

Engineering a Responsive, Low Cost, Tactical Satellite, TacSat-1

Michael Hurley, Timothy Duffey, Christopher Huffine, Ken Weldy, Jeff Cleveland, Joe Hauser
Naval Research Laboratory

4555 Overlook Ave, SW, Washington, DC 20375; (202) 767-0528

mhurley@space.nrl.navy.mil, tduffey@space.nrl.navy.mil, huffine@wopr.nrl.navy.mil, kweldy@space.nrl.navy.mil,
cleveland@nrl.navy.mil, jhauser@space.nrl.navy.mil

ABSTRACT: The Secretary of Defense's Office of Force Transformation (OFT) is currently undertaking an initiative to develop a low-cost, responsive, operationally relevant space capability using small satellites. The Naval Research Laboratory (NRL) is tasked to be program manager for this initiative, which seeks to make space assets and capabilities available to operational users. TacSat-1 is the first in a series of small satellites that will result in rapid, tailored, and operationally relevant experimental space capabilities for tactical forces. Components of the resulting tactical architecture include a highly automated small satellite bus, modular payloads, common launch and payload interfaces, tasking and data dissemination using the SIPRNET (Secret Internet Protocol Routing Network), and low cost, rapid response launches. The overall goal of TacSat-1 is to demonstrate the utility of a broader complementary business model and provide a catalyst for energizing DoD and industry in the operational space area.

This paper first provides a brief overview of the TacSat-1 experiment and then discusses the engineering designs and practices used to achieve the aggressive cost and schedule goals. Non-standard approaches and engineering philosophies that allowed the TacSat-1 spacecraft to be finished in twelve months are detailed and compared with 'normal' satellite programs where applicable. Specific subsystem design, integration and test techniques, which contributed to the successful completion of the TacSat-1 spacecraft, are reviewed. Finally, lessons learned are discussed.

BACKGROUND

The Department of Defense under the guidance of the Office of Force Transformation (OFT) is seeking to develop new, revolutionary, operational concepts and technologies for the conduct of military operations. Space is one venue "...where a new business strategy combining new technology with new operational concepts can have a profound impact on how information energy can be applied on the battlefield. This may involve capabilities to generate very small payloads, very quickly on orbit."¹

The Naval Research Laboratory (NRL), in concert with the OFT, developed a tactical space system concept that makes space an organic part of the Joint Task Force. Three enabling elements of this system are: capable microsatellites, low cost and rapid launch systems, and tactical networks, primarily the SIPRNET. The first experiment, TacSat-1, provides a tangible example of a system that integrates each of these key elements.

TACSAT-1 OBJECTIVES

The overall goal of TacSat-1 is to demonstrate the utility of a broader complementary business model and

provide a catalyst for energizing DoD and industry in the operational space area. Specific objectives for the TacSat-1 experiment fell logically out of the desire to provide a physical substantiation that integrated the enabling system elements for the first time.

The first objective for TacSat-1 is to provide a micro-satellite with a relevant capability. The criteria here was to use a 100 kg class satellite to provide an impressive capability that would help address an operational need. An RF payload with cross-platform geo-location and signal identification capability was provided to meet this objective.

The second objective is to launch within a year to show responsiveness. A multi-year development would not be an example of responsive space. This one year launch objective will not be met, but the spirit of this objective has been partially satisfied by completing the spacecraft within one year. Figure 1 shows the TacSat-1 spacecraft in vibration testing in March 2004. The TacSat-1 program received its go ahead on May 5, 2003. All other systems, from the ground element to the launch vehicle, have also advanced at a pace consistent with the responsive nature of the experiment. The SpaceX Falcon launch vehicle was selected for the

TacSat-1 experiment because their low cost, and rapid launch goals are consistent with the needs of a tactical space system. The Falcon is a new vehicle that has the potential to expand the industrial base of the small launch community, and provide space access to many microsatellite programs.

The third objective is to make the TacSat-1 an organic part of the Joint Task Force by providing direct access to payload tasking and data via tactical networks, primarily the SIPRNET. Ultimately, tactical space assets will be completely networked, providing an additional layer of tiered support. For TacSat-1, a collection of software tools has been integrated to create a “mission operations center” software capability, allowing for virtual (web-based) tasking, data dissemination, and user collaboration. TacSat-1 will be the first semi-operational, i.e. long-term, non-demonstration use of such a software system. To enhance this software and networking capability, two low-resolution cameras were included on the spacecraft to provide a user-intuitive source of data. Operational experimentation using TacSat-1 will be performing by US Pacific Command (PACOM) and others to provide space asset integration and direct war fighter feedback.

PROGRAMMATICS

A critical factor in the success of TacSat-1 to date has been the strong leadership and support from the Office of the Secretary of Defense’s OFT. From the beginning, the OFT has provided a motivating vision, a great challenge, and sponsor level support whenever needed.

To meet this operationally responsive space challenge, a small team of dedicated, highly motivated engineers and technicians was assembled. This team consisted of a healthy mix of personnel with space experience and those with UAV or aircraft experience. This mix was important for implementing new and creative ideas while avoiding critical pitfalls and tailoring understood best practices. In all cases it was essential that core team members take full ownership of their portion of the job. This responsibility requires these individuals to have the authority necessary to successfully perform their job. Most of this core team was co-located at NRL since the highly compressed schedule demanded exceptional communication.

The Tacast-1 team was asked to accomplish a lot, however the team was also given some latitude regarding risk. OFT wants space “experimentation” to become a reality. In general, experimentation allows society to discover and advance faster. True experimentation also defines failure as a data point, not as catastrophe; a point Mr. Lloyd Feldman at OFT is

particularly keen on. The closest space industry definition to the TacSat-1 approach is NASA’s Class-D mission definition.

EXPERIMENT COMPONENTS

The TacSat-1 spacecraft is a 132 Kg satellite based on the Orbcomm bus, with two additional rings added to house the payload electronics, and to provide attachment points for the payload antennas, and visible and IR cameras. Figure 1 shows the TacSat-1 satellite without thermal blankets at the completion of system level vibration testing.

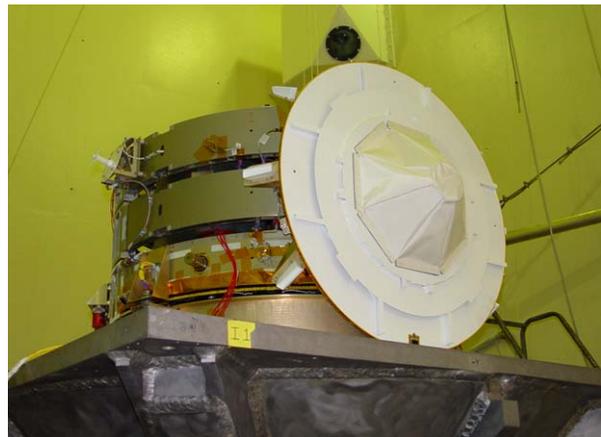


Figure 1. TacSat-1 Vibration Testing

The TacSat-1 satellite contains three primary payloads; a RF package that performs cross-platform geo-location, a signal identification package, and an imaging system with both visible and IR cameras. Each of the payloads can be tasked via the SIPRNET. To support the experiment budget the spacecraft needed to be, and was, completed for less than \$10M.

The TacSat-1 spacecraft will launch on the inaugural flight of the SpaceX Falcon launch vehicle. The Falcon is a small launch vehicle capable of delivering approximately 1000 lbs to low earth orbit. SpaceX is targeting a \$6M cost per launch for the Falcon. The TacSat-1 launch will occur at SLC-3W on Vandenberg Air Force Base. The Air Force is providing VAFB range support as well as a highly tailored mission assurance process and support. The launch is expected in the Fall of 2004 timeframe.

The Blossom Point ground station, located in southern Maryland, is responsible for command and control of the TacSat-1 spacecraft during its one-year mission life. A SGLS link is used for spacecraft-ground station communications. Blossom Point will also maintain the SIPRNET server with the web-based tactical user

interface. An interesting aside, Blossom Point was the first US ground tracking station; it has been in operation since 1956.

The last major component of the experiment is the aircraft that performs cross-platform experimentation. NAVAIR and the VQ-1 squadron are installing TacSat-1 related equipment into several EP-3 aircraft. This equipment allows the spacecraft and aircraft to communicate and collaborate using the data each has collected. Some Rivet Joint aircraft are also expected to participate pending Fall 2004 testing at the AFMC Det-2's "Arctic Lab" test bed.

The remainder of this paper focuses on the TacSat-1 spacecraft.

ENGINEERING PRACTICES

The core spacecraft team, consisting of both government and industry members, was located at the NRL. All of the disciplines required to design, assemble, integrate, and test the satellite were represented and most were in the same building. Co-locating most of the team with the integration and test facilities allowed a highly parallel design, development, and testing process to be used throughout the program. Co-location also encouraged the exceptional and low-overhead communication necessary on TacSat-1 to meet the schedule.

At the program level only a Mission Requirements Review (or System Requirements Review), a Critical Design Review, and a Test Readiness Review (TRR) were held. During the SRR, mission class, radiation approach, configuration management, quality control, and documentation requirements were clearly summarized in four PowerPoint slides. This defined the primary "rules of the game" up front in a way everyone heard and understood. This was the information individuals needed to make proper and consistent decisions about design, integration, and testing of the spacecraft. The fifty page spacecraft mission assurance plan was completed several months later, as usual only a few people have ever read this plan.

Due to the requirement of finishing in less than a year, a mission needed to be designed that was achievable in this time frame. By designing a mission centered around existing UAV payloads and commercial cameras, a program was established that was achievable within the cost and schedule constraints while providing a relevant capability.

Many aspects of the spacecraft and mission designs had to work with, or around, existing hardware and

software. This required exceptional design discipline to effectively realize the 80/20 rule (where 20 percent of the work produces 80 percent of the results) for each subsystem. Having in-depth team understanding in each sub-system area allowed complex trades to rapidly converge at, or near, this ideal point. Programmatically this should not be confused with setting the bar low. Instead, this practice actually maximized all aspects of the mission by not going past the elbow in the difficulty and cost curves.

TacSat-1 did not implement a formal configuration management or quality assurance program until after TRR, when system level testing began. Instead the configuration management and quality control were the responsibility of the cognizant subsystem lead. This is only possible with technically excellent and responsible subsystem leads. Once system level testing was started, a program-level version of a typical configuration management and quality processes were utilized. The rationale was that the subsystem leads could work the bulk of the development period using their best judgement to get the job done as quickly as possible. System level testing would, theoretically, catch any design or manufacturing mistakes made prior to TRR. However, any anomalies or failures that occur during system testing must be formally documented and resolved as there is no other period to catch and correct errors before launch. On a related note, a Mission Review Board role was informally provided throughout the development by the NRL management who collectively possesses tremendous space mission experience.

The subsystem lead engineers were empowered to take the following actions without program management approval prior to system level testing.

- Modify mechanical piece parts
- Assemble flight hardware without released assembly drawings
- Apply staking to flight electronics with marked up pictures or verbal direction
- Create and implement designs for standoffs, harness mounting, thermal blanket Velcro installation, and blanket grounding
- Correct hardware discrepancies with or without formal documentation

Following the test readiness review and start of system level testing, test configurations were documented, all discrepancies were recorded, and more formal processes were followed.

The drawing release process for fabricated piece parts was streamlined considerably compared to a typical

program. Structural and Thermal analysts were involved in the design process. When the Computer Aided Design model of the part was complete, it was sent by e-mail to the Structural and Thermal analyst while the drawing was being created. Once the Design Engineer completed the drawing, it was checked by another Design Engineer, and the drawing was updated if required. At this point, the drawing was considered released and sent out for fabrication. The time between initial drawing completion and drawing release was typically less than one day. Also, unlike a more formal spacecraft development program that requires completing a critical design review before fabrication and assembly is started, TacSat-1 started fabrication of piece parts as soon as the design of each subassembly was completed. The first of these came immediately after SRR.

The TacSat-1 environment minimized the need for formal documentation. For example, only two formal ICDs were created: one between the spacecraft and launch vehicle and a second between the spacecraft and aircraft. No ICDs internal to the spacecraft were formalized. Instead the SRR and CDR, which were assembled into organized notebooks prior to the review, were used as primary sources of design information. Updates were made to the CDR documentation as needed on a sub-system by sub-system basis. Any additional information required was worked out at an engineer-to-engineer level and codified only in engineering notebooks and the designs themselves. The reasons this approach was possible are 1) a true government-industry team not divided by contract issues, 2) technically excellent and responsible subsystem leads, and 3) excellent communication fostered by co-location.

PROBLEM RESOLUTION

As discrepancies were discovered the review process typical to most programs frequently occurred, but with one critical difference. Instead of creating paperwork, writing dispositions, and going through a signature cycle, the relevant parties would be brought to the hardware or teleconferenced into the discussion of the problem, a decision would be made as to how to fix the problem, and implementation of the decision initiated. This would typically occur in a matter of minutes to hours instead of days to weeks. NRL management would weigh in on serious problems or less clear decisions, acting as an informal MRB when necessary.

NON-STANDARD HARDWARE APPROACHES

To meet the program's aggressive schedule and cost goals, existing hardware from previous programs was

used extensively for TacSat-1. The basic bus structure, avionics, and solar arrays were from an Orbcomm bus. Additional hardware leftover from other programs was either used as is (SGLS transponder and antennas, RF filters, camera cover), or modified (Mission Interface Unit) for use on TacSat-1. Most of the basic components for the payload structure (structural rings and honeycomb panels) were also available from previous programs.

Commercial electronics were used extensively for the TacSat-1 payload. This included individual piece parts (Martek power converters), board level assemblies (Ethernet switch, IDM modem, ipEngine), and entire electronics boxes (UHF tactical radio, GPS receiver, rubidium oscillator). These commercial electronics offered substantial savings in terms of both cost and schedule over space rated components. For example, a space-grade GPS receiver cost \$250k and would take nine months to deliver. The TacSat-1 GPS receivers cost \$10k, and multiple units were received within a month. These Trimble Force 5 units included the software required for functioning at orbital velocities, and were tested in a fully simulated, GPS on-orbit environment at NRL. The trade off was that space qualified electronics are designed for more rigorous environments. In addition, they are tested, and qualified to much more rigorous standards than commercial electronics. To accommodate for these differences a variety of methods were used to adapt the commercial electronics for the launch and space environments they would be subjected to.

The primary environments the commercial electronics had to be modified or enhanced for were the vibration and acoustic loads they would see during launch, and the on-orbit thermal loads. Most commercial electronics are designed for convective cooling, either free convection for low power devices, or forced convection, using a fan, for high power devices. In addition, commercial boards are generally poor thermal conductors, and are not designed to remove heat from the components. Space electronics, on the other hand, are typically designed to conduct the heat generated by the components through the boards on which they are mounted to the box enclosure where the heat is either radiated away, or conducted to an external radiator.

Two methods were used to address the thermal environment the commercial electronics would be exposed to. High power boards were packaged in hermetic enclosures with fans to provide forced, convective heat transfer from the boards to the baseplate of the enclosures in which they were mounted. These enclosures were first evacuated and then backfilled with dry nitrogen to provide a known,

contamination free environment. The boards were mounted in an internal chassis, with the fans oriented so that the nitrogen would flow over the boards, and then over the ribbed baseplate of the enclosure. Ducting was also added to the highest power enclosure to guide the nitrogen flow. Each enclosure had two fans for redundancy, both fans pointed in the same direction. Two payloads utilized this design, so they were mounted on the payload deck such that the angular momentum of the fans in one enclosure cancelled that of the fans in the second enclosure. The Copperfield-2S enclosure is shown prior to closeout in Figure 2, and during component level vibration testing in Figure 3.

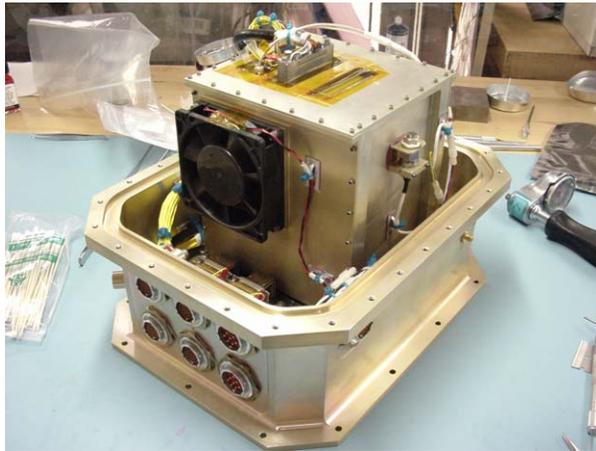


Figure 2. Copperfield -2S Enclosure Prior to Closeout



Figure 3. Copperfield-2S Component Vibration Testing

The lower power boards did not require a hermetic enclosure. Instead these boards were sandwiched between part of the box structure and a backing plate using a high thermal conductivity gap filler. This gap

filler provided a path for the heat to pass directly from the components mounted on the boards to the box structure. From there the heat was conducted to a radiator mounted on the outside of the satellite's structure. An added benefit of the gap filler was that it provided additional structural support for the boards and the components mounted on them. This eliminated the need to reinforce any of these boards for vibration.

To address the vibration and acoustic loads of launch, the commercial electronics were disassembled down to the board level. Each board was examined to determine if it required additional reinforcement, and the components that required additional support were identified. Staking was applied to the components, and if needed stiffeners were added to the boards. The commercial electronics were then reassembled replacing all of the original fasteners that did not include a locking feature with fasteners that did.

The power distribution unit and payload power unit were designed to be resistant to single event upsets and single event latch-ups or burnouts. A part level radiation analysis was performed for all other components. The results of this analysis were used to categorize each part in terms of risk based on its hardness and criticality to the design. The radiation environment provides the highest risk to the TacSat-1 spacecraft. Design modifications were made only where part failure was very likely to occur. Modifications (voltage deratings) were done only to the power converters as failures to them were most likely, and would be fatal. For additional protection, an operational constraint was put in place to turn the payloads off when the spacecraft is in the South Atlantic Anomaly.

CUSTOMIZED COMPONENT TEST PLANS

A customized test plan was created for each non-qualified component to streamline the component level integration and test process. While most payload components were tested, only tests that decreased risk significantly were performed at the component level. This risk assessment was made using engineering judgement. For example, the IR camera is small (about 1x1x2 inches) and designed to military ground vibration specifications, therefore vibration risk was low and component level vibration testing was not done. However, thermal vacuum was a significant risk for the IR camera so this component testing was performed. At the system level all components underwent vibration, acoustic, sine burst, thermal vacuum and shock testing to protoflight levels.

For the commercial electronics, a short thermal vacuum test was conducted early on at the box level to verify

vacuum compatibility prior to going through vibration and multiple thermal vacuum cycles. These vacuum compatibility tests were performed first because they were deemed the highest risk.

Two of the commercial electronics components did not survive the thermal vacuum testing the first time through. In both cases, the part that failed testing was scrapped, and a nearly identical component passed the same test without additional modifications. Only one commercial component failed the vibration testing, with the failure due to a bad solder joint. For this box the damaged part was replaced, and the box passed the vibration testing on the second attempt.

Although this is a small sample size, our experience indicates that when commercial electronics are used, additional spares should be purchased. Screening tests can then be conducted early in the program to identify deficient components. Early component level testing provides the design and workmanship confidence needed to avoid costly spacecraft level integration and test problems. TacSat-1 relied heavily on component testing. Fifteen different components were vibration tested and seventeen were thermal vacuum or thermal cycle tested at protoflight levels prior to system level testing.

PREVIOUSLY QUALIFIED COMPONENTS

For the most part, components that were qualified by a previous program did not undergo any additional environmental testing prior to the system level testing. If the vibration, shock and thermal vacuum levels to which these components were tested were similar, or more severe than the TacSat-1 component test levels, then no further testing was required. Some exceptions were made for critical or time sensitive items. For example, the camera cover mechanism underwent limited thermal vacuum testing in order to verify it would still function over the required temperatures after multiple years of storage. The SGLS transponder was also thermal vacuum tested due to an unknown storage environment, questionable test documentation, and its critical role. The mission interface unit (MIU) was a previously qualified electronics box that required some minor board level changes. Since it was previously qualified, and the changes made were small, only thermal cycle testing was performed on this box.

MODULAR STANDARDS-BASED PAYLOAD ARCHITECTURE

Few satellite programs have the latitude or the ability to take risks that the TacSat-1 experiment has. The TacSat-1 experiment allows innovative leveraging of

both GOTS and COTS hardware components, as well as novel approaches to creating payload software that provide for maximum flexibility, and standards-based operation. The risk philosophy allowed the utilization of a modular payload that scales from UAV applications to a spacecraft application. Identically, a modular software and communication system were expanded for TacSat-1, extending the role of standards-based open-source software such that it provides reusable software infrastructure suitable for flexible command and control of the TacSat-1 payload and for space and terrestrial uses as well. The Copperfield-2S payload architecture was intended to provide as much flexibility as possible. Space applications, however, were not targeted during its development. It is a testament to the architecture, and the OFT initiative philosophy, that extension of the UAV payload was possible.

NETWORKING ARCHITECTURE OF COTS PROCESSORS

The core payload component, Copperfield-2S, provides two key functions for the mission. First, it is itself a sensor system that receives signals of interest, and provides for machine-to-machine collaboration between air and space assets for geo-location. Secondly, it serves as a general-purpose computer system that provides the capability for storage and data handling. In fact, there are multiple general purpose processors as part of the Copperfield-2 payload, each communicating via an Ethernet network. A payload block diagram that illustrates these interconnections is shown in Figure 4. An industrial temperature range Ethernet switch, originally based on a PC/104 design, utilizing a single chip ASIC design serves as the hub of the “star” Ethernet architecture. Embedded processors are also used in other components, but are not part of the Ethernet network. These processors are embedded in the GPS receiver, UHF tactical radio, and rubidium oscillator. The details of these embedded processors are listed in Table 1.

GATEWAY TO THE BUS LEGACY EQUIPMENT

To capitalize on the Ethernet, TCP/IP, standards based architecture of the UAV payload, while remaining compatible with the Orbcomm bus’ legacy OX.25 interfaces, a module was designed specifically to perform the necessary conversions. This module was called the high speed interface (HSI). The Orbcomm bus MIU provides an FPGA interface that allows injection of 1 Mbps high speed data as well as lower speed data into the SGLS data stream and avionics buses. The low rate data interface provides payload access to the avionics network utilized by the Orbcomm

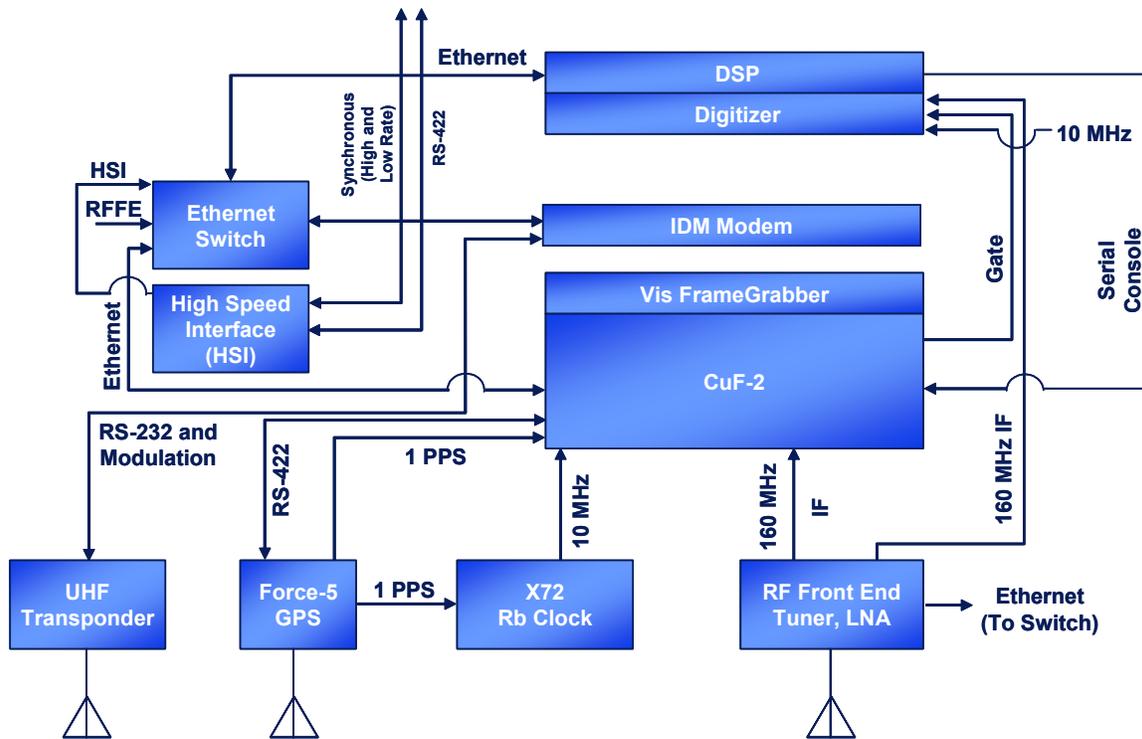


Figure 4. Copperfield-2S Payload Block Diagram

bus for all of its essential functions; this allows for the passing commands and telemetry between the bus computers and the payload. The high speed MIU interface provides the capability to fill the 1 Mbps downlink pipe with payload data, which is not a standard Orbcomm interface. The FPGA in the MIU interfaces into the FPGA in the HSI.

Table 1. TacSat-1 Copperfield-2S Ethernet Connected Embedded Systems

Component	Vendor	OS	Processor
High Speed Interface (HSI)	Bright Star Engineering (Custom adapter board)	Linux 2.4 custom distribution	PowerPC MPC823
IDM Modem	Innovative Concepts	Proprietary	PowerPC 860
Copperfield-2 MR.DIG Card	Aeronix /NRL	Linux 2.4 custom distribution (DENX ELDK based)	PowerPC PowerQuicc II 8260
RF Front End Controller	Bright Star Engineering (Custom adapter board)	Linux 2.4 custom distribution	StrongARM 1110

The HSI hardware is implemented as a combination of high speed FPGA hardware and a general purpose PowerPC 823 embedded processor, which is implemented on a commercial processor mezzanine card, the ipEngine, specifically designed for tasks such as this TCP/IP gateway. The FPGA provides the hardware components necessary to meet timing requirements for the data link, decoupling the processor from the data bus. The PowerPC runs a Linux 2.4 based kernel, and the HSI FPGA interface is implemented as a standard Linux device driver. No special real-time extensions are utilized on this implementation of the HSI, and a Linux-based application provides the interface between the TCP/IP networking stack, using standard protocols, and the more hardware specific device driver implementation. The HSI system allows multiple processes, and processors, to communicate into the data stream. Routing information is embedded in the data packets, which are routed to the proper avionics box. In practicality, most of the packets do get routed through the main Copperfield-2S processor, so that the data can be logged and managed appropriately by the payload controller.

TCP/IP based systems provide tremendous flexibility and standardized communications between various devices. The commonality of the TCP/IP communications and Linux-based operating systems

allow tremendous software reuse. For example, code running on the SA1110 processor controlling the RF front end can also be cross-compiled and run on the PowerPC 8260.

MODULAR PAYLOAD HARDWARE DESIGN

Copperfield-2 was designed from the ground-up to provide a modular payload infrastructure that can be adapted to changing needs and requirements. The core hardware architecture is based on a 3U CompactPCI architecture, utilizing the user-defined P2 connector pins for input-output wiring which significantly simplifies the wiring required. This modular capability is demonstrated in the TacSat-1 program with the addition of support hardware for the visible camera. The PCI bus allowed the “frame grabber” card to be utilized by the general-purpose processor, and the frame grabber card manufacturer’s driver to be utilized with minimal modifications. This code and hardware re-use enabled the development timeline to be compressed significantly, even allowing a hardware change to a new camera and frame-grabber card well into the program.

The modular design continues from bus through to the custom boards utilized in the Copperfield-2S system. The Copperfield-2S core sensor and processor is modularized into a digital card (MR.DIG) and an analog card (MR.IF). The architecture allows different analog cards to be plugged into the standardized digital card, providing a stable infrastructure for rapid development of new payload sensor capabilities.

RAPID PAYLOAD SOFTWARE DEVELOPMENT MAXIMIZING REUSE OF EXISTING TOOLS AND UTILITIES

While hardware allows the physical interconnection of payload components, the most custom part in any conventional satellite program is the payload control software. However, since many of the Copperfield-2 payload components with processors run the LINUX operating system, some interesting software options were available. Much of the payload software was implemented through the use of BASH (Bourne again shell) scripts operating on the various processors. During the very rapid development of the payload software, the philosophy was to attempt to divide up the software development into two parts, custom and reused software modules. This philosophy called for minimizing custom code to very limited functions, and programs with very specific purposes. These specific custom programs and drivers allowed for control of the other payload elements to be done through small command-line utilities that could be completely and

easily tested in their limited functionality. These programs were developed with the UNIX command-line functionality in mind, data input through STDIN (standard in), and data output through STDOUT (standard out).

This combination of utilizing the BASH scripting language, leveraging GNU utilities, and custom command line applications is unique. This approach leverages the GNU software components used on LINUX (and other UNIX-like operating systems) and well tested via tremendous peer reviews. Custom software components that are required to interface with specific hardware or software can be of limited scope. For TacSat-1, most of the custom code utilized involves the conversion of data from the TCP/IP world to proprietary OX.25 formats. Custom code is also written to handle sensor and communications hardware through custom interfaces.

DISTRIBUTED DEVELOPMENT AND COLLABORATION

The extensive use of TCP/IP based systems and the common LINUX operating system provided unique opportunities for a distributed development environment. Early in TacSat-1, the PowerPC 8260 development hardware had very limited availability. The design cycle for much of the payload software began on Intel x86 based computer systems, migrated to generic PowerPC embedded processors, and eventually made its way to the final target. The software design team was spatially distributed, and tied together through a virtual private network (VPN) architecture. Remote power control devices allowed developers who were operating off-site to cycle power hardware components, almost as if they were on-site. A web-based collaboration tool allowed the posting and dissemination of ICD documents. Some developers also used instant messaging technology to stay in contact with each other.

The TCP/IP nature of the payload data network allowed developers to test communications between payload elements at each step in the design process – from developing on a standard PC, to final communications before inserting the proprietary hardware required to communicate with the bus. Even after complete integration of the payload into the bus, an Ethernet “test port” allowed network access into the satellite, which was invaluable for collaborative remote debugging of the system.

The payload software design team consisted of experienced satellite and ground station software experts, as well as team members accustomed to the

TCP/IP world for data communications. This combination provided a nearly perfect balance of skills and ideas for interfacing the payload to the spacecraft bus, while using innovative methods to maximize the use of existing software. The extensive remote collaboration, interface testing, and networking capability provided a smooth bus-payload integration.

The Orbcomm spacecraft bus provides an interesting distributed development comparison. The bus has four computers and runs on a token ring network. This network allowed the OSC team developing Orbcomm the same distributed development and testing advantages in the mid-1990's. However, the openness of TCP/IP made it, not token ring, the defacto standard. So TCP/IP components should be used as much as practical in foreseeable future, to cheaply network and realize distributed development benefits.

SPACECRAFT-GROUND SOFTWARE APPROACH

The NRL is a strong proponent of using a "Fly like you test, test like you fly," approach whenever practical. This implies two things. First using the same software for spacecraft integration and test as for ground station operations; TacSat-1 used COMET (Common Environment for Test). Second, using the same command and telemetry database for the flight and ground software. This approach is the most robust in terms of pre-launch testing. This approach is also, theoretically, the cheapest. TacSat-1 used this approach successfully.

In particular, command and telemetry databases, telemetry display screens, and perform files are only created once. These files are testing during system integration and test, and important information is captured. For example, perform files developed during integration and test often codify important command sequencing and hardware subtleties. These tested files are then known to be functional (actual testing vs. simulated testing) before using them to command the spacecraft on-orbit. A more subtle benefit is developing and debugging "useful" telemetry display screens. Finding that a particular current is helpful to see during an expected activity or anomaly allows the telemetry to be added to the appropriate display(s) pre-launch. Discovering this during flight operations could lead to missed pass opportunities and other bad situations that put the spacecraft at risk.

The above approach also results in a smooth transition of the spacecraft to the ground station personnel. This transition is minimized since many products are already coded and delivered. ICD documentation is minimized

since there is no translation needed for databases, perform files, or display screens. Finally, ground station personnel can use spacecraft test time to become familiar with flying the spacecraft.

On a related note, specific to flight software reuse, TacSat-1 was able to leverage 60,000 lines of flight Orbcomm code. However, it was necessary to understand this code in detail since the mission and payload changed the use of the bus significantly. Blindly "using-as-is" would have lead to multiple mission ending failures. Examples include violated battery charging algorithms, and improper attitude or power safe-hold modes.

LESSONS LEARNED

The TacSat-1 experiment has already resulted in many lessons learned. Many more will come as we move into the launch and flight operations phases. The lessons learned could, themselves, be an entire paper. The list below highlights the most prominent lessons to-date.

TacSat-1 Responsiveness

- First, we learned a relatively complex micro-satellite can be brought from concept to completion in one year for under \$10M. There were many doubters, even we were not sure at times!

Management Must Create the Best Environment Possible for the Team to Succeed.

- Design a mission that is achievable
- Minimize the burden of financial management.
- Co-locate where practical
- Provide appropriate contracting vehicles and incentives.

Team

- A good team experience mix is essential. Different backgrounds and inexperience provide fresh eyes and creative ideas. Space experience provides best practices know-how, and avoidance of critical, often subtle, mistakes.
- Eliminating real and perceived boundaries in responsibilities between managers, engineers, and technicians fosters increased creativity, and quicker problem resolution. Good communication is the key to avoiding errors.
- A true government-industry team must exist. This team cannot be conflicted with contractual issues or incentives and expect to operate efficiently.

- Having in-depth team understanding in each sub-system area allows complex trades to rapidly converge at, or near, the ideal point.

Co-Location

- A job such as TacSat-1 required extremely efficient communication. Co-locating the team went a long way toward fostering the needed communications by minimizing overhead. If dispersing core team members is unavoidable, they should be located as mini-teams, not individually. Dispersed individuals tend to lose touch with other groups, and be less productive.
- Use of collaborative working techniques such as a web-based library, PR tracking system, and Instant Messaging (IM) technology helped keep geographically dispersed teams in constant contact.

Part Time Personnel

- Expert, part time help is essential for providing a reliable or “optimized” design while minimizing costs. However, TacSat-1 experienced information exchange problems between the core team and part-time persons. This problem is believed to be the result of two groups of people “running” at very different speed. To exchange information, like passing a baton, either the part-time person had to speed up significantly, or the core team had slow down. The result was not enough information exchanged until it was critical, until the 11th hour of integration. This put an undue strain on the integration and test team. This situation is estimated to have added a month to the integration schedule. This may be a common part time - full time problem exacerbated by TacSat-1’s extreme schedule.

Design Balance

- A disciplined approach is required to achieve a design at or near the 80/20 point. Where applicable, the spacecraft and mission may need to be designed around hardware and software that is available in the near term.

Modular Payload Design

- The compact-PCI architecture approach used for a UAV program has proven to be very flexible.
- Board level modularity is also proving useful for a TacSat-2 payload.

“Fly Like You Test, Test Like You Fly.”

- This is the most cost effective and robust way to perform spacecraft integration, testing and ground station operations. The key is to use the same software for both testing and operations.
- The same databases should also be used for both the flight and ground software.

Flight Software Reuse

- When reusing software it is essential to have a detailed understanding of the code. Changes in missions and payloads can significantly alter how the bus is used.
- On TacSat-1, a blind “use-as-is” attitude would have lead to multiple mission ending failures.

Using Commercial Components

- A surprising number of the commercial components survived the thermal vacuum and vibration environments with minimal mechanical enhancements. Examples include the rubidium clock, UHF radio, and GPS receiver.
- The use of hermetically sealed, fan-cooled chassis work well for high-powered electronics. Both compact PCI and VME based bus designs were used successfully. For this type of design, fan momentum needs to be canceled.
- If short life and additional risk are acceptable, then tremendous cost and schedule savings are possible using commercial components.
- When cost and schedule differences are minimal, industrial or military grade components can efficiently increase system robustness. Using pre-screened components can also reduce the amount of testing required.

Testing

- Testing is a key element for success in this type of rapid development environment. Testing early and often is necessary to avoid system level problems.
- Intelligently customizing component test plans can reduce costs.
- Formal test plans are essential at the program level for system testing. Because they are largely decoupled from the design details, they should be worked early in the program to avoid surprises and last minute test delays.

Configuration Management and Quality Assurance

- Cost savings are possible here if a technical and responsible sub-system leads are on the team.

REFERENCES

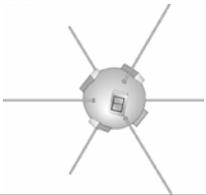
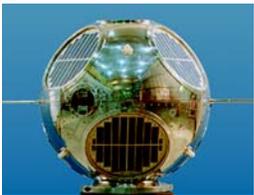
1. Vice Admiral (ret.) Arthur K. Cebrowski, Director, Office of Force Transformation, "What is Transformation?," October 2002.

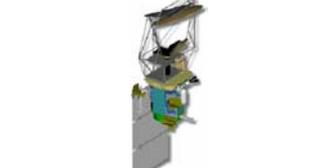
APPENDIX

NRL & Naval Space History : Transformational Space Programs

The Naval Research Laboratory is a pioneer in space systems. NRL has developed and launched 84 satellites, many of which fall into the microsatellite class. The oldest U.S. satellite in orbit today is the Vanguard satellite designed and built by the NRL and launched in 1958. Vanguard was also the first solar powered satellite. NRL's Time Navigation Satellite series provided the core technology and system prototyping leading to the Global Positioning System. The LIPS program demonstrated the first direct tactical downlink from space, this work matured into the TRAP/TRE broadcast system. This tactical downlink capability work naturally led NRL to help pioneer onboard data processing to provide product directly and immediately to the warfighter.

NRL's specific role is to develop new, often transformational, space systems for the country that are transitioned to industry as appropriate. The following table highlights some of NRL's successes.

1956	<p>Blossom Point</p> 	1st Satellite Ground Tracking Station, led to NAVSPASUR
1958	<p>Vanguard</p> 	First Solar Powered Satellite and the U.S.'s Oldest Orbiting Satellite
1960	<p>GRAB</p> 	1st U.S. Reconnaissance Satellite
1967 to 1976	<p>Timation/NTS</p> 	1st Time Navigation Satellites; Last of Series Became GPS Satellite #1
1980 to 1990	<p>LIPS (TRAP/TRE); MATT & IDM</p> 	<p>Global Tactical Broadcast System</p> <ul style="list-style-type: none"> • <i>LIPS</i>: 1st Tactical Broadcast From Space • <i>MATT & IDM</i>: Tactical Radios Transitioned to Operational System

<p>1994</p>	<p>Clementine</p> 	<p>First "Faster, Cheaper, Better" Satellite; Rotary Club Award</p>
<p>1996</p>	<p>Onboard Processor</p> 	<p>Largest Supplier of Tactical Direct Downlink Reporting; Transitioned to Operational System</p>
<p>2003</p>	<p>WindSat</p> 	<p>First Passive Wind Speed and Direction Measurement from Space; Provides Ocean Coverage; Will Transition to NPOESS</p>