TACSAT-4 EARLY FLIGHT OPERATIONS INCLUDING LESSONS FROM INTEGRATION, TEST, AND LAUNCH PROCESSING

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ABSTRACT

TacSat-4 is an experimental Ultra High Frequency (UHF) communications satellite that launched on a Minotaur IV+ from Kodiak, Alaska on September 27, 2011. The spacecraft and ground capabilities are briefly described for context. The integration, testing, launch processing, early flight operations, and initial end user results are then discussed. Unique approaches and lessons learned are highlighted. For example, the "launch powered off" approach used to test new Operationally Responsive Space (ORS) bus standards worked particularly well, and had several benefits during launch processing. The ORS Office is leading the Joint Military Utility Assessment of the TacSat-4 mission.

1 BACKGROUND

Tactical Satellite 4 (TacSat-4) is a United States (US) Navy led joint mission to augment Ultra High Frequency (UHF) satellite communication (SATCOM) capabilities and to advance Operationally Responsive Space (ORS) systems. The user mission, selected jointly at the Flag and General Officer level, is UHF SATCOM for underserved users and regions of the world. This includes users on the move as well as users in challenged environments, such as mountainous or high-rise urban areas. The science and technology mission objectives are to advance spacecraft bus standards, achieve a long dwell low earth orbit for a relatively low-cost mission, demonstrate effective command and control automation, increase mission planning automation and user access, and mature multiple spacecraft technologies.

The TacSat-4 space vehicle (SV) is comprised of the ORS Phase III Standardized Bus (Phase 3 Bus) and the "COMMx" payload. The Phase 3 Bus was jointly designed and built by the Naval Research Laboratory (NRL) and the Johns Hopkins University (JHU) Applied Physics Laboratory (APL). The NRL designed and built the COMMx payload. A separate group, the Integrated System Engineering Team (ISET), consisting of representatives from industry, academia, and government organizations, produced a set of standards for an ORS spacecraft system. The standards produced include "Mission Requirements and Concept of Operations (CONOPS) for the ORS Missions," "General Bus Standards," "Payload Developers Guide," and "ORS Standard Data Interfaces: Bus to Payload, Bus to Ground." The Phase 3 Bus was designed and built to these standards. TacSat-4 used this prototype standardized bus so the SATCOM "COMMx" payload was designed and built to a preliminary version of the Payload Developers Guide.

The Phase 3 Bus, Figure 1, and COMMx payload, Figure 2, were developed largely independently from one another in order to evaluate and validate the ORS concept, and more specifically to pathfind and mature the ORS developed "General Bus Standards" and "Payload Developers Guide." Included in this demonstration are the validation of select bus standards and payload interfaces, feedback for updating the standards based on lessons learned, and the retirement of non-recurring engineering costs for future systems.

Figure 1. Phase 3 Bus with Payload Mass Simulator for Environmental Testing

Figure 2. COMMx Payload with its Reflector Deployed

2 TACSAT-4 MISSION CONTEXT

The TacSat-4 SV is a small class (468 kg, 1000W) spacecraft flying in a low, highly elliptical orbit (HEO) with a four hour period. The payload provides ten channels of UHF capability for communications-on-the-move (COTM), friendly (blue) force tracking (BFT), and data exfiltration (Data-X). The 12 foot diameter, high gain antenna enables COTM for legacy radios and low power Data-X sensors. The payload is tunable enabling flexible up and down channel assignments to improve the ability to operate in busy and interfered (but not jammed) environments. The 24 hour tasking cycle allows for dynamic reallocation to different theaters worldwide if necessary. The HEO provides a long dwell capability (2+ hours per pass) and betters supports mountainous and urban areas as the satellite is "higher in the sky", from the horizon, than geostationary satellites in many cases. TacSat-4's orbit provides near global, but not continuous, coverage and is especially good in the northern latitudes which compliments the geosynchronous SATCOM. Continuous coverage over multiple theaters of interest can be accomplished with a HEO constellation of three or four spacecraft. Optional in-theater ground terminals also allows for experimentation with advanced networked communications including voice and data over SIPRNET, bridging multiple communication channels, and flexible channel selection for theater's in which one is deployed.

Command and control of the spacecraft is performed by NRL's Blossom Point (BP) Tracking Facility, and mission planning is handled via the Virtual Mission Operations Center (VMOC™). Once the initial spacecraft checkout phase was completed, BP transitioned to an automated process for daily TacSat-4 command and control functions. VMOC™ mission planning and scheduling tool, handles all of the task requests and scheduling for the TacSat-4 mission. The VMOC™ is on the Secret Internet Protocol Router Network (SIPRNet) with Authority To Operate (ATO) certification.

The first year of operations is for experimentation, user training, and the ORS Office led Joint Military Utility Assessment (JMUA). Experimentation is well underway. Users include the US Army Space & Missile Defense Command Battle Laboratory (SMDBL), the US Navy's Trident Warrior 2012 experiment, Space and Naval Warfare Systems Command (SPAWAR), US Coast Guard, and US Marine Corps. International partners are also involved. International participants include the United Kingdom and Canada through the Tri-Lateral Technology R&D Project (TTRDP). They are using TacSat-4, along with the Australians, during the Navy's Trident Warrior as well as for their own in-country experiments.

Transition to operations is being worked with STRATCOM, ARSTART, NORTHCOM and interested users others during the first year of flight operations. Using TacSat-4 to augment coverage in the high northern latitudes is of particular interest.

3 SPACECRAFT and SYSTEM DESIGN HIGHLIGHTS

Several advanced elements of the space system are worth highlighting. Most visibly, the payload antenna is a 3.66 m (12 ft) diameter, high gain antenna that was designed and qualified for $2M US, about 1/5 the cost of most similar sized antennas that tend to have much tighter surface requirements than needed for UHF frequencies. The payload thermal system is one of the most advanced space systems flown, and uses a central thermal bus design with multiple heat pipes. In general, communications payloads require high power, most of which is dissipated as heat, so the advanced thermal system was necessary. The spacecraft bus was built to standards as mention earlier. The battery was designed for rapid field replacement without spacecraft disassembly. The flight of the TacSat-4 battery also qualified a new lithium ion cell design for the space community. Finally, the high level of automation in both the VMOC™ mission planning system and the BP Space Operations Center (SOC) required substantial upfront mission operations work and associated software coding; this affected spacecraft integration and testing to some extent as well.

4 INTEGRATION and TESTING

Structure and Harness: The Phase 3 Bus structure, designed and built by APL, was delivered to NRL for system integration. The basic bus structure is an octagon with the propulsion system integrated to the aft deck, and the payload interface ring and an equipment panel integrated to the forward deck. Once at NRL, three parallel integration paths were used. The eight side panels and the top panel were removed from the structure for flight component installation. The aft deck was removed from the structure for propulsion subsystem integration. Finally, a mock-up of the structure was used to assemble the flight harness. These three integration flows came together just prior to the start of system testing. Early in the flight component integration, simulators were used to support functional and interface tests, and flight software development, until the flight units became available.

This approach worked well, but issues did develop during the integration process. The panels were designed with hinges to facilitate component installation and troubleshooting. However, some harness lengths were insufficient to allow the panels to be opened far enough to allow component installation and removal. As a result, any subsequent work on flight components was difficult. Access to the spacecraft was limited once encapsulated in the launch vehicle (LV) fairing. This access issue made it necessary to install a new harness to allow arming of the SV through a fairing access door shortly before launch. The difficult panel access impeded this harness effort and the replacement effort for an electronics box. Finally, due to several issues, the flight battery was

integrated late in the flow, after environmental testing was nearly complete. Battery electrical and mass simulators were used during this time, but the late integration of the battery complicated environmental testing in some cases.

Thermal: One consequence of TacSat-4 being in a HEO is that the COMMx payload is used primarily over one theater at a time while at apogee. This CONOPS results in high payload heat dissipation (600 W) for a portion of the orbit and low heat dissipation (30 W) for the remainder of the orbit. In order to meet this requirement, the COMMx payload has an active thermal control system that is integral to the mechanical design. A loop heat pipe is integrated onto a central honeycomb deck with the critical electronics attached to both sides of this deck. The loop heat pipe interfaces with two radiator systems that surround the outside of the payload structure. Because the loop heat pipe radiators cover the outside of the payload, and are mechanically attached to the loop heat pipe in the central deck, any time the electronics needed to be accessed, the thermal system had to be partially de-integrated. Although it did not affect the end performance of the system, it did lead to an increase in the time required for troubleshooting when issues were found during system level testing. Additionally, the thermal design of the COMMx payload affected some testing that was done at the payload system level. Although sufficient for on-orbit operations, the system was not capable of maintaining electronic component temperature limits under full load in air at room temperature. This was due to the radiator panels viewing a room at 20C instead of deep space at -270C (3K). To resolve this problem, cold plates were thermally attached to the payload radiators, and attached to a chiller system running at ~10C. Fans were used to provide forced convection for removing heat from the payload during functional testing. Although it was not possible to run the payload at full power for a full two hours of operation, the mechanical aerospace ground equipment (MAGE) allowed the payload team to successfully validate all necessary operations of the payload.

UHF Antenna: The COMMx payload has a 3.66 m (12 ft) deployable UHF reflector antenna. This antenna was built using an umbrella-like deployable rib structure with Kapton-copper flex circuit material for the radio frequency (RF) reflecting surface. The key aspect for making this deployable antenna low cost was using the loose surface requirement at the frequencies of the payload. By building the reflector to ~6.4 mm (0.25 in.) RMS tolerance, much of the complicated and expensive surface verifications required on a typical reflector antenna became much more economical. The UHF antenna was completely qualified at the subsystem level. The antenna underwent in-air deployment testing, vibration testing, and thermal vacuum testing, including multiple deployments. The surface of the antenna reflector was checked between tests, and RF validation of antenna performance was done before and after all functional and environmental testing. The antenna reflector was deployed using a gravity offloading mechanism. By completing the antenna mechanisms qualification at the subsystem level, the gravity offloader design became much simpler, saving time and cost for the program. Once the antenna was integrated to the rest of the payload for system level testing, no full deployments were conducted. The antenna deployment circuit was tested via a “pop and catch” test at both the payload and spacecraft level. For other system and spacecraft level tests, the antenna reflector was “soft stowed” and deployed with specially designed MAGE that used a drive motor attached to each of the spring-loaded ribs.

Because the COMMx payload is capable of uplinks and downlinks over a wide range of frequencies in the UHF spectrum, it was important to conduct thorough integrated testing to ensure that all of the many electronics boxes in the payload would function together properly. The most important of these tests was the Electro-Magnetic Interference/Electro-Magnetic Compatibility (EMI/EMC) test performed in an anechoic chamber at NRL. During EMI/EMC self-compatibility testing it was discovered that one of the power amplifiers, which amplifies the output signal before being radiated by the antenna, generated more interference than expected. Even though this interference was small in power, it was within the nominal uplink frequency range of a highly sensitive receiver. This self-

interference issue had the potential to limit the effectiveness of some of the operational modes of the payload by, for example, adding more noise to UHF voice communications through the payload. The mitigation strategy for this issue was two-fold. First, four filters were engineered and added to various locations in the uplink and downlink signal chain to further attenuate undesirable out-of-band interference. Second, careful frequency selection is necessary for a small set of uplink/downlink frequency combinations that are not affected by the filters. This is not a significant impact on the usability of the payload. Overall, these approaches have proven effective at making the TacSat-4 payload a highly flexible UHF communication payload.

5 SV INTEGRATION and TESTING

In keeping with the ORS concept, the TacSat-4 payload was not integrated either electrically or physically with the Phase 3 Bus until both items were essentially complete. Both the Phase 3 Bus and COMMx payload independently went through a typical system level test sequence, including functional and performance testing, vibration and acoustic testing, thermal vacuum testing, and EMI/EMC testing. Only "pop and catch" deployment tests were performed on the Phase 3 Bus solar arrays.

Once system level testing began, the Phase 3 Bus and payload were tested electrically using an umbilical. Mating procedures were developed and dry run at NRL prior to shipment to the launch complex. The success of this approach required well-defined interfaces that were clear, unambiguous, and properly implemented by both the bus and payload.

One of the challenges of the ORS concept is the need to verify the interfaces between standard buses and multiple compatible payloads that may not be electrically or physically mated until just prior to launch. To meet this need, it is important to have interface simulators for all bus electrical functions. The TacSat-4 payload has multiple serial communication and power interfaces to the Phase 3 Bus. To fully verify these interfaces during payload standalone testing, NRL developed simulators of the bus interfaces. These simulators were high fidelity, and as flight-like as possible, following the mantra "test like you fly." This flight-like testing allowed for seamless integration with the Phase 3 Bus at the launch complex with minimal risk.

6 LAUNCH PROCESSING and LAUNCH VEHICLE

To advance the ORS rapid launch concept, the TacSat-4 spacecraft was the first demonstration of the launch depot storage followed by launch facility integration of a standardized bus and payload. The "storage" was a by-product of launch delays due to launch vehicle development and national priorities, but it served as a better example of a launch call-up for a pre-built bus and payload system. Ultimately the ability to call-up multiple types payloads and standardized buses for integration and launch would enable in rapid response to urgent national needs.

The Phase 3 Bus and TacSat-4 payload, which were stored separately, were given one month to be removed from storage, functionally verified, readied for shipment, packed along with all test equipment and MAGE, and shipped to the Kodiak Launch Complex (KLC) in Kodiak, Alaska for launch. To keep with the ORS concept-of-operations, the bus and payload were checkout and shipped without being electrically or mechanically mated. Upon arrival at KLC (the launch depot), the standardized bus and payload were again tested independently (in parallel) to verify functionality following the cross-country transport. Only after independent functional testing were the bus and payload integrated into the full TacSat-4 SV, Figure 3.

To support the rapid launch processing, the interface between the SV and LV was simple. The mechanical separation system, a 38.8-in. motorized light band with six separation switches, was the only interface between the SV and LV, Figure 4. The separation switches, four on the SV side of the interface and two on the LV side, were used to indicate when the SV had physically separated from the LV, and to initiate the power on sequence on the SV. This is not how most DoD and National spacecraft are launched. Most spacecraft launches included a LV umbilical for power and data that provided the capability to remotely charge the battery and to monitor spacecraft telemetry until launch. The Phase 3 Bus power system was designed such that the only way to power on the vehicle was by using the separation switches, so the turn-on process was thoroughly ground tested. The battery was charged via external connectors at the checkout facility and connected electrically into the spacecraft, but was isolated from the spacecraft loads until just prior to launch.

Figure 3. Tacsat-4 Ready for Fairing Encapsulation

Figure 4. TacSat-4 During Fairing Encapsulation

Because the SV was powered off at launch, an umbilical between the LV and the SV was not required. However, this meant that the battery could not be charged remotely, nor was any telemetry available once the SV was encapsulated. This made the interface with the LV clean and simple, but it also meant that once the SV was encapsulated, there was very little for the SV team to do until launch. To maintain the battery as long as possible, the final arm plug was not installed until just prior to launch (~T-20 hours). The countdown procedure for the SV team was also simple since the SV was powered off at launch. With no SV battery charging to perform and no telemetry to monitor, the critical SV launch constraints were ground communication between KLC and the BP SOC, and between the BP SOC and the Air Force Space Control Network (AFSCN) Operational Control Node (OCN) and the primary Remote Tracking Station (RTS) at Diego Garcia.

The TacSat-4 team arrived at the KLC in the beginning of March 2011 to begin launch site processing for an early May 2011 launch. In late April, after the failure of a similar Taurus LV and subsequent changing launch priorities, the TacSat-4 launch was delayed until Fall. However, by this time the COMMx payload had been mated to the Phase 3 Bus, and the team was preparing for TacSat-4 SV fueling operations. The decision was made to store the TacSat-4 SV in the mated configuration in the Payload Processing Facility (PPF) at the KLC. This presented another opportunity to evaluate aspects of the ORS depot concept, which were captured in a launch site contingency storage plan. The TacSat-4 team returned to the KLC in mid-August 2011 after the LV had been cleared for launch, and the launch priority issue had been resolved. TacSat-4 was successfully launched 27 September 2011 from the Alaska Aerospace Corporation (AAC)-managed KLC, Figure 5. TacSat-4 is NRL's 100th satellite launched into orbit.

Figure 5. TacSat-4 Launch from Kodiak Launch Complex

The Minotaur IV+ LV configuration used for this launch is an upgrade to the standard Minotaur IV. This upgrade is accomplished by replacing the Orion 38 fourth stage motor with a thrust vector controlled Star 48 motor. This new configuration significantly increases the payload mass to orbit and/or orbit altitude. The Minotaur IV+ performed well within its specifications for its first flight. The Star 48 with thrust vector control and the overall Minotaur IV+ vehicle are now proven capabilities for future use by the space community. The Space Development and Test Wing and Orbital Science Corporation performed this launch with a small and efficient launch team. The TacSat-4 Minotaur IV+ launch was their 6th Minotaur launch in less than one year at three different launch sites. All were successful.

7 EARLY FLIGHT OPERATIONS

Preparations for launch and initial flight operations included Mission Dress Rehearsals (MDRs), flight operations testing, and MOC testing with the AFSCN. The nominal LV insertion orbit for TacSat-4 was 185 km by 12,050 km. The low initial perigee required the implementation of a perigee raising burn at apogee on the first orbit. In fact, most of the critical events occurred during the first half of the first orbit, including spacecraft power up and activation, checkout burn, first apogee burn, and solar array deployment and checkout. A pictorial summary of the first orbit events is shown in Figure 6. Significant development and testing focused on these events during the MDRs. Multiple contingency operations for communications outages, component failures, subsystem constraint exceedances, failures to deploy, etc. were also formulated and rehearsed during the MDRs.

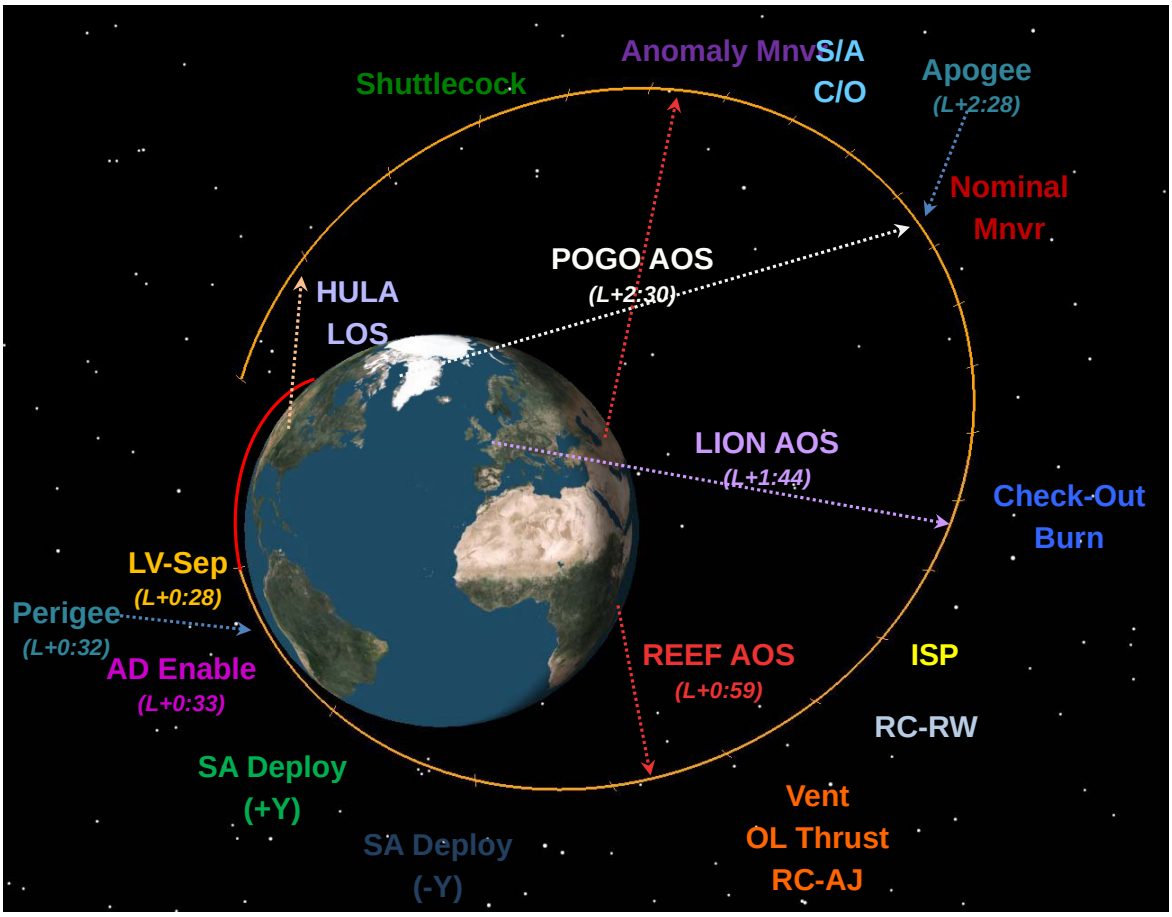

Figure 6. TacSat-4 First Orbit Overview

By the end of the first week of flight operations the spacecraft command and control automated operations mode was being phased into use. The basic pass plans, done in view of a ground station antenna, were being performed using the monitor mode where the system automatically plans the pass with an operator watching and approving each step. The fully automated mode was being used by week two for known operation. The automation continues to be refined and made more by regular updates of actual, versus predicted, subsystem operations.

8 GROUND SYSTEMS

NRL's Blossom Point Tracking Facility (BPTF) provides the command and control functions for the TacSat-4 mission. BPTF is the oldest US ground station with its startup in 1956. See Figure 7. Since NRL designs and prototypes many kinds of new missions, it has been a requirement on BPTF to be able to accommodate multiple types of space missions without changing the ground station's core hardware and software baseline. Additionally, minimizing operations manning and costs has been a ground station design driver placed on BPTF by many programs. As a result, BPTF has evolved its Common Ground Architecture (CGA) into a highly automated and robust system proven over several decades of operations. This system is also called "Neptune", clearly showing a Navy influence. Once the initial spacecraft checkout phase was completed, BP transitioned to an automated process for TacSat-4 command and control. The BPTF is also certified SOC on the AFSCN; TacSat-4 regularly uses this the AFSCN antennas to take passes outside of BPTF's field-of-view. Baseline operations only require the 3 (out of 6) TacSat-4 passes that BPTF can take directly. However AFSCN was critical for the initial post-launch orbits and regularly improves daily operations by allowing BPTF additional contact opportunities. In preparation for launch, BPTF participated in approximately 30 MDRs; these MDRs also served as a way to keep the crews trained during the two launch delay.

Figure 7: NRL's Blossom Point Tracking Facility

The VMOC™ mission planning and scheduling tool, handles all of the task requests and scheduling for the TacSat-4 mission. The VMOC™ is on the Secret Internet Protocol Router Network (SIPRNet) with Authority To Operate (ATO) certification. The VMOC™ fundamentally supports three different users. First the VMOC™ enables authorized organizations (i.e. STRATCOM's Operational SATCOM Manager, SATCOM Support Centers, and/or COCOM J6) to set and adjust User and mission priorities. Second, the VMOC™ increases user access to space capabilities by allowing authorized users, both expert and non-expert, to submit tasking requests and received "FEDEX" style tracking of the status of their request – pending, scheduled, uploaded, etc. Third, the VMOC™ supports the spacecraft operator by automatically producing spacecraft schedules based on user requests, assigned priorities, and engineering constraints such as ground contacts and thermal limits. For TacSat-4 a multi-day schedule, called the mission plan, is sent to the BPTF ground station daily for processing and tasking upload.

Figure 8: VMOC Mission Planning Tool

Additionally, SATCOM networking capabilities can be achieved by including a network ground terminal in a theater. These ground terminals are not needed for regular SATCOM. Rather they can enable users with only handheld radios to connect to the SIPRNET and talk, or exchange data, with other users including those out of theater. TacSat-4 will work with any Joint Base Station capability. TacSat-4 has also developed one, full capability In-Theater-Ground-Terminal (ITGT) which provides networked SATCOM, Friendly Force Tracking, and ODTML payload data exfiltration for much of the NORTHCOM area. The TacSat-4 Program also provided several

smaller, Portable Ground Terminal (PGT) systems hardware to select users. Both the ITGT and PGTs are based on the JBS design and key components.

9 END USERS RESULTS

To date, multiple organizations have been experimenting with and performing utility assessments of the TacSat-4 mission. The US Army SMDBL has been leading the Joint Military Utility Assessment, particularly in the areas of COTM and VMOC™, on behalf of the ORS Office. They have conducted evaluations using multiple legacy radios (PRC-117F/G, PRC-148, PRC-152, PSC-5D, PDA-185) and a variety of antenna configurations (eggbeater, spitfire, x-wing, baton, whip, etc.) that have allowed them to identify the best combinations of equipment. They have performed evaluations in mountainous and urban terrains, on foot, and in moving vehicles, with good results. SMDBL has also demonstrated the ability to send large data files, exercised a "time sensitive" task, i.e., a request submitted less than 24 hours before execution, and proved that TacSat-4 can be used to uplink data collected by Unattended Ground Sensors (UGS). The suitability of non-SATCOM "whip" antennas was also investigated and evaluated by the SMDBL. The results for these non-SATCOM antennas have been only 25% successful when unturned (not tunedfor SATCOM frequency range) and 75% when tuned for the SATCOM frequencies. While it is impressive to talk via SATCOM to these radios with non-SATCOM whip antennas, the reliability is not high enough for operational use.

SPAWAR has performed TacSat-4 testing, and verified that the system works in accordance with the Joint Interoperability Testing Command (JITC) standards that apply for legacy SATCOM with certified radios. Fundamentally, SPAWAR verified that TacSat-4 can augment UHF SATCOM for mobile users using standard SATCOM equipment including SATCOM omni-directional antennas.

The formal Navy utility assessment occurs in Trident Warrior 2012. In this experiment TacSat-4 will be used to provide SATCOM between many platforms: Navy ship-to-shore Marines, a US Navy ship to Allied ship, sub-to-shore, sub-to-Marine, and Marine-to-SIPRNET via the TacSat-4 Portable Ground Terminal. This testing will exercise much of the US Navy's UHF SATCOM equipment to verify that TacSat-4 works with this equipment and normal CONOPS as expected.

The US Coast Guard has been the most active user to leverage TacSat-4 for operations. The Coast Guard Cutter Healy used TacSat-4 as it returned from the Bering Sea from its ice breaking mission with the Russian tanker Renda to deliver emergency fuel supplies to Nome, Alaska. The Coast Guard has put SATCOM antennas on several of their ships and has tested TacSat-4 with their helicopters which already have eggbeater (omni-directional) SATCOM antennas installed.

The US Air Force (USAF) provided the Compact Environmental Anomaly Sensor (CEASE) payload to Tacsat-4. CEASE is a radiation experiment which is especially valuable in TacSat-4's relatively unusual orbit. The CEASE instrument is showing that proton radiation levels in TacSat-4's orbit are higher than previously known and higher than the models had predicted. It is conversely showing lower than predicted levels of electrons. The USAF's Air Force Research Lab (AFRL) is working to update the current radiation models with this new data. This data is a near term benefit to TacSat-4 and will be a long term benefit to the space community.

10 LESSONS LEARNED

There are many lessons learned to date from the TacSat-4 mission. Some are specific to how the program was structured, managed, and funded; others are configuration specific and/or deal with details of particular subsystem or components. Those most relevant to the small spacecraft community are summarized below by functional area.

Mission Capability:

- UHF SATCOM has been realized in this small satellite size and class of mission. The SATCOM capability works well with strong signal strength and low bit-error-rate results.
- The four hour HEO orbit has proven valuable by providing "long dwell" capability for a small satellite class of mission. The primary user limit with a single satellite is the lack of continuous (24-7) service; however, this orbit scales well as only three or four satellites can provide 24-7 coverage for many selected areas. One negative still being characterized is that this orbit is seeing higher proton radiation levels than the models predicted; although the lower than predicted electron radiation positive. Work is being done to update the radiation models, and the TacSat-4 mission operations will track the affect(s) on the spacecraft.
- The VMOC™ has shown itself to be a solid tool for increasing mission planning flexibility via automation and for increasing user insight into payload tasking.
- The BPTF SOC automation has again shown reliable, advanced, and cost effective command and control for spacecraft.
- A new Minotaur IV+ capability has been developed and successfully validated. It is now a vehicle configuration available to the community with increased payload mass and/or orbit altitude.

Bus Standardization:

- Developing useful standards and interface documentation for standardized buses and payloads requires significant up front systems engineering effort including design, analysis, and validation.
- Standardized designs are not optimized designs. For example, the standardized bus prototype used for TacSat-4 was not optimized for SATCOM. As such, its design included many requirements that the TacSat-4 mission did not need for its SATCOM mission.
- The "launch powered off" standard required extra design and verification work for the electrical power system, but it provided real benefits at the launch range. Specifically, it eliminated procedures, such as maintaining spacecraft battery charge on the LV, and simplified the launch countdown. The cost was increased design complexity and risk especially in the spacecraft and early orbit operations.
- The primary penalties TacSat-4 faced from standardization had to do with being a prototype to mature standards, which required working to standards that were still in development. As a result, the spacecraft structure mass was high and payload thermal support was low.
- An adiabatic thermal interface between the spacecraft bus and a primary payload places excessive burden on the payload and underutilizes straight-forward spacecraft thermal capabilities. On TacSat-4, this led to an advanced thermal design with several heat pipes. Also the mission operations impact of the on-orbit failure of one of the heat pipes is exacerbated by the adiabatic interface. Note: The matured bus standards do NOT specify an adiabatic interface.

Mission and Ground Operations:

- Mission operations are complicated and require significant advanced planning and coordination. The use of mission dress rehearsals with both hardware and process simulators was essential.
- Mission simulators can be expensive to develop and implement, but typically pay for themselves in the long run.
- Automated ground station operations are essential for cost effective mission operations. They reduce operator errors by doing the proven procedures automatically, and letting the operators

focus on the actives people are better at, such as trending, preventing, and resolving operational problems.

- As the mission and ground operations team encounter and resolve on-orbit problems, the resolutions are added to the automated operations in the form of new procedures or constraints. The result is increasingly robust automated operations as time goes by and flight operations experience increases.
- The VMOC™ has shown itself to be a solid tool for increasing mission planning automation and for increasing user insight into payload tasking. Like the command and control automations, the mission planning automation and user interface improve as user experience and mission operations experience build up.
- The UHF spectrum has proven to be a busy environment. RF surveys of the frequencies of interest in the area(s) of use are a good way to help make sure interference is not, and will not be, a factor in user operations. Automation of some of this interference testing using TacSat-4 ground terminals and spectrum analyzers has been helpful.

Launch Processing and Launch Vehicle:

- The Orbital Sciences team, under contract to and working with the Space and Missile System Center (SMC) Space Development and Test Directorate (SDTD), provided six Minotaur launches within 12 months. The SDTD and Orbital Sciences field operations were highly efficient and appropriate for small satellite launches.
- The AAC-managed KLC was a highly efficient place to prepare for launch and to launch from. The facilities and personnel were excellent.
- One key tenet of ORS is responsive launch. To shorten processing time at the launch site, the LV must be stacked and either ready for launch or require minimal processing. Any remaining tasks can require a few hours to a day or two at most. The spacecraft buses and payloads must be checked out when they first arrive at the launch depot, and the mission team must trust that the bus and payload are still good when call up occurs, or rely on a quick test to verify bus and payload functionality. A pathfinder approach was successfully applied to the TacSat-4 bus and payload.
- The launch mission assurance approach was not tailored for the TacSat-4 mission, and decisions were made independent of cost and schedule impacts that are not paid for by the launch decision makers. As launch approached there was less willingness to accept the level of risk originally envisioned. The only way to launch quickly is to avoid the cycle of "one more review," "one more analysis," or "one more test" to address all possible concerns prior to launch. The program that funds the launch and who is affected by the schedule, should have more authority on decisions.
- The TacSat-4 launch site processing schedule did not attempt to minimize the time required from call-up to launch. The original schedule from arrival at the launch site to launch was nine weeks. This schedule was based on a six day work week, working eight hours per day. Included in this schedule were six days of management reserve and 17 days for post-mate LV activities. This schedule could have been reduced to as little as five weeks without significantly increasing risk by eliminating off days, schedule reserve, and working additional tasks in parallel. Additional schedule reductions would have required significant effort by both the SV and LV organizations.

Programmatic:

- High risk programs are easy to explain at a top level, but difficult to explain at the implementation level, e.g., what is or is not analyzed, documented, controlled, or verified.
- Higher risk missions (Class C/D) must guard against requirements creep as they approach launch and flight operations.
- Consistent high-level advocacy for a program is required to maintain funding and launch priorities. The TacSat-4 launch was slipped multiple times due to changing DoD launch community priorities.

11 CONCLUSION

The TacSat-4 mission successfully delivered flight hardware for on-orbit test, evaluation, and military utility assessment. The program also matured the ORS bus standards, and demonstrated many elements of the ORS concept. The experimentation and utility assessment are being performed during the first year of operations to verify the utility of the TacSat-4 mission and further refine several of the ORS concepts of operation. Although at five (versus 10) channel capacity, the SATCOM performance is as-good or better than current capabilities and the TacSat-4 coverage compliments the existing geosynchronous satellites well. The decision to transition TacSat-4 into full operations will be made once the utility assessment is complete. This information will also be used to inform future spacecraft acquisition decisions.