TacSat-4 Prototype Bus & ORS Phase III Bus Standards Update

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ABSTRACT

The continuing effort of advancing sound and accepted spacecraft bus standards is the objective of the Office of the Secretary of Defense’s (OSD) Operationally Responsive Space (ORS) Bus Standards Initiative. This effort involves multiple government, industry, and academia participants assembled into an Integrated System Engineering Team (ISET). The initial release of the standards was presented at the 21st AIAA/USU Conference on Small Satellites as “ISET ORS Bus Standards and Prototype” and contains important background information. This paper updates the status of the ORS Bus Standards, including a major update to the software standards and data protocols. All of these standards are freely available for download from http://projects.nrl.navy.mil/standardbus/. This paper provides an update on the status of the prototype developed to support the TacSat-4 Mission is provided, as well as a report of other ORS standards implementation efforts. The first half of this paper reviews the process as discussed in previous papers. The second half of this paper describes the specific implementation of the bus prototype including design highlights and lessons learned.

REVIEW OF PHASE III OBJECTIVES

The first objective of the ORS Phase III Bus Standards effort has been to establish a national systems engineering working group with the US small satellite industry and academia to develop primary interface standards for a class of ORS spacecraft. The second objective has been to obtain consensus and buy-in by maturing the bus standards in an open environment with broad government, industry, and academia participation.

Lastly, Phase III has intended to bridge the gap between Science and Technology (S&T) buses and an operational bus capability. The NRL and JHU/APL engineering team successfully designed and developed a prototype bus according to the ORS bus and interface standards. This prototype bus has completed environmental testing and acceptance testing and is now ready for payload integration and flight. Not all of the ORS standards have been validated through the first prototype build; however, critical elements such as mechanical, electrical, and software data interfaces between major space vehicle
segments, including the payload to bus, launch vehicle to bus, and bus to payload data interfaces, were validated. Additionally, other parties have implemented or are in the process of implementing hardware and software to the latest ORS standards.

ORS BUS STANDARDS DEVELOPMENT

Since early 2005, several phases and efforts have shaped the development of the ORS standards. Over a dozen aerospace companies have participated substantively in the standards development, most as part of the ISET.

The analysis from the Massachusetts Institute of Technology/Lincoln Laboratories (MIT/LL) Phase I effort was the starting point for the ISET in determining the proper balance between cost and performance of ORS spacecraft to be militarily useful. The MIT/LL report had several findings based strictly on the utility analyses:

- A tactical spacecraft bus, standardized across a variety of National Security Space (NSS) missions, can meet many, but not all the needs of a tactical commander.
- Small tactical satellites can achieve large increases in mission utility if used in constellations to improve persistence.
- There exist standard performance specifications for a small tactical satellite bus that satisfy a wide range of NSS missions.

Table 1 summarizes various performance characteristics for the type of spacecraft bus applicable to an ORS system. Each column presents the results for a single spacecraft and show that actual ORS spacecraft characteristics should not be less than presented or they will not be useful.

Based on the study and a preliminary ISET deliberation session, the ISET adopted the following charter:

"Generate a set of spacecraft bus standards, in sufficient detail to allow a space vehicle manufacturer to design, build, integrate, test and deliver a low cost spacecraft bus satisfying an enveloping set of mission requirements (launch vehicle, target orbit, payload, etc) in support of a tactical operational responsive space mission."

From the charter, the ISET identified the following four objectives and goals to achieve in support of tactical ORS missions:

- Develop Top Level Mission Requirements and Concept of Operations Envelope
- Identify and Establish External Interface Standards for a Spacecraft Bus
- Establish Functional and Performance Standards for a Spacecraft Bus
- Establish Programmatic, Mission Assurance, and Quality Assurance Standards for Spacecraft Bus Procurement

Once the goals and the charter of the ISET were established, a series of deliberation session were held, resulting in the preliminary version of the standards. The draft standards were released just prior to System Requirements Review in November 2005. The first revision of the standards was released in July 2006 in conjunction with the ORS Phase III Prototype Preliminary Design Review, and the second revision was released after the Critical Design Review in January 2007. Revision 2 focused on answering the TBRs and TBDs throughout the documents.

Of particular note is the distinction that the ISET has made between “Bus Standards” and “Standard Bus.” These two terms are sometimes interchangeably used to refer to the ORS Phase III Effort interchangeably, this equivalency is incorrect, and the terms represent two distinct approaches. A “standard bus” designates a single spacecraft bus and configuration for all
missions or mission classes, and the design must meet all stated requirements and specifications. This approach has been tried in the past and usually leads to a “least denominator approach, and an over designed system”.

For the ORS Phase III effort, the goal has been to develop “bus standards,” which provide a set of requirements that can be used to satisfy a defined range of mission performance characteristics. These standards may be tailor-able/selectable for mission specific capability, and provide a framework for overall spacecraft design approach and philosophy. Furthermore, they provide procurement flexibility, which allows for a “family” of spacecraft, with individual members applicable to a defined performance envelope.

These standards are considered live documents; the ISET and ORS office encourages and welcomes feedback to define these standards better for future procurements.

**ISET Product: Bus Standards Documents**

Four documents establish the ORS Phase III bus standards and represent the final deliverables from the Phase III team to the Phase IV team, depicted in Figure 1.

A unifying organization, such as the ORS Office at Kirtland AFB will be responsible for the overall ORS system and as such would need to understand the interaction of all of the requirements contained in this set of documents, as well as applicable, complementary efforts by collaborating organizations such as SMC’s Standard Interface Vehicle program.

**Mission Requirements and CONOPS Document**

This document represents a top-level definition of the overall ORS mission, as defined by the ISET and consistent with STRATCOM’s initial CONOPS for ORS (May 2007). The primary focus of this document is to outline the orbital environments, envelope the multi-mission support requirements, establish concepts for tactical support and define concepts for operational responsiveness and develop scenarios. Based on these assumptions the system can be decomposed into segments and the document defines the scope of the standards in each segment. It presents the basic CONOPS timelines (Figure 2) for asset call up, integration, launch, and on-orbit operations. It also discusses basic mission definitions, assumptions with which these standards are based and the evolution from the Phase I efforts.

**Figure 2: Top-level Timeline**

The ORS system is intended to provide responsive launch upon demand to support tactical needs in the theater. In order to achieve the modularity and responsiveness envisioned for an ORS satellite system, the executing agency specifies standardized interfaces between the busses, payloads, and boosters. Initial modularity is also specified for the propulsion system, battery, and tactical communication link. In order to achieve the cost efficiencies envisioned, bus, payload, and booster interfaces would remain constant allowing for multi-year bulk purchases. Spiral changes for new technology insertion would be approx every 2-5 years with modularity expected to increase The envisioned System Architecture is shown Figure 3.

Future activities for refining this particular document will be limited to refining the concepts and the concept of operations, and will be heavily dependent on feedback from the ORS community.
to develop effective standards, it was necessary for the ISET to research the mission needs and payload support requirements across a wide range of potential missions that were representative of a typical mission for the ORS program. Table 2 shows the capabilities available to a potential payload.

A description of the range of missions reviewed and the resulting data set for each mission is contained in the ORS Mission Requirements and Concept of Operations document, the support level results are summarized in Table 3. The requirements in the table are the maximum potential requested support levels for each type of mission, and where payload envelope levels have been chosen at less than the mission’s maximum level, smaller or less aggressive missions of the same type may be supportable by the standard capabilities.

### Table 2: Supported Payload Capabilities

<table>
<thead>
<tr>
<th>Payload Support Item</th>
<th>Selected Capability</th>
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<tbody>
<tr>
<td>Mass [kg]</td>
<td>175</td>
</tr>
<tr>
<td>Volume [m^3]</td>
<td>0.62 m^3</td>
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<tr>
<td>Orbit Average Power [W]</td>
<td>200</td>
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<tr>
<td>Peak Power [W]</td>
<td>700</td>
</tr>
<tr>
<td>Orbit Position Knowledge-3σ [m]</td>
<td>90</td>
</tr>
<tr>
<td>Attitude Knowledge-3σ [deg]</td>
<td>1 arc-min at I/F</td>
</tr>
<tr>
<td>Attitude Control-3σ [deg]</td>
<td>0.05</td>
</tr>
<tr>
<td>Slew Rate [deg/sec]</td>
<td>2.0</td>
</tr>
<tr>
<td>S/C SB Ops Data Rate [Mbps]</td>
<td>5</td>
</tr>
<tr>
<td>Tactical D/L Data Rate [Mbps]</td>
<td>274</td>
</tr>
<tr>
<td>PL Data Storage [GB]</td>
<td>0</td>
</tr>
<tr>
<td>Thermal Dissipation to SB [W]</td>
<td>60</td>
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### Table 3: Mission Set

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<tbody>
<tr>
<td>LEO</td>
<td>224</td>
<td>5</td>
<td>60</td>
<td>2.0</td>
<td>0.05</td>
<td>1 arc-min at I/F</td>
<td>90</td>
<td>200</td>
<td>700</td>
<td>5</td>
</tr>
<tr>
<td>HEO</td>
<td>274</td>
<td>5</td>
<td>60</td>
<td>2.0</td>
<td>0.05</td>
<td>1 arc-min at I/F</td>
<td>90</td>
<td>200</td>
<td>700</td>
<td>5</td>
</tr>
<tr>
<td>LEO Maneuverable</td>
<td>224</td>
<td>5</td>
<td>60</td>
<td>2.0</td>
<td>0.05</td>
<td>1 arc-min at I/F</td>
<td>90</td>
<td>200</td>
<td>700</td>
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<tr>
<td>LEO</td>
<td>274</td>
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<td>90</td>
<td>200</td>
<td>700</td>
<td>5</td>
</tr>
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</table>

It is important to note this document is not a complete design standard for the payload itself; it only covers the interfaces and support accommodations with the spacecraft bus and launch support service. As the Phase III Prototype development progressed, much more detail, including specific implementation specifications, was added to the Implementation Payload Developer’s Guide. The
modifications/deviations taken from the standards to meet the TacSat-4 mission were provided to the ISET for consideration in the latest revision of the ORS Standards and were openly documented for the community, as has been done at the design reviews.

**Data Interface Standards Document**

The Data Interface Standards Document defines the information exchange protocols, data transport envelopes, message structures and data fields for the Bus/Payload interface and the Space/Ground Interface. Both the Bus/Payload and Bus/Ground interfaces conform to CCSDS recommended standards. The Bus/Payload interface definition provides conduit services for payload specific (i.e. unpublished) commands and telemetry while also supporting a published set of control and monitoring messages between the bus and the payload. This interface provides the means for the payload to utilize both the real-time downlink and solid state record (SSR) services provided by the bus.

The Bus/Payload interface minimizes dependencies on the link and hardware characteristics. All transport and message protocols are identical for both types of standardized Bus/Payload communication links comprised of SpaceWire and RS-422/HDLC. The interface definition establishes a balanced approach for the Bus/Payload interface to eliminate stringent timing and interface activity requirements. Either the Bus or the Payload can initiate or re-establish communications without regard to the state of either side of the interface.

The Bus/Ground interface definition extends the payload communication services to the ground and provides for the direct communications required for bus control and monitoring.

The ORS Phase III bus fully implemented the Bus/Payload and Bus/Ground interfaces. The COMM-X payload utilized the RS-422/HDLC link and implemented a proper subset of the interface standards. The UIE R&D payload component, provided by Microsatellite Systems Incorporated (MSI) under OSD’s ORS Technology Initiative, exercised the SpaceWire link and implemented a proper subset of the interface. The Bus/Payload interface allows for the payload to pick and choose the services it requires and does not require implementation for handling all published message exchanges.

**ORS PHASE III PROTOTYPE BUS IMPLEMENTATION**

**Background**

The second objective of the ORS Phase III Bus Standards program has been to validate and mature a meaningful subset of the bus interface standards developed by the ISET and to provide a qualified bus for the TacSat-4 experimental mission. The prototype bus was developed jointly by JHU/APL and NRL with subsystem leadership and technical support divided between the two organizations as an integrated team. The bus was integrated and has been fully tested and accepted at the bus level in April 2008. The COMM-X payload for the TacSat-4 mission is under development at NRL, and its hardware and software have been used to verify and validate the critical bus/payload interface standards defined by the ISET.

To provide continuity with the ISET bus standards efforts, and the critical feedback of issues, challenges, and new ideas, the ISET team members have acted as part of the design review panel at every major design review. Consistent with ISET deliberation sessions, all design reviews for the prototype bus build have been open to the ORS community with an extremely broad distribution of information for those who chose to attend, or are interested in following developments through the material provided on the project website.

The program approach has relied upon the use of working peer reviews at the system and subsystem level to provide more frequent, but informal review of development efforts. Milestone design reviews were implemented to provide additional oversight by the community, to share progress, and to improve both the prototype bus and the processes – all of which has been tracked and considered by the ISET team for inclusion in the standards documents that have been produced (either formally or as suggested lessons learned).

A summary of the milestone design reviews follows:

November 2005: System Requirements Review (SRR)
- ISET presented results of 5+ months of effort to define primary interface standards, as well as ORS context driving technical decisions
- Rough draft of deliverable documents

Jaffe 5 22 nd Annual AIAA/USU Conference on Small Satellites
February 2006: Concept Design Review (CoDR)
- Prototype bus implementation team presented initial conceptual design against ISET-derived bus standards

July 2006: Preliminary Design Review (PDR)
- Prototype bus implementation team presented preliminary detailed designs and trade results, including implementation against Baseline Rev 4b requirements/standards from the ISET
- At PDR, the ISET released first complete set of ORS bus standards documents: Rev 1.0 10July2006.

December 2006: Critical Design Review (CDR)
- Prototype bus implementation team presented detailed designs prior to fabrication and delivery to integration and test, including implementation against Baseline Rev 4b requirements/standards from the ISET

December 2007: Test Readiness Review (TRR)
- Prototype bus implementation team presented Bus subsystem and integration readiness for Bus System level acceptance and environmental testing.

April 2008: Bus Buyoff
- Prototype bus implementation team presented the results of the Bus system level acceptance and environmental testing and the post test status for each subsystem.

A critical aspect of the relationship between the prototype bus implementation team and the ISET bus standards effort is the manner in which the process was managed – perhaps unique due to the nature of the program. Specifically, the bus implementation team baselined (Baseline Rev 4b) an early set of ISET standards and interfaces to provide a consistent means of comparison throughout the life of the program. It was known, however, that many issues were still unresolved at that particular time and that additional standards/interface development was in process.

As the ISET continued maturing the standards, the prototype bus implementation team provided inputs and technical responses to ISET queries, but new or refined ISET standards were not imposed on the bus implementation team. Thus, the bus implementation team was able to inform the ISET efforts but was not required to react to a continuous flow of changes and considerations generated by the ISET. This resulted in the progression of the prototype bus implementation towards completion while at the same time produced a more complete and informed set of released ISET standards (Rev 3.0 7 April 2008). This process is depicted in Figure 4.

The integration and test of the prototype bus has concluded. At this point, the bus implementation team can compare the implemented bus to the ISET standards as a means of validating a subset of those standards.

**Bus Standards Implementation**

The implementation team initiated a prototype spacecraft bus development to accomplish two primary objectives: (1) validate as many of the ORS Bus Standards as feasible within cost and schedule constraints, and (2) produce a qualified spacecraft bus to support the COMM-X payload under development at NRL to achieve the payload related objectives of the TacSat-4 program.

To accomplish this within the context of a continual review and refinement of the initial ORS bus standards by the ISET, a version of the standards was baselined by the bus implementation team in March of 2006 and served as the basis for the system-level requirements for the System Requirements Review of the bus implementation. This section summarizes trades and design decisions that have been made to date, and provides an overview of the prototype bus.

Figure 4: Prototype Bus Implementation and ISET Standards Progression
Requirements

Requirements flowed down from the ISET derived ORS bus standards with identified excursions for the TacSat-4 mission, the Minotaur-IV with Star 48V launch vehicle, and the COMM-X payload. Each subsystem lead engineer was responsible for identifying all ISET standards, which could be validated at the subsystem level within programmatic constraints, and then deriving any additional requirements to meet mission or payload requirements. Feedback to the ISET was provided at reviews and deliberation sessions where baselined standards were felt to be missing or in need of refinement.

In general, ISET standards related to quantity builds (such as I&T flow, production, etc) as well as requirements related to storage/depot operations are not validated because they are not applicable to a single prototype build and are not part of an operational responsive space bus/payload supply enterprise. ISET defined interfaces were ranked in terms of importance relative to efforts to validate standards, with the bus to payload and bus to launch vehicle interfaces being selected as the most critical.

A limited number of standards that are not necessary to the specific TacSat-4 mission but were identified by the ISET were implemented, including SpaceWire.

From a basic mechanical interface perspective, a standard bus to launch vehicle mounting definition of a 0.98 m circle with 60 evenly space bolt holes was selected for standardization.

From an electrical interface perspective, it was determined by the team that the space vehicle would be launched unpowered, thereby simplifying the electrical interface for rapid integration, test and launch feasibility. In addition, there will be no spacecraft monitoring after space vehicle fairing encapsulation and no trickle charging of batteries. Thus, the only ground or in-flight connection with the spacecraft will be through redundant loopback wires that provide the separation indication and power enable functions to the bus.

From a data interface perspective the Bus to Payload and Bus to Ground interface definition effort was an integrated effort with the other ISET sponsored specification efforts. The Bus to Payload interface was developed independently from the payload design and specification efforts.

Mechanical Subsystem

A critical aspect of the bus development relative to the defined standards was the mechanical system. The baselined set of standards proved to be inadequate in specifying the bus mechanical characteristics sufficient to envelope the desired range of payloads, including the target COMM-X payload. Specifically, the baselined standards required a minimum payload frequency of 50Hz, axial and lateral (in the Payload Developer’s Guide). For the bus, the General Bus Standards specified a minimum frequency of 45Hz, axial and lateral fixed base. Having the bus and payload frequencies so similar resulted in their coupling, which increased system loads. Separating the frequency requirements for the bus and payload, preferably by an octave, would reduce system level coupling. In addition, allowing the space vehicle (bus and integrated payload) frequency to drop to 12-15Hz rather than the launch vehicle mandated 25Hz would allow greater frequency separation of the bus and payload without excessive mass growth.

The design and implementation of the prototype bus structure proved to be a considerable challenge because of the immaturity of the Minotaur IV launch vehicle and the loads imparted on the bus by the payload design. Note that it was determined by the TacSat-4 mission that the nominal configuration of the Minotaur IV (with an Orion-38 upper stage) was insufficient to achieve the target orbit and therefore a configuration of the Minotaur IV with a Star-48V thrust vector controlled upper stage has been pursued by the mission.

The parallel development of the launch vehicle configuration and the prototype bus structure produced a situation in which a significant increase in loads occurred late in the structure development. Specifically, early analysis by the launch vehicle developer that guided bus structural requirements decidedly underestimated the loads imparted on the bus by the launch vehicle.

Based on an initial launch vehicle developer study, an 8g lateral load requirement that incorporated a conservative measurement uncertainty factor was used for the structure design at CDR. Subsequent preliminary coupled loads data received at the time of the program CDR indicated much higher lateral loads from the second stage ignition event, necessitating an increase in the lateral load requirement to 12g’s.
Combined with the loads the payload imparts at the bus to payload interface and their effects on the primary structure that was implemented to simplify access during integration and test, additional design margin was required and thus a development refinement effort to address the significantly increased loads was implemented after CDR. Another important point here is that the need for thermal isolation at this interface also made the structural interface more difficult to achieve. Adding the necessary thermal resistance reduced the joints structural stiffness. The prototype ORS spacecraft configuration is shown in Figure 5 and Figure 6.

The successful early delivery of the prototype bus shear panels by the panel vendor exacerbated the programmatic effects of the structure design refinement. For rapid-turn programs, this type of risk is important to understand, and it is most easily articulated by noting that schedule drivers that lead to early procurement and delivery of long-lead parts subject the program to significant cost and schedule risk in the face of changing requirements. While it was necessary to rework the shear panels, the impact was mitigated by the fact that other primary structural elements were being developed in-house and that it had not been necessary to proceed with processing the acquired raw materials.

**Thermal Subsystem**

The nature of the envisioned ORS operational system, in which buses and payloads can be developed separately and integrated at the launch site, requires that the bus be designed such that it is effectively isolated from the payload and therefore able to operate with a range of payload designs. Thus, this prototype maximized thermal isolation as an approach to handle various payloads designs. The physical connection between the payload and bus required conductive isolation, see Figure 7, and the radiative effects on the bus by the payload were minimized.
The thermal design must also account for the fact that the use of radiators on the bus may expose non-blanketed areas to thermal radiation from the payload, and the bus itself could affect payload performance. Specific requirements on the bus include that the bus must be able to accept a maximum of 60W radiated from the payload and to have a 10 °C/W minimum resistance between the payload and bus. For the TacSat-4 mission, these requirements must be maintained in a 700x12050km highly elliptical orbit with a Beta angle range of ±80 degrees.

The conductive resistance between the payload and the bus is provided by the use of G-10 spacers. There are two G-10 spacers used in each bolt connection. The larger spacer is used between the payload interface ring and the bus, physically separating the two. This spacer provides the main resistance between the bus and the payload. The second smaller spacer is used between the bolt head and the payload interface ring to minimize heat flow from the payload into the bolt and then to the bus. This configuration appears in Figure 7. This design achieves all the requirements of the initial ISET ORS Bus Standards. The ISET has since factored in the soft joint resulting from such isolation as well as lessons from the Standard Interface Vehicle’s (SIV) approach to thermal and since updated the ORS Bus Standards’ thermal requirements to be similar to SIV’s.

The thermal design used allows the bus to be capable of automated thermal control by activation and deactivation of heaters. In addition, the thermal subsystems must be capable of dissipating a minimum of 265W while maintaining all components within temperature limits. Other design aspects call for the propulsion tank to be fully blanketed and conductively tied to the propulsion deck and the thruster valves to be isolated from the deck with G-

10. Each thruster valve has its own mechanical thermostat and heater.

The thermal subsystem implementation passively controls the internal bus temperature, specifically the propulsion lines and tank, and does not use heaters directly on the propulsion lines, as shown in Figure 8. Heaters on the bottom deck are used to control the inside temperature of the bus and the propulsion lines are covered with Kapton to establish a strong radiation connection from the lines to the bottom deck and inside of the bus. Furthermore, the inside of the bottom deck is painted to create a high emissivity surface and allow for stronger connection to the propulsion lines. A primary advantage of this thermal subsystem approach is ease of heater integration. This approach also supports the modularity of the propulsion system (a standards requirement) without impacting the thermal subsystem hardware installation.

The controller for the ORS Phase III Bus was a non-redundant modular design composed of an RHC-3001 based Standard Spacecraft Processing Module (SSPM) from Harris, an 8051 based Command and Telemetry Controller Module (CTC), the Attitude and Propulsion Interface Module (API), a Processor and Interface Module (PAI), a Payload Data Handler Module (PDH) and a Power Supply Module (PSC).
A custom VME backplane tied the VME-based cards together, as shown in Figure 9. The SSPM is based on a Harris rad-hardened 20 MHz MIPS R3000 RISC architecture with a floating-point coprocessor (RHC-3001/RH-3010A). The SSPM has 0.5 Mbytes of boot EEPROM, 1.5 Mbytes application EEPROM, 64 Mbytes of DRAM, 0.5 Mbytes I-Cache, and 0.5 Mbytes of D-Cache all EDAC protected. The SSPM utilizes a VME bus, is rated at >1 MRAD and has a published bandwidth of 31 Dhrystone MIPS.

The PAI module provides SSPM processor interfaces to the Star Tracker, Inertial Memory Unit, CTC and the CEASE experiment. The PAI also provides 256 Kbytes of PROM based boot storage for the SSPM. The SSPM is externally and dynamically configured by the CTC to boot from internal EEPROM or the PAI based PROM. The PAI distributes timing within the CDE.

The PDH module implements the 512 Mbyte EDAC protected SDRAM based Solid State Recorder, 2xRS-422/HDLC payload interfaces, 2xSpaceWire Interfaces, the Transponder Wideband return link interface, 32xDMAs, external CDE time distribution, and a VME interface. The SpaceWire interface utilizes the NASA Goddard Spaceflight Center VHDL SpaceWire link core, which is freely available to U.S. users, as is a SpaceWire router core.7 The PDH provides a logical unit lookup table and DMA capabilities to route data from the RS-422/HDLC and SpaceWire interfaces to SSR segments based on the data communications destination address. The PDH also provides a prioritized and virtual machine architecture to enable multiplexed DMA transfers from the SSR to the transponder wideband return-link interface while providing FPGA control formatting to enable transport protocol compliance. The eight-channel CCSDS Channel Access Data Unit (CADU) multiplex function provides for mission data routing to the S-Band downlink. Digital logic was implemented in an Actel RTAX2000 FPGA, and onboard RAM is used in a Triple Module Redundancy (TMR) configuration to mitigate Single Event Effects (SEE). The primary SpaceWire port is intended for the payload interface, while the second port could be used to route data to a future wideband tactical downlink, or to connect to a more extensive SpaceWire network through a router. Interfaces to Space Plug and play Avionics (SPA) devices, such as those employed on the ORS office’s PnPSat mission, could also be implemented since both share SpaceWire as a common physical, data, and network interfaces.

The CTC module implements the low-level Bus hardware command actuation and telemetry acquisition using A/Ds, D/As, digital inputs, digital outputs, pulse train outputs, high-level outputs, serial inputs, and serial outputs. The CTC handles the SGLS transponder forward link and low-rate return link interfaces. The CTC supports low level direct commanding from and direct telemetry to the ground when placed in a diagnostic mode. Otherwise, the SSPM/PAI provide the primary command handling and telemetry generation services. The CTC utilizes a radhard Aeroflex 8051 at 20 MHz (12 clock cycles/instruction cycle) with 64 Kbyte instruction PROM, 64 Kbyte alternate instruction SRAM, and 32 Kbyte data SRAM. The HW level interface and control is provided by an Actel FPGA.

The API module implements the attitude control interfaces to the reaction wheels and magnetic torque rods. The API module also implements the control interfaces to the release mechanisms, propulsion latch valves, and thruster valves. The HW level interface and control is extended to the CTC 8051 by an Actel FPGA.

The CT&DH system was compliant with the bus standards with the following exception:
512 Mbyte SSR in lieu of 1 GByte SSR (COMM-X payload required <= 256 Mbytes).

Note: The ORS Phase III bus is not configured with a GPS unit, therefore time synchronization to UTC is accomplished using time correlation of a time tagged bit within the return link data stream. This space/ground correlation mechanism accomplished a time synchronization accuracy of <1 msec with a time maintenance accuracy over 24 hours of <100 msec (approaching 10 msec). The CDE oscillator is not temperature controlled therefore the flight software provided continuous bias adjustment using the temperature from a proximity thermistor. The ORS Bus Standard requirement for time maintenance is <0.125 milli-seconds to UTC. The COMM-X mission requires <100 msecs.

**Flight Software System**

The flight software resident in the controller for the ORS Phase III Bus consists of three Computer Software Components (CSCs) identified as the Boot CSC, Operational CSC and the Command & Telemetry Control CSC. The Boot and Operational CSC are resident on the Harris RHC-3001 based Standard Spacecraft Processing Module (SSPM). The Boot flight software initializes the SSPM, PAI, and PDH slices and initiates the execution of the Operational CSC. The Operational CSC provides all high level processing functions and handles the interfaces to the Payload Data Handler (PDH), Inertial Measurement Unit (IMU) and Star Tracker. The high-level functions include primary command and telemetry, attitude determination, attitude control, payload communications, autonomous operations, and Fault Detection, Isolation and Recovery.

The Command and Telemetry Control (CTC) CSC is resident on the 8051 based CTC slice and provides software control of the CTC and the API functions. The CTC slice handles the low-level generic command and telemetry interfaces to the spacecraft avionics external to the CDE. In addition, the CTC handles the forward and low rate return link interfaces to the transponder.

The flight software is comprised of non-proprietary and COTS software. The non-proprietary code is an NRL Federal Government based solution. This embedded software system is modular in nature and represents a re-usable core with a layer of mission specific functions. A portion of the core layer provides an operating system abstraction and the implementation for ORS Phase III Bus utilizes VxWorks as the operating system. The COTS product is the tasking and autonomous control module implemented by the Spacecraft Command Language (SCL). This product is delivered and integrated by Interface Control Systems, Inc.

The architecture of the ORS Phase III Bus software meets the intent of modularity and open systems goal outlined in the Bus Standards.

The ORS Phase III Bus Flight software fully implements and is compliant with the Bus/Payload and Space/Ground Interfaces as defined by the Data Interface Standards Document. The Bus Flight Software supports both the SpaceWire and RS-422/HDLC type payload electrical interfaces. The CT&DH provides for two SpaceWire and two RS-422/HDLC links. One of each type is utilized for...
payload communications, while the other of each type is utilized for ground test related communications. The data protocols, data transport envelopes, message structures and fields are implemented per the Data Interface Standards Document.

The flight software and CT&DH underwent extensive integration and acceptance testing using test beds that stimulate all external CDE input interfaces and capture all CDE external output interfaces. The test beds provide flight equivalent electrical simulation of all interfaces, high fidelity simulation of the ACS components, medium fidelity simulation of the payload and a high fidelity attitude and orbit dynamics simulation. These test beds have been designated as candidates for the ORS Payload Test Bed (OPTB). The OPTB is intended to provide a platform to support the development and verification of the Bus/Payload interface for Bus Standards compliant Payloads. The OPTB is also intended to support mission simulations with any compliant payload or payload simulation.

**Telecommunications System**

The Telecommunications System for the ORS Phase III Bus Implementation is designed to the ISET-developed bus standards with a few specific departures made to accommodate the TacSat-4 mission.

**TT&C Link / No Wideband Tactical Link**

The RF subsystem will be Air Force Space Communication Network (AFSCN)-compatible, as dictated by the bus standards, but telemetry, tracking, and command (TT&C) links will be primarily operated through NRL’s Blossom Point (BP) Satellite Tracking and Command Station. The subsystem architecture for TT&C is single-string and straightforward, using a SGLS transponder (L/S-Band) with COMSEC capability, an RF switch assembly of passive components, and two low gain antennas (LGAs) located on opposite sides of the spacecraft. A separate, tactical communications link is identified as an option by the bus standards but is not implemented because of the nature of the TacSat-4 mission. The Bus Standards specify the tactical link (high rate CDL or low rate UHF) as an option due to wide data rate variations in payloads and the impracticalities (cost and technical) of implementing a tactical link for missions that do not require it. The TacSat-4 the payload fundamentally provides tactical communications. Still the SGLS link will be used by the payload operators as a demonstration of an alternate T&C path for the payload. A block diagram of the system is shown in Figure 13.

**Transponder: Encryption, Ranging, Data Rates/Modes**

The RF subsystem achieves the bus standard of encrypting and decrypting its TT&C link using NSA-approved algorithms by designing in the CXS-810C SGLS transponder from L-3 Communications - Telemetry West. The transponder also supports the ground ranging requirement, originally intended as a backup to a GPS spacecraft location capability but ultimately baselined as the primary method for spacecraft orbit determination. The transponder will provide SGLS commanding at 2 kbps and narrowband (low rate) convolutionally encoded state-of-health telemetry downlink at rates up to 32 kbps on a SGLS sub-carrier. A wideband capability will also be available at rates up to 1 Mbps convolutionally encoded direct-on-carrier.

![Figure 13: RF System Block Diagram](image)

**Quality Assurance**

Product assurance between JHU/APL and NRL is a cooperative process. This is fundamental to the approach to development defined by the ISET. The goal is to pursue development and quality assurance (QA) with the processes and procedures that are inherent to each organization. A challenge within this is to verify that a sufficiently high level of program-wide product assurance and safety is maintained while still allowing organizations to maximize the efficiency by using their own processes.

Program quality and product assurance was achieved by appropriate adherence to established processes and procedures for all flight items built at or procured by JHU/APL or NRL. Joint development of quality assurance approaches and processes early in the prototype build allowed effective interaction between the two organizations. While some differences in levels of testing or particular terminology for...
component designations were identified, time and effort were expended to make sure such differences were understood and incorporated into the overall mission success goals.

Both JHU/APL and NRL incorporate QA functions within the primary structure of the project organization, under the purview of the program manager and part of the core team, there is a very strong independent path to upper management within each organization allowing effective independent oversight of programmatic issues.

QA was involved in requirements review and development to verify compliance to program requirements and application of those requirements to procurements. Parts procurement, testing and screening was based on INST-002 requirements and issues were handled through a parts control board operation chaired by the electrical systems lead.

Both organizations typically apply established standards as a default; for the ORS Phase III Bus Standards program, the Institute for Interconnecting and Packaging Electronic Circuits (IPC) J standards were successfully applied in certain instances. Components built for previous programs were selected for their successful mission operations. Some components, however, that were procured and used for space missions may not necessarily adhere to full space flight manufacturing and assembly standards. For these suppliers and manufacturers, JHU/APL evaluates their processes to determine the level of compliance relative to IPC and/or NASA standards as well as ISO 9000 and AS9100. Contamination control, material selection, and safety are all required evaluation criteria during supplier/manufacturer assessments.

While existing standards are typically very mature, they also present a level of rigidity and detail that is potentially cost-prohibitive for rapid-turn missions. Through industry efforts, IPC standards have matured to a point that they can provide acceptable products for this class of program, following established procedures, audits, corrective actions, etc. The use of IPC standards by the program was also consistent with the desire to allow organizations to use effective, internal procedures rather than placing burdensome and costly requirements that were not necessary to achieve the quality level specified. This approach is consistent with the ORS Standards Documents allowing bus vendors to apply their own internally processes for quality control.

All internal assembly at both JHU/APL and NRL followed internal requirements as dictated by the mission assurance plan. Joint QA program support between the two organizations has occurred throughout the program. This effort provided benchmarking opportunities between the teams to fully utilize each other’s approaches toward a successful bus system for the TacSat 4 mission.

**Material Responsibilities**

NRL has overall material review board (MRB) authority for the program; however, minor assembly issues are dispositioned through the JHU/APL material review process. All associated end-item documentation is presented to NRL mission assurance for inclusion in the overall Bus end-item data package.

All assemblies and procurements led by JHU/APL engineering underwent an end-item review or buy-off to ensure compliance to applicable configuration management (CM) mission assurance requirements as well as performance specifications.

**Mechanical Integration and Test - Pre-Text Readiness Review (TRR)**

Pre-TRR integration started in May of 2007 with a wooden mock-up of the ORS Phase III bus.

![Figure 14: Bus Mock-Up for Wire Harness](image)

This unit was created to begin the wire harness build and start preliminary component integration testing as those components became available. In July the bus structure was received from JHU/APL.
Figure 15: Removal of Bottom Deck for Propulsion Integration

The lower deck was removed and sent for integration with the propulsion unit to begin the propulsion equipment installation. This design and integration approach supported the standards requirement for propulsion modularity. Concurrently, removable panels had thermal equipment and components attached and the mock-up wire harness build continued.

Figure 16: Shear Panels

During September 2007 the propulsion equipment build was completed allowing the bus lower deck to be reinstalled. The bus structure was then mounted to the turnover dolly and rotated to an inverted position to begin panel installations.

Figure 17: Typical Configuration During Bus System Integration

The inverted position prevented damage to sensitive propulsion equipment in case of inadvertent release of any untethered hand tools. By November 2007, full pre-TRR electrical integration testing had commenced and solar array fit checks completed. The bus was ready for TRR by mid-December 2007.

As pre-TRR activities progressed a couple of issues emerged. One of the features of the design was to have hinged panels allowing access to the bus interior. Panels would open like cabinet doors with components being attached to the inward side of panels. Once panel cables were attached to panel connectors and over-wrapped with monel, they became rigid and didn’t allow for panel opening. This resulted in bus access problems and increased I&T scheduling complexities. A second issue concerned the battery. During component level testing a temperature chamber malfunctioned and overheated the lithium-ion battery. The battery had to be replaced preventing it from entering the bus I&T flow. A battery simulator was used in its absence. Notably, the standards requirement for the battery to be modular, specifically for rapid depot integration in the field, has increased flexibility during the integration and testing phase.

Mechanical Integration and Test - Post Test Readiness Review (TRR)

Environmental testing was accomplished using a typical series of spacecraft tests. It started with a pre-environmental alignment test and was followed by EMI/EMC, acoustics/vibration, mass properties, thermal-vacuum, post environmental alignment, and finally, a comprehensive post functional test. During the summer of 2008, the bus will join to the COMM-X payload to perform the magnetic dipole moment and space vehicle level EMI/EMC testing.
Again, as with pre-TRR evolutions, bus access was limited due to the inability to open panels. Instrumenting the vehicle for environmental tests was challenging and scheduling was adversely affected. It was also determined here that the new flight battery would not be available until space vehicle level integration.

**Component Level Testing**

Component level testing was completed to the requirements in Table 4.

<table>
<thead>
<tr>
<th>Component Level Testing Methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tests</strong></td>
</tr>
<tr>
<td>Mass Properties</td>
</tr>
<tr>
<td>Thermal Properties</td>
</tr>
<tr>
<td>Environmental</td>
</tr>
<tr>
<td><strong>Table 4: Components level testing methodology</strong></td>
</tr>
</tbody>
</table>

**System Level Testing**

System level testing was completed to the requirements in Table 5.

<table>
<thead>
<tr>
<th>System Level Testing Methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tests</strong></td>
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<tr>
<td>Static Balancing</td>
</tr>
<tr>
<td>Thermal Cycles</td>
</tr>
</tbody>
</table>

**ADDITIONAL ORS PHASE III BUS STANDARDS IMPLEMENTATIONS**

In addition to the prototyping effort for the ORS Bus, other implementers have used the standards documents to produce compliant systems.

MicroSat Systems, Inc. developed and tested against ORS Bus prototype hardware and software the Universal Interface Electronics (UIE), a versatile multifunction unit that employs SpaceWire and RS-422 interfaces. Its different interfaces and various configurations allow it to perform as a protocol translation, power distribution, data storage, or telemetry collection and consolidation node. The UE employs the LEON3 processor in an Actel RTAX2000 FPGA and also includes a Xilinx Virtex II FPGA for mission-specific configurations.

Design Net Engineering during its development of a Flight Software Standards Testbed (FSST) has created hardware and software that complies with the ORS standards. An interface test is scheduled for the near term to prove compatibility with the ORS Bus prototype and OPTB and to discover any subtleties or ambiguities that may need attention in the Data Interface Standards Document. Because the ORS and SPA standards share a common physical and link layer implementation in SpaceWire, it has been shown that the Reconfigurable Processor Boards (RPBs) used for the FSST development are usable for either of these complementary standards approaches.

**BUSINESS CASE IMPLICATIONS**

As the ISET has been focused on the technical aspects of developing and refining the bus standards, an individual from each of the ISET participant organizations has represented the Business Team. The goal of the business team has been to incorporate relevant business case information, as determined by industry, into the transition plan to improve the government’s transition from R&D to acquisition of operational buses. The transition plan was written by the Business Team and used to solicit a broad range of industry ideas on policy, incentives, markets, etc. as well as for transition advocacy and planning by ORS office and supporting government organizations. The business team’s charter includes maturing the standards as needed for business/cost factors.

The Business Team companies provided cost estimates based on the Preliminary Design Review level bus standards. These estimates were evaluated and used to modify and refine the standards with balanced consideration for business and technical
The Business Team is in the process of providing final cost estimates based on the final (REV 3) versions of the ORS Bus Standards Documents.

The ORS Phase II Bus Standards logo represents the broad participation and the focus on both technical and business factors.

![ORS Phase III Bus Standards Logo](image)

Figure 18: ORS Phase III Bus Standards Logo

**CONCLUSION**

The prototype build of the ORS Phase III spacecraft bus was completed in April 2008. For the TacSat-4 Mission, this bus will be integrated with the COMMx Payload and launched on a Minotaur IV vehicle from Kodiak in September 2009. Through the efforts of the Integrated System Engineering Team, the program has successfully produced an extensive and well-documented set of standards and interfaces for cost-effective spacecraft bus systems of the class of missions considered.

Validation of a subset of these standards proceeded through the development of the prototype bus in an open manner that has allowed government and industry insight into successful implementation approaches and challenging issues that have arisen. Because JHU/APL and NRL have led the development of the prototype bus, no proprietary claims have been exercised and any design aspects and techniques are available to the government sponsor for future consideration in industry-supplied operational builds.

Both technical and business aspects have been considered and documented to enable ORS to realize near-term bus standardization allowing modularity for rapid mission tailoring and launch. An open process for continued standards improvements, such as increased modularity, is also well documented to best position government and industry to continue standards advancement while remaining coordinated.

**ACKNOWLEDGEMENTS**

The information contained in this paper is a consolidated summary of the combined effort of the ISET and the NRL-JHU/APL Bus Implementation Team. The authors would like to recognize the contributions of each of the team members, listed in alphabetical order by company affiliation: Mr. Aaron Rogers and Mr. Bob Summers (each formerly of AeroAstro, Inc.); Mr. Eric Finnegan (JHU/APL), Mr. Paul Tarbuck from Boeing; Dr. Gerry Murphy from Design Net; Mr. Bob Smith from General Dynamics-Spectrum Astro; Dr. Walter Gelon from Space Systems Loral; Dr. Kirk Stewart and Mr. Paul Graven from Microcosm; Mr. Jeff Summers from MicroSat Systems; Mr. Larry Slivinski from Orbital Sciences; Dr. Allan Mense and Mr. Chuck McMullin from Raytheon; Mr. Blake Crowther and Mr. Jim Dyer from the Space Dynamics Laboratory, and Mr. Jeff Baker and Ms. Deborah Westley from Swales.

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