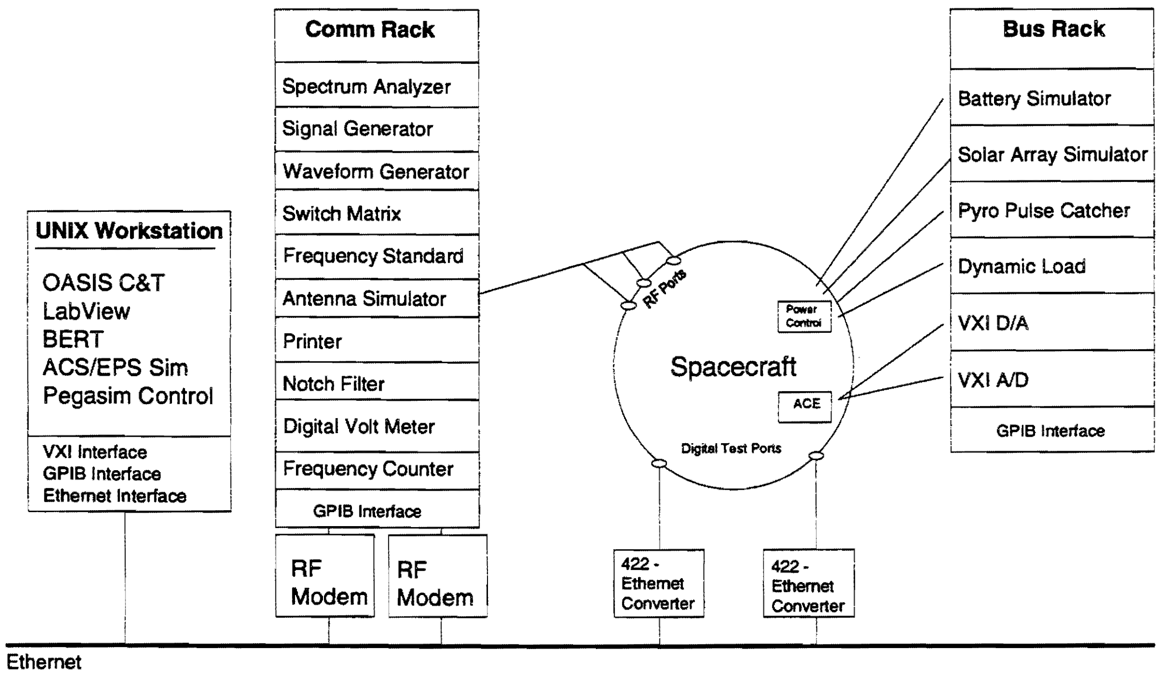

Figure 3 Spacecraft Test Equipment

STE supports all spacecraft testing and unit level troubleshooting. The STE provides many features:

- Ethernet based communication between the spacecraft's test ports and EGSE
- Remote monitoring of spacecraft and EGSE performance
- Closed loop control via GPIB IEEE-488.2 bus
- VXI chassis with complete suite of A/D, D/A, DIO, and high current D/A converters
- Ability to test entire RF communication paths
- Command and decommutate spacecraft command and telemetry with identical tool used during on-orbit operations
- Multiple user interface choices for automated testing and debugging

The reliability and maintainability of the STE is designed to be high. All complex EGSE hardware pieces are commercially purchased and maintained equipment. The custom equipment in the STE consists of an RF switch matrix (GPIB controlled) and the separation/deployment device pulse catcher.

Hardware

The central component of the STE hardware is a UNIX based workstation. From this workstation, an operator can remotely and automatically control all the hardware through GPIB, VXI, or TCP interfaces. The test equipment consists of three full height racks—one bus rack and two racks for the RF communication payload. An Ethernet local area network links all the STE assemblies.

Software

The STE software consists of a UNIX operating system running several applications. The largest application is the command and telemetry system, OASIS (by Laboratory of Atmospheric and Space Physics, University of Colorado). OASIS is the same application used to control the spacecraft on-orbit. Using the same tool provides tremendous confidence in the interface between OASIS and the spacecraft especially during the already tense early orbit operations.

OASIS provides custom screen building capability for clear user interface, scripting capability, and data logging capability. All these features enable OASIS to support automated testing. Custom screens and scripts provide the step by step test operator interface. The display shows the status of each step and is under operator control. The system automatically logs the result of each step for future information and input to the on-line production status database. OASIS communicates with the other software applications via TCP, enabling remote control of applications if desired.

LabView (by National Instruments) controls most of the electrical ground support equipment (EGSE). OASIS communicates with LabView in the same manner it communicates with a spacecraft—through command and telemetry tables. Besides the commercially available software, several custom applications have been developed. The attitude control system (ACS) is tested through a real-time simulation that provides closed loop control of the ACS. The ACS simulation controls the EGSE through GPIB and VXI interfaces. The simulation also provides serial communication directly to the attitude control electronics box to simulate GPS messages and receive attitude information. Other custom software include bit error rate testing software and a launch vehicle simulator, both controllable from OASIS.

Hardware Verification Test (HVT) Development

In any spacecraft program, environmental testing is both time-consuming and poses the highest potential for hardware failures—the reason for environmental testing. The ORBCOMM spacecraft software development, as with many modern spacecraft programs, is critical path. To mitigate the schedule risk posed by hardware environmental testing, the program has implemented the concept of hardware verification testing. The HVT allows the development of software and the integration of the spacecraft hardware to proceed in parallel, thus permitting the spacecraft to undergo environmental test as early as possible.

The HVT requires a rudimentary software release that exercises the lowest level spacecraft hardware functionality and is the earliest software release. Developing the HVT procedures and automated scripts gives the integration and test engineers the first opportunity to work with the EGSE in an automated environment. HVT procedures are written for each box as the first software release for the box becomes available. The HVT is a sequential test of each of the spacecraft's boxes. It uses basic software to exercise each box's hardware and system level hardware interactions. This results in early flight spacecraft undergoing environmental testing as soon as possible. As higher level software functionality is built and released, functional tests are performed on the flight spacecraft at ambient conditions. Once the launch-ready flight software is tested and released, the HVT is no longer performed in the production flow.

Spacecraft Performance Test (SPT) Development

The proper spacecraft system test is critical to an efficient production flow. The test must verify all interaction between subsystems such as box software resets, bus communication, and payload communication. It also must test system level functionality such as power reset strategies and contingency operations. The customer requires traceability between system requirements and test flows. The challenge is navigating between testing all requirements and maintaining a fast production flow. To accommodate both needs, design verification testing is separate from production testing.

Design Verification Testing

The design verification tests satisfy system design requirements and are performed on the qualification model spacecraft (QM) and the engineering development unit spacecraft (EDU). The tests verify software algorithms and requirements not dependent on unit hardware variance. These include verifying navigation algorithms and attitude control algorithms using actual hardware with simulated sensor inputs and outputs, as well as rigorous testing of the power control and battery charge algorithms. Other features tested during the design verification phase include regression tests, where alternate digital and RF communication paths are characterized and redundant systems are exercised.

The design verification tests perform several functions. The development of design verification tests on the EDU or QM spacecraft, serve as a test bed for production tests. By running procedures on non-flight hardware, the debugging of test procedures pose no risk to flight hardware.

Changes to spacecraft hardware and software are verified on the QM or EDU spacecraft prior to incorporation into the flight production units. The design verification testing minimizes risk to flight hardware while maximizing the robustness of the spacecraft.

Production Testing

Production functional tests are a subset of the design verification tests. The production tests focus only on manufacture and workmanship variance and screen out unit specific discrepancies.

Production testing also tests critical spacecraft functions. For example, the test plan includes execution of the launch and deployment sequence. While viewed as a design verification test, because this test sequence is very important and easy to perform, the production program included its execution.

Example Of Classic Battle: R&D Versus Production Viewpoint

Attitude control system design engineers desire a hardware-in-the-loop (HITL) test for each production spacecraft, in addition to the QM and EDU spacecraft. This test allows the attitude control electronics (ACE) to command simulated actuators through the ACE digital to analog and receive simulated analog sensor inputs through the ACE analog to digital under control of the real-time simulation. Integration and test engineers desire only sensor and actuator phasing. Phasing determines sensor or actuator's electrical continuity/polarity and does not require time consuming setup and simulation. The integration and test engineer only requires HITL testing on the QM and EDU spacecraft and only after a hardware or software change.

The solution to the problem balances the hardware design requirements, the box level unit qualification of those requirements, and the spacecraft system requirements. The current design of the ACE box matches specific sensor serial numbers to ACE box serial numbers during unit level acceptance testing. ACE box qualification testing proved the design was tolerant of environmental influences. The resultant test flow only requires HITL testing on the QM and EDU spacecraft and not on the flight production spacecraft. This approach saves time during production and reduces handling of flight hardware while maintaining a reliable system.

Test Automation

Automated testing on the ORBCOMM program saves time during production but is not without its price. The ORBCOMM program chose to pay the high up-front cost of automated test development for the reward of accelerated schedule during production functional testing. Automated testing on the ORBCOMM program starts with the HVT. The HVT concept is simple and lends itself well to focus on the automated aspect of the procedures.

The EGSE hardware and software must be capable of supporting automated testing. Test equipment design must address issues of I/O capacity, computational capacity, user interface, timing between EGSE software, reliability, closed loop EGSE hardware control, and safe operation.

Data Review and Archive

Automated testing benefits the program by recapturing schedule during the spacecraft production phase. While tests can be designed to run automatically and quickly, performing the test only fills the hard drives with data; it does not mean the procedure is complete and the spacecraft functions properly. Data review cannot be overlooked. The final step before a test procedure can be closed is a complete review of the test data. The OASIS test scripts and the LabView test executor check all data real-time during the functional test. These real-time tests only check for simple limit conditions. For more complex data analyses, logged data are converted to engineering units and run through a complex series of mathematical analyses scripts using a popular math scripting language. These scripts will identify telemetry points that are suspect. The post test data analyses tools identify complex relationships between telemetry points. These include manipulation on a time history such as an Eb/No curve, or performing FFTs and providing spectral analysis.

Before closing a functional test procedure, the Product Assurance (PA) engineer must agree that the cognizant engineer has reviewed each relevant telemetry point. Because of the volume of data, it is in the best interest of the cognizant engineer to automate as much of the data review process as possible. After the PA closes a functional test procedure, the data is transferred to a central UNIX workstation on the LAN for archiving the on magnetic tape. The tools and methods used to archive the test data are the same used for on-orbit spacecraft data.

Streamlined Testing

Approach

The goal of the test program is to produce spacecraft that will survive both launch and on-orbit environments and function reliably for their design life. These goals must be achieved within the market-driven constraints of a tight schedule. The ORBCOMM test process balances the need to perform rigorous and comprehensive testing on all spacecraft with the need to launch the spacecraft as early as possible. The risk analysis to decide which tests to do and which tests to eliminate resulted in a streamlined process that reduces significantly the spacecraft integration and test (I&T) time compared to that of past programs.

Failures that occur after completion of spacecraft assembly are the most costly as far as impacts to the overall schedule and risk to hardware. It is most efficient to weed out failures early. Rigorous screening of piece parts, circuit card assemblies, and assembled units allows for an abbreviated spacecraft system I&T process that confirms workmanship, top level hardware and software functionality, and interface integrity issues (such as harness connections). To that end the test program includes several items.

- Dedicated development, qualification, and flight hardware
- Exhaustive unit level testing on all flight boxes and components
- Full spectrum of environmental testing on a set number of spacecraft
- Scaled back spacecraft system environmental testing for the remainder of the spacecraft (i.e., progressive reduction of environmental tests)
- Parallel functional test development and system environmental testing.

The ORBCOMM production program is based on the test criteria established in MIL-STD-1540 and modified to meet the specific requirements of the ORBCOMM mission. Where possible, the design utilizes previously qualified and flown components to reduce cost, testing complexity, schedule and risk.

Test Phases

Test hardware includes two "flat sats", one engineering development unit spacecraft, one qualification model spacecraft, and thirty-four flight models (FM). Engineering performs a dry run of all integration procedures on the EDU before use on the qualification or flight vehicles. The flat sats and the EDU spacecraft are test beds for software development, test development, and debugging. After environmental test completion, the qualification model supports software development, problem solving, and test.

Development Testing

An engineering development unit is a flight-like vehicle with flight-qualified components to the maximum extent possible. It is a pathfinder to debug procedures and software and trouble-shoot problems that may occur in qualification and flight model production.

Stress testing takes place on either the EDU or qualification model to verify worst-case functional situations. These tests include cases such as maximum loading and invalid commands.

Qualification Testing

Qualification testing takes place on a dedicated qualification vehicle and its dedicated components. The qualification model is built in parallel with the EDU, using the same parts, components, processes, and techniques as the flight models. The qualification tests ensure that hardware has adequate design margin.

Flight Testing

The test plan for flight spacecraft progressively reduces the amount of testing in accordance with expected test results. It reflects the expected risk mitigation due to increased component-level testing and the experience gained in early model testing.

Unit Level Testing

The production plan requires comprehensive and rigorous testing before system level integration. Demanding testing and screening at the piece part, circuit card, and box levels minimize the chances of unit failure detection during spacecraft system level testing. Box level acceptance tests must be performed at protoflight levels.

Piece Parts, Circuit Card Assemblies

Piece part selection follows strict guidelines that include extensive analysis, testing, and screening before assembly onto the printed circuit boards. Circuit card assemblies are thermal shocked and functionally tested before integration into flight boxes. All flight boxes require comprehensive functional testing and environmental testing to protoflight levels before being integrated into the spacecraft.

Boxes

All hardware designs require qualification verification. Except for batch-sensitive items, existing designs previously qualified for applications with requirements comparable or more extreme than those for ORBCOMM, are qualified for use on ORBCOMM without additional qualification testing. Modified designs or areas where ORBCOMM requirements are more extreme than those applied for the previous program, may require additional testing. This may include full requalification or delta-qualification of the component depending upon the extent of the modifications.

To help screen out failures early, flight boxes must undergo testing more harsh than those required by most programs. Acceptance testing of all ORBCOMM components and subsystems must meet protoflight levels. Hardware must undergo functional acceptance testing and exposure to protoflight environmental stresses. In general, the ORBCOMM program defines protoflight environments as qualification levels for flight durations.

Spacecraft Environmental Testing

One of the most discussed aspects of the production program is the spacecraft system level environmental testing. The plan includes an extensive array of environmental testing on a set number of spacecraft and the progressive reduction of environmental tests on subsequent vehicles. Elimination of a test occurs only after enough spacecraft have successfully completed the test such that there is high confidence that the assembly process is reliable and repeatable. If a failure occurs during testing, that spacecraft test does not count towards the minimum required testing.

Once the assembly process has been proven reliable, the amount of spacecraft system testing is drastically reduced. Besides calibration tests and tests that verify basic functionality, the majority of spacecraft undergo only vibration testing to verify workmanship. This test is a relatively short test (as compared to a thermal cycle test) and will give a good indication that the spacecraft has been assembled correctly. Table 1 shows the list of required tests on the development, qualification, and flight model spacecraft.

Parallel Paths

Because of the schedule constraints, functional software is not available at the beginning of system environmental testing. In order to proceed with flight hardware integration without flight software, the production process uses a Hardware Verification Test (HVT) that verifies hardware functionality during the assembly and environmental test process. Debugging and testing of the higher functionality operational software takes place in parallel with spacecraft environmental testing. This allows the qualification vehicle and early flight models to continue in parallel with EDU software development.

After the flight operational software has been successfully integrated and tested on the EDU it replaces the software on the qualification model and early flight models. System Performance Testing (SPT) verifies full functionality. Instead of repeating the full array of environmental tests, the first several complete flight spacecraft systems undergo full functional verification at temperature extremes. Spacecraft initiated after flight software integration do not use the HVT and instead use the SPT throughout their environmental test sequence.

Table 1 Required Spacecraft Tests

	Spacecraft System and Environmental Tests									
	Static Loads	Modal tap / Sine	Magnetic Calibration	Random Vibe	Shock	Thermal Balance	Thermal Vacuum	Thermal Cycle	EMI	Functional*
EDU	X		X					X	X	X
QM	X		X	X	X	X	X		X	X
FM3-4	X	X	X	X			X		X	X
FM5	X	X	X	X			X	X	X	X
FM6	X	X	X	X			X	X	X	X
FM7	X	X	X	X				X	X	X
FM8	X	X	X	X				X	X	X
FM9	X	X	X	X					X	X
FM10	X	X	X	X					X	X
FM11	X		X	X					X	X
FM12	X		X	X					X	X
FM13-36	X		X	X					X	X

* Hardware Verification Test will be performed until flight software is available.
A System Performance Test to verify full functionality will be used after flight software is available.

Summary

The ORBCOMM production process is a departure from a conventional spacecraft production process. The production of the FM3-36 commercial ORBCOMM satellites combines an on-line production process, automated functional testing, and a streamlined environmental testing to achieve a rapid production schedule and highly reliable satellites.

The ORBCOMM program has developed a relational database application to facilitate an automated electronic production process. Data associated with the execution of a procedure is stored in a central location along with the actual procedure. A spacecraft status database allows efficient access to this data. The database system is based on a network server and is accessed through personal computers. The on-line production procedures and status system greatly reduce the time and paperwork required to build a spacecraft and track its status.

The ORBCOMM production program uses automated functional testing. While automation requires schedule and resource commitment early in the program, it allows for repeatable and consistent testing during the production phase. The tests save time during production by minimizing operator involvement and real-time decision-making, providing real-time limit checking, and maximizing automated data analysis. Test results and status tie directly to the status database.

The test program is designed to produce reliable spacecraft within the constraint of an extremely tight schedule. The ORBCOMM test process uses dedicated development, qualification, and flight hardware. Functional test development and system environmental testing occur in parallel. Failures are weeded out early through exhaustive unit level testing on all flight boxes and components. Spacecraft system environmental testing is progressively reduced to result in a streamlined process for the majority of spacecraft.

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