ISET ORS BUS STANDARDS AND PROTOTYPE

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ABSTRACT

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 core ISET industry team members include AeroAstro, Boeing, Design Net Engineering, General Dynamics Spectrum Astro, Loral, Microcosm, MicroSat, Orbital, Raytheon, and Swales. Government and Laboratory team members include the Naval Research Laboratory (NRL), The Johns Hopkins University Applied Physics Laboratory (JHU/APL), Air Force Space and Missile Command (AF SMC), Air Force Research Laboratory (AFRL), MIT/Lincoln Laboratories (MIT/LL), Army Space and Missile Defense Command (SMDC), and Space Dynamics Lab. The ISET generates standards for ORS spacecraft and uses them to build a prototype in order to evaluate and mature the standards. The ISET recently made the second major release of the bus standards documents that are available at the 21st AIAA/USU Conference on Small Satellites. This ISET team is also complemented by an open membership Business Team who provides business case factors for consideration in the standards definition, as well as for input for the acquisition transition plan. This paper describes the status of the ORS Bus Standards developed by the ISET to date including the implementation for the prototype build.

REVIEW OF PHASE III OBJECTIVES

The first objective of the ORS Phase III Bus Standards effort is 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 is 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 intends to bridge the gap between Science and Technology (S&T) buses and an operational bus capability. This is being accomplished by prototyping a bus using the ORS system-level standards. Though not all of the standards will be validated through the prototype build, some critical elements such as mechanical and electrical interfaces between major space vehicle segments, including the payload to bus and launch vehicle to bus interfaces, will be validated.

The paper is divided into two major subsections: the first section provides details of the Integrated System Engineering Team (ISET) and the bus standards, the second section details the bus standards implementation for the TacSat-4 mission.

ORS BUS STANDARDS DEVELOPMENT

The ORS Phase III effort began with an industry day briefing on 31 March 2005 at the Naval Research Laboratory, US small satellite integration companies were encouraged to submit proposals to participate in the ISET. The eight companies that were selected are: Swales, Design-Net, Microcosm, Loral, GD-Spectrum Astro, Microsat Systems Incorporated, Boeing, and Raytheon. A ninth company, Aero-Astro, was selected to participate as a consultant to the ISET, based on their expertise with the ESPA ring satellite interface. The first ISET meeting was held at JHU/APL on 3 June 2005.

The analysis from the Massachusetts Institute of Technology/Lincoln Laboratories (MIT/LL) Phase 1 effort[1] 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. The ORS spacecraft characteristics should not be much more or they will break the low cost and responsiveness model.

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

Table 1 ORS Bus Characteristics Phase I Study

	Max Utility, "Low" Cost	400 kg Limit	250 kg Limit	Max Utility / Cost	Units
PL Power	250.0	200.0	100.0	250.0	W
PL Mass	200.0	150.0	100.0	100.0	kg
DL Rate	50.0	50.0	50.0	10.0	MBps
Num Orbits	12.0	8.0	3.0	12.0	#/day
Point Know	10.0	10.0	10.0	10.0	Arc-s
Point Control	40.0	40.0	60.0	60.0	Arc-s
Slew Rate	10.0	10.0	10.0	10.0	Deg/min
Mission Life	2.0	2.0	2.0	2.0	Yrs
PL Duty	0.2	0.5	0.2	0.2	Fraction
DL Band	7.5	7.5	7.5	7.5	GHz
Max DV	500.0	100.0	0.0	100.0	m/s
Total Mass	566.8	378.1	238.4	264.7	kg
Bus Mass	366.8	228.1	138.4	164.7	kg
Bus Dry Mass	288.7	216.2	137.8	156.4	kg
Avg Power	183.6	228.7	140.9	166.2	W
Peak Power	432.8	411.2	249.5	414.4	W
Array Area	1.1	1.4	0.9	1.0	m2
Bat Capacity	306.2	381.1	234.1	276.9	W-hr
Total Volume	0.4	0.3	0.2	0.3	m3

Once the goals and the charter of the ISET were established, a series of deliberation session were held over the next several months, 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.

Items forwarded to Revision 3 were requirements defining Contamination Control and Flight Software. These and other minor requirements will be flushed out during the revision process through August 2007.

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

The next section describes the status of the standards documents, and highlights the known areas for refinement. These standards are considered live documents; the ISET 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.

Figure 1 presents a basic flow down between and among this document set.

The following subsections present a basic description of the contents of these documents. It was expected that a unifying organization, such as the recently established ORS Squadron 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 XR, AFRL, and the Standard Interface Vehicle program.

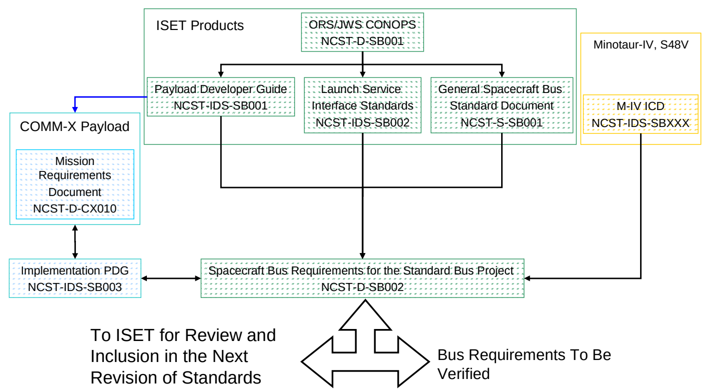

Figure 1: ORS Bus Standards Document Structure

As the mission designer or architect, this organization/entity will need to ensure that the combined selection of operations, launch vehicle (LV), payload, and bus form a valid mission design for any one specific mission instantiation. Finally, it is expected that any vendor manufacturing a bus under the ORS system would need to be responsive to the applicable information established by all four of the documents.

Mission Requirements and CONOPS Document[2]

This document represents a top-level definition of the overall ORS mission, as defined by the ISET. The primary focus of this document was to investigate the orbital environments, envelope the multi-mission support requirements, establish possible 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.

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 would develop standardized interfaces between and potentially within the busses, payloads, and boosters. In order to achieve the cost efficiencies envisioned, bus, payload, and booster design would remain constant allowing for multi-year bulk purchases. Spiral changes for new technology insertion would be approx every 3-5 years. The envisioned System Architecture is shown Figure 3

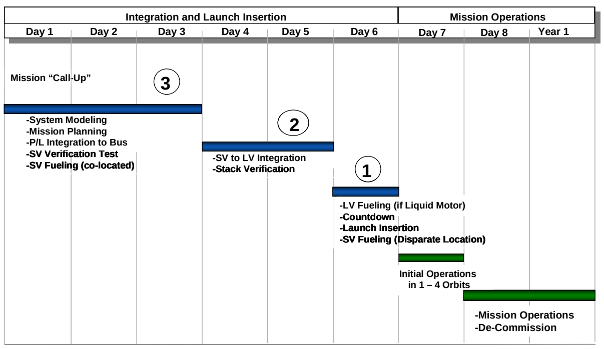

Figure 2: Top-level Timeline

Future activities for refining this document will be limited to refining the concepts and the concept of operations, and will be heavily dependent on feedback from the ORS community/enterprise.

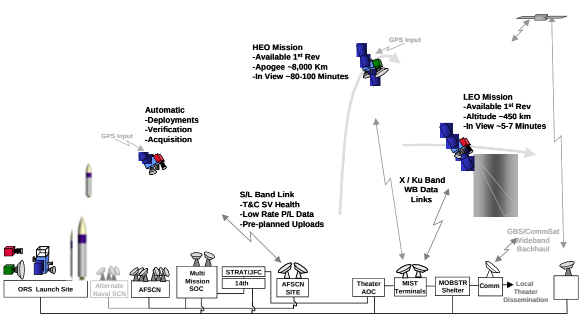

Figure 3: System Architecture

The recent developments in the ORS Enterprise are summarized in "ORS AND TacSat ACTIVITIES INCLUDING THE EMERGING ORS ENTERPRISE[3]," the ISET assumptions are aligned along the Tier 2 of the Tiered approach of ORS goals.

Launch Vehicle Interface Standards (LVIS) Document[4]

The LVIS defines, in sufficient detail, the interfaces of the spacecraft bus to a generic ORS LV. It is expected that no additional LV information would be needed for a spacecraft manufacture to build a spacecraft bus to fly in the ORS system. Thus, this document should be considered more than a "guide"; it is actually an interface control document from the LV perspective. It includes Pre- and Powered-flight environments and all interfaces (mechanical, electrical, thermal, etc.)

The LVIS is intended to be used as the sole input for launch vehicle related aspects during spacecraft bus development governed by the ORS Standards. This document will cover all aspects of the launch vehicle interface, launch site processing, and mission design associated with launching spacecraft built to the ORS Standards. This document is to be used to directly or indirectly derive information and requirements needed to further the design of spacecraft busses through the Critical Design Review (CDR) phase of the mission. This document shall stay in effect throughout the development of the bus.

Table 2 Summarizes the space vehicle (combined bus built to the standards and an ORS payload) compatibility with various launch vehicles.

As part of the prototype development and the TacSat-4 mission, which uses the Phase III prototype spacecraft bus, it became evident that for HEO missions, ISET benefited from enveloping the 4-hour orbit. The Minotaur IV as baselined for the standards development does not have the performance required to achieve a 4-hour HEO orbit for the mass class of space vehicle developed for TacSat-4, therefore a Minotaur IV Plus option is under development by the Responsive Space Launch Program.

Future activities for refining this document will include enveloping the environments for the Minotaur-IV Plus. Furthermore, as flight data is made available for various ORS vehicles the standard will be updated on a periodic basis.

Payload Developers Guide (PDG)[5]

The PDG presents the envelope of capabilities and the requirements for support of the selected range of potential missions. It identifies the necessary performance requirements, interface definitions, and general ORS philosophies needed by mission designers and payload developers to be compatible with the ORS spacecraft bus and launch capability. Given the close system interactions between the payload, spacecraft bus, and launch vehicle, this standard in some cases may refer to other standards developed under the Phase III ORS effort, to eliminate the duplication of information, but is intended to be standalone document from the payload provider perspective.

Table 2: Summary of Launch Vehicle Compatibility

	ESPA	Pegasus	Taurus	Minotaur I	Minotaur IV
Mass & CG	No	No	Yes	Yes	Yes
Envelope	No	No	Yes	Yes, for larger fairing	Yes
Mounting	No	Yes	Yes	Yes	Yes
Electrical	Yes	Yes	Yes	Yes	Yes
Quasi Static Loads	No	Yes	Yes	Needs Load Isolation	Needs Load Isolation
Random Vibe	Not Yet Specified	Needs Load Isolation	Covered by Acoustics	Yes	Covered by Acoustics
Sine Vibe	Not Yet Specified	None Specified	Needs Load Isolation	None Specified	Yes
Acoustics	Yes	Yes	Yes	Yes	Yes
Shock	Yes	Yes	Yes	Yes	Yes
Pressure	Yes	Yes	Yes	Yes	Yes
Thermal	Yes	No, usually not a driver	Yes	Yes	Yes
Safety	Yes	Yes	Yes	Yes	Yes

	Space-X Falcon 1	Space-X Falcon 5	Delta II, IV	Atlas V	DARPA FALCONs
Mass & CG	Yes	Yes	Yes	Yes	Yes
Envelope	Yes	Yes	Yes, except dual payload height	Yes, except dual payload height	Yes
Mounting	Yes	Can conform	Can conform	Can conform	Yes
Electrical	Yes	Yes	Yes	Yes	Yes
Quasi Static Loads	Yes	Not Yet Specified	Yes	Yes	Yes
Random Vibe	Yes	Not Yet Specified	None Specified	None Specified	Covered by Acoustics
Sine Vibe	None Specified	Not Yet Specified	No, need analysis	No, need analysis	None Specified
Acoustics	Yes	Not Yet Specified	Yes	Yes	Yes
Shock	Yes	Not Yet Specified	No, usually not a driver	No, usually not a driver	Yes
Pressure	Yes	Yes	Yes	Yes	Yes
Thermal	Yes	Yes	Yes	Yes	Yes
Safety	Yes	Yes	Yes	Yes	Yes

The support accommodations for the payload contained within this document was derived from an enveloping process conducted by the ISET. In order 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 3 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 4. 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 3: Supported Payload Capabilities

PL Support Item	Selected Capability
Mass [kg]	175
Volume [m^3]	.62 m^3
Orbit Average Power [W]	200
Peak Power [W]	700
Orbit Position Knowledge-3σ [m]	90
Attitude Knowledge-3σ [deg]	1 arc-min at I/F
Attitude Control-3σ [deg]	0.05
Slew Rate [deg./sec]	2.0
S/C SB Ops Data Rate [Mbps]	5
Tactical D/L Data Rate [Mbps]	274*
PL Data Storage [GB]	0
Thermal Dissipation to SB [W]	60

Table 4: Mission Set

Mission / Orbit Class	Selected Level	RADAR LEO Theater Single Target	Electro-Optical - LEO Imaging (Single Target)	Signal Collection - LEO Global	Electro-Optical - LEO Push Broom	Electro-Optical - LEO Imaging (mosaic)	Weather Sensing	RADAR LEO Theater Single Target	Hyper-Spectral: LEO Push-Broom Earth Mapper	Hyper-Spectral: TacSat 3	Hyper-Spectral: LEO Target Imager (mosaic)	Blue Force: HEO Long Dwell	Signal Collection–HEO	Navigation (GPS): HEO Theater Long Dwell	Comm - HEO Theater Long Dwell	Space Surveillance: LEO Maneuverable	Space Control - LEO Maneuverable
Mass	200 kg	100	117	100	120	171	200	75	250	200	250	92	125	168.2	200	200	200
PL-OAP (Payload Orbit Average)	200	14		40			100		250		250	200	75	217	350	100	250
Peak Power during Collect	700 w	40	58	115	135	345	400	700	700	190	1000	200	215	250	500	200	1000
Knowledge Accuracy (3-σ)	0.01 deg		0.05	0.1		0.003	0.03	0.02	0.05	0.002	0.005	0.05	0.1	1.6	0.01	0.005	0.01
Pointing Accuracy (3-σ)	0.05 deg	0.1	0.1	0.25	0.25	0.03	1	2	0.5	0.03	0.05	0.5	0.25	1	0.1	0.05	0.1
Slew rate	2 deg/sec		1	2		4	0.1	1.00	1	3	1	2	2	2	2	1	2
Data Storage Req'd	0 GB	20	0.8	8	20	16	1	100	2	16	2	0.1	4	0		60	20
Low rate DL	2000 kbps	1000	2000				128	64	64	2000	64	200		16		100	64
High-rate D/L	274 Mbps		274	45	110	110	0	270	30	548	30		2	0	45		274
Dissipation during Collect	TBD W			65	130	345	400	1000	500	500	500		115	250		150	
Orbit Knowledge	20 m	20	20	20	20	10	20	20	20	10	10	20	20	20	20	20	20

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 has continued, much more detail, including specific implementation specifications, has been added to the Implementation Payload Developer's Guide. The modifications/deviations taken from the standards to meet the TacSat-4 mission will be provided to the ISET for consideration in the next revision of the ORS Standards and openly documented for the community, as has been done at the previous significant design reviews.

General Bus Standards (GBS) Document[6]

The GBS contains general programmatic requirements for interactions of the vehicle manufacturer with the government, RF communications interfaces, interfaces with the ground operators for the spacecraft command and control (C2), bus functional and performance requirements, ground support equipment and integration facility requirements, and mission/quality assurance provisions.

The capabilities and the requirements for the design, development, manufacturing and testing of a spacecraft bus to support a class of ORS mission are captured. It identifies the necessary performance requirements, interface definitions, and general ORS philosophies needed by mission designers and spacecraft bus manufactures to be compatible with other segments of the overall ORS system (i.e., launch vehicles, payloads, etc.). There are many performance requirements that the spacecraft bus must meet which are contained in the ORS Payload Developers Guide (ORSBS-003) and the Launch Service Interface Standard (ORSBS-004). These two documents in combination with this document represent a complete set of requirements for the spacecraft bus.

ORS PHASE III PROTOTYPE BUS IMPLEMENTATION

Background

The second objective of the ORS Phase III Bus Standards program is to validate a subset of the bus interface standards developed by the ISET and provide a qualified bus for the TacSat-4 experimental mission. The prototype bus has been developed jointly by JHU/APL and NRL with subsystem leadership and technical support divided between the two organizations as an integrated team. The bus will be integrated and tested at NRL during the Summer/Fall of 2007. The COMM-X payload for the TacSat-4 mission is also under development at NRL and it will be used to verify and validate the critical bus/payload interface standards defined by the ISET.

The prototype bus implementation team consists of engineers from JHU/APL and NRL. 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 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: (http://projects.nrl.navy.mil/epi/index.php)

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 designs 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 four deliverable documents:
- General Bus Standards Document
- Payload Developer's Guide
- Mission Requirements & CONOPS Document,
- Launch Vehicle Interface Document

February 2006: Concept Design Review (CoDR)

- Bus implementation team froze ISET standards/requirements at Baseline Rev 4b in February 2006 to provide a consistent point of comparison between the ISET bus standards and the implementation.
- 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
- Partial, preliminary coupled loads data received from launch vehicle (Minotaur IV with Star 48V fourth stage) developer indicating variance from previous developer studies loads.

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 1.0 10July2006). This process appears in Figure 4

Once integration and test of the prototype bus is concluded, and no later than the Pre-ship Review (PSR), the bus implementation team will compare the implemented bus to the ISET standards as a means of validating a subset of those standards. This will include comparison to both the Baseline Rev 4b standards that were used from CoDR as well as the final (anticipated Rev 2.0) release of the ISET standards that were in parallel development with the prototype bus.

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 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 2005 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.

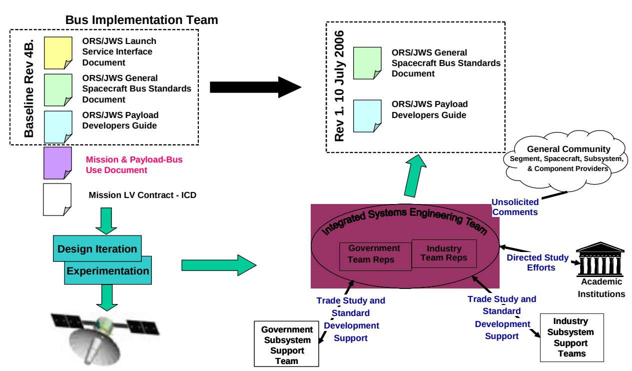

Figure 4: Prototype Bus Implementation and ISET Standards Progression

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. The general flow of requirements, including general ISET derived requirements and specific mission/payload implementation requirements appears in Figure 1.

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 a electrical interface perspective, it was determined by the team that the space vehicle would be launched un-powered, 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 loop-back wires that provide the separation indication and power enable functions to the bus.

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.

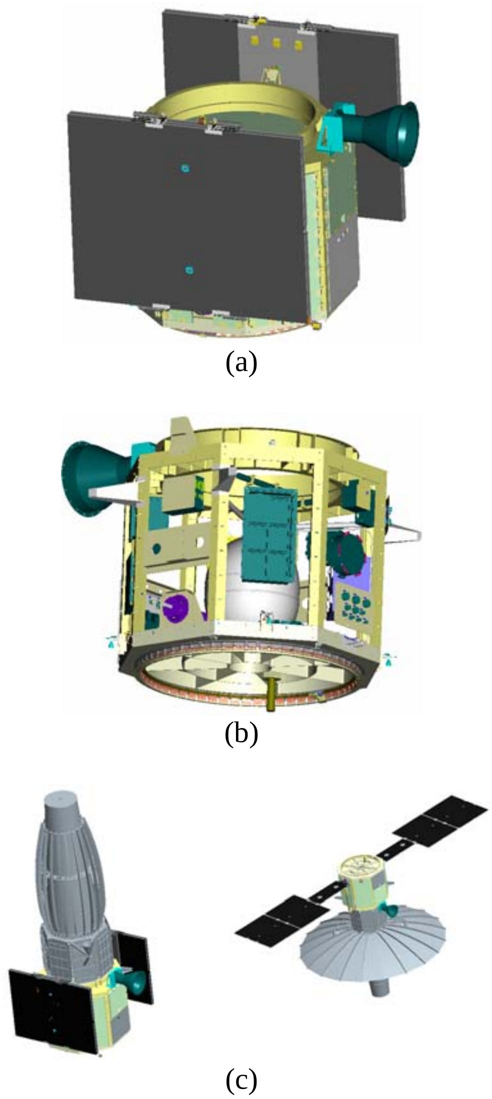

Figure 5: Prototype ORS Spacecraft Configuration: (a) and (b) Spacecraft Bus Component Layout; (c) Space vehicle configuration, stowed and deployed

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, the physical connection between the payload and bus requires conductive isolation and the radiative effects on the bus by the payload must be minor such that various payload designs can be supported.

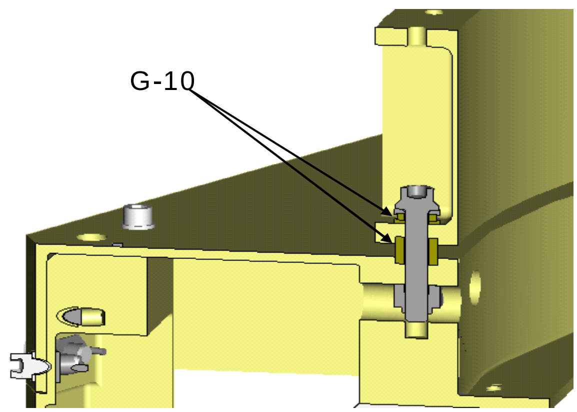

Figure 6: G-10 Washers For Resistance

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 there must exist a 10 ºC/W minimum resistance between the payload and bus. For the TacSat-4 mission, that 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 6.

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.

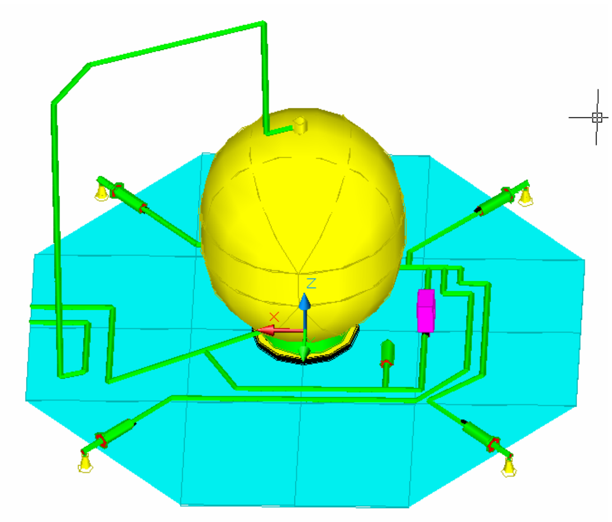

Figure 7: Passive Thermal Design For Propulsion Subsystem Temperature Control

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 7. 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.

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, steer able tactical communications link at 274 Mbps identified as an option by the bus standards is not implemented because of the nature of the TacSat-4 mission. In addition, its implementation for demonstration purposes only would be unnecessarily difficult due to the sheer size of the obstruction introduced by the COMM-X payload itself. Instead, 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 8

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.

Omni-Directional Coverage Using Two Hemispherical LGAs

The overarching driver on the RF subsystem design is the bus standard requirement to achieve as close to omni-directional acquisition coverage as possible, so as not to constrain, for communications, the attitude control of any particular ORS-class mission. The use of two opposing hemispherical pattern low gain antennas, either switched or arrayed, offers a simple approach to meeting this requirement, assuming the LGAs are unobstructed. If the antennas are arrayed, as they are for one configuration of the TacSat-4 RF subsystem, an angular region of interferometric nulling is introduced where the patterns overlap, which may prevent the combined pattern from obtaining complete omni-directional coverage.

At LEO distances, link margins may be high enough for typical transponder transmit powers (nominally 5W for TacSat-4) to communicate through these nulls, but at HEO distances (such as those for TacSat-4) the pattern overlap represents a region where communications may realistically be unavailable. This region will obviously depend on the type of link being attempted (i.e. - carrier only, commanding, telemetry), shape of the antenna radiation patterns, slant range, transmit power, and data rate. The nominal planned TT&C telemetry rate for TacSat-4 is 32 kbps but may be varied operationally according to the link margin available at a given angle to the spacecraft. Although TacSat-4 does not implement it, the option exists for HEO missions to add a higher power transmit amplifier as one approach to increasing angular coverage.

Placement of One LGA on Payload

Due to the large deployed size of the COMM-X payload, it would be very difficult to obtain near omni-directional coverage with antennas mounted strictly to the spacecraft bus, especially using two hemispherical pattern antennas. Deployment mechanisms and multiple additional antennas were considered but to keep within the scope of the program, the standards option was exercised to carry one of the LGAs on the payload structure itself.

The RF signal from the payload-side antenna will be routed through the bus-payload-interface panel to the Phase III bus Telecommunications Subsystem. This approach provides a clear hemisphere of coverage on the payload-side of the space vehicle with the added benefit of having a direct SGLS line-of-sight to the ground during payload operations. During these operations the payload team will periodically be commanding and receiving telemetry from the payload via the TT&C link. The opposite hemisphere of coverage is obtained by placing the bus-side antenna on the spacecraft deck containing the launch vehicle interface ring. Careful attention is paid to the obstruction due to the interface ring and to the keep-out areas required by the launch vehicle. The solar arrays introduce additional minor gaps in coverage, which depends on the roll angle of the arrays relative to the bus-side antenna deck.

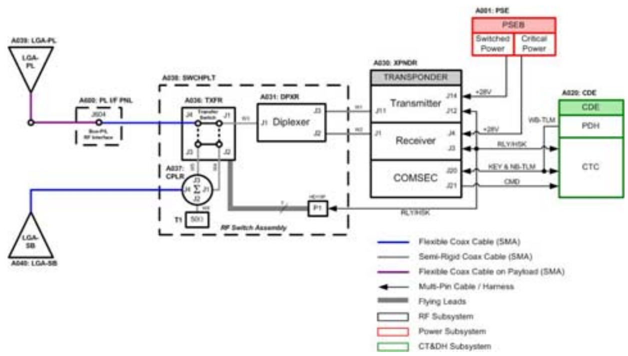

Figure 8: RF System Block Diagram

High Telemetry Rate Accommodation: RF Switch & Higher Gain LGA

In order to maximize the amount of time that the payload could operate and therefore, for power balance reasons, minimize the amount of downlink time, the COMM-X team desired to take advantage of the wideband telemetry capability of the TT&C subsystem while nadir pointing the payload. However, given the constraints of the transmit power at HEO link distances and the passive losses inherent to the subsystem design, a hemispherical pattern antenna on the payload would not have sufficient gain to maintain the 1 Mbps link. Two design modifications were therefore introduced:

1) AN RF switch to select the single payload-side antenna as opposed to the combined pattern of both antennas (providing a 3dB boost in signal strength), and

2) A slightly higher gain design for the payload-side antenna (monofilar vs. quadrifilar helix).

Figure 9 and Figure 10 show the payload and bus antennas respectively.

Without a strict coverage requirement for the wideband link, a goal was adopted to maintain the 1

Mbps link over the full subtense of the Earth at maximum orbit altitude (~±25˚ at 12,050 km). This goal is complicated by the fact that the LGA to be used for the wideband link would be located very close to the focus of the large COMM-X reflector. The peak gain required to maintain the wideband link had to be balanced with the competing requirement to provide near omni-directional coverage when combined with the opposite antenna, while minimizing the pattern interference introduced by the COMM-X environment. Furthermore, the payload required the LGA weigh less than 0.4 lbs (181 g), be resistant to the effects and creation of passive inter-modulation, and mount to an interface bracket agreed upon by both the bus and payload teams. Both antennas are required to operate over a temperature range of -150C to +100C and be wrapped with Germanium-coated Kapton due to the high charging environment of the mission orbit.

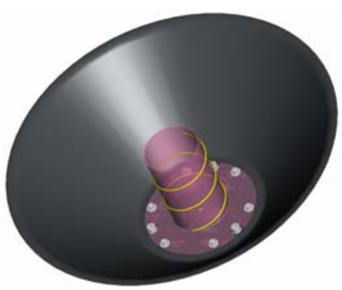

Figure 9: Payload-side TT&C antenna (monofilar helix with conical shield; Ge-Kapton cover not shown).

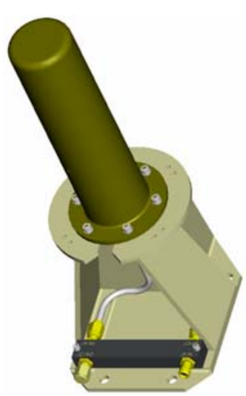

Figure 10: Bus-side antenna (Quadrifilar helix w/ radome)

The RF subsystem design evolution resulted in a simple yet flexible architecture, which meets both the philosophy of the bus standards and the desired capabilities of the HEO TacSat-4 mission. However, for future ORS builds, some procedural hurdles will need to be overcome to enable quick bus-payload integration at a joint program office.

Frequency allocation in its present form does not fit with the ORS philosophy. Frequencies will need to be pre-allocated to an ORS program office, or radios will require the capability to tune across the full range of SGLS/USB frequencies upon a quick turn-around frequency allocation process.

COMSEC key material and equipment approval/dissemination is also disjoint from envisioned ORS needs. Keys may similarly need to be pre-assigned to an ORS program office for installation at bus-payload integration.

User tasking of a space vehicle through the TT&C system requires each user to have the correct set of keys. An ORS method for disseminating this information to the users operationally, while still meeting the safeguarding requirements of each, needs to be addressed.

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 is 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 pointed to the closely aligned processes allowing 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 is involved in requirements review and development to verify compliance to program requirements and application of those requirements to procurements. Parts procurement, testing and screening is based on INST-002 requirements and issues are handled through 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 are 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.

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 will undergo an end-item review or buy-off to ensure compliance to applicable configuration management (CM) mission assurance requirements as well as performance specifications.

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, and solicit a broad range of industry ideas on policy, incentives, markets, etc. for potential avocation or action at the OSD level. The business team's charter also includes maturing the standards as needed for business/cost factors.

The ISET companies were asked to provide cost estimates based on the Conceptual Design Review level bus standards. The goal is to evaluate these estimates and use them to modify and refine the standards to reduce bus cost in an effort to effectively balance cost and utility. All inputs have been received and are now under review.

FUTURE WORK

Subsequent revisions of the standards will focus on defining the software and data protocols, and incorporating cost inputs provide explicit insight into cost/utility breakpoints. All the departures taken form the ISET bus standards for the Phase III prototype are being reviewed by the ISET to further improve the standards.

The prototype build of the ORS Phase III spacecraft bus to support the TacSat-4 mission is scheduled for completion in April 2008 for a launch on a Minotaur IV vehicle. 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 is proceeding through the development of the prototype bus in an open manner that allows 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.

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 (formerly of AeroAstro, Inc.) and Mr. Bob Summers from Aero Astro Inc; 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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