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Different Approaches to Developing Small Satellite Missions

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ABSTRACT

While lower cost and increased launch opportunities provide easier access to space, there are different approaches to developing solutions for a small U-class satellite to support scientific research and government missions. JHU/APL has successfully led and flown two 3U CubeSat missions and is currently working on a third mission. The first mission, ORS TECH, was a two spacecraft mission for the United States (US) Department of Defense (DoD). The second mission, RAVAN, was a single spacecraft mission for the NASA Earth Science Technology Office (ESTO). JHU/APL is leading a third 3U CubeSat mission, CAT, scheduled for launch in 2018 for the United States (US) Department of Defense (DoD). For each of these missions, JHU/APL took a different approach in the development of the 3U small satellite. This paper will review the three different methods used at JHU/APL for the development of 3U CubeSats and will provide insights and lessons learned for developing future small U-class satellites for educational, commercial, and government missions.

INTRODUCTION

With the launch of Flock 3d, a constellation of 88 3U CubeSats, by Planet on February 14, 2017[1], small ride-along satellites are no longer 'Cute-Sats' and these 3U class satellites are able to support scientific research, government, and commercial space missions. Companies are not only providing components and subsystems with space flight heritage for small spacecraft, but are now delivering spacecraft to support different payload missions. Companies providing services for space missions are also performing the integration and verification testing of the spacecraft, securing the frequency allocation, demonstrating compliance with the launch vehicle requirements, and the daily operation of the spacecraft. While most 3U CubeSats are LEO missions making observations of the earth, small spacecraft are being considered for missions to the moon and the outer planets.[2] As we begin to consider all the possible missions that these small spacecraft can accomplish, this paper looks at the different approaches to small satellite missions that were used by the Johns Hopkins University Applied Physics Laboratory.

The most utilized CubeSat standards are a 1U and a 3U; a 10 cm cube shaped satellite weighing up to 1 kg and a 34 x 10 x 10 cm rectangular shaped satellite weighing up to 5 kg respectively.[3] A CubeSat chassis can be fabricated from the ground up or simply purchased off the shelf from a vendor. All the critical subsystems driving large mission satellites have been scaled to fit within a 3U CubeSat form factor with analogous capability and can also be purchased off the shelf from a vendor. With the standardization of the CubeSat Deployer and the increasing number of CubeSat launch opportunities, the different approaches to developing the ORS TECH and RAVAN missions will be applied to future small 3U satellite mission.

The Space Exploration Sector of the Johns Hopkins University Applied Physics Laboratory has launched and operated 69 satellites and over 150 instruments, including three 3U satellites (ORS TECH 1, ORS TECH 2, and RAVAN). Based on the mission requirements, available technology, and funding, the Space Exploration Sector of the Johns Hopkins Applied Physics Laboratory has used different approaches to develop the bus and payload, integrate and test the spacecraft, perform mission operations, and deliver payload telemetry. Table 1 provides and overview of the approach used on each mission.

Table 1: Overview of Missions

Mission	Bus	Payload	SC Integration	SC Test	LV Integration	Mission Operations System
ORS TECH	3U: First JHU/APL	1U: JHU/APL	JHU/APL	JHU/APL	JHU/APL	JHU/APL: InControl™
RAVAN	XB3: First BCT	1U: L-1 Standards	BCT	BCT	BCT	BCT: COSMOS
CAT	XB3: BCT	1U: Third Party	JHU/APL	JHU/APL	JHU/APL	JHU/APL: InControl™

THE FIRST MISSION: ORS TECH

The first mission, ORS TECH, was a two spacecraft mission for the United States (US) Department of Defense (DoD). This 3U spacecraft mission demonstrated the operational military utility of a small satellite. Leveraging past spaceflight missions, JHU/APL developed the spacecraft bus and payload. JHU/APL was the spacecraft integrator, spacecraft environmental tester, launch vehicle integrator, and operator of the spacecraft. Both 3U spacecraft, ORS TECH 1 and ORS TECH 2, were launched and deployed on November 19, 2013 and were able to successfully provide payload telemetry before de-orbiting in April 2015. Figure 1 is an artist's conception of the ORS TECH 1 spacecraft in flight.

Figure 1: An artist conception of the ORS TECH 1 spacecraft in flight

ORS TECH Spacecraft Bus

At the time of ORS Tech 1 and 2 flight system design and development in 2010, there were very few companies providing CubeSat components or spacecraft buses with space flight heritage. After careful review, the ORS TECH design team was left without applicable commercial off the shelf (COTS) components or flight heritage hardware to meet payload mission requirements without modification. Nearly every facet of the ORS TECH space vehicles is deliberately designed to maintain optimum payload mission performance at any altitude and orbit. Figure 2 shows a transparency view of the spacecraft bus hardware arrangement, the stowed solar array configuration, and the deployed solar array configuration. Key details of the JHU/APL space vehicle designs are:

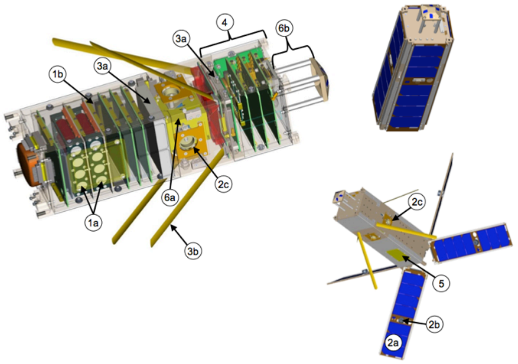

Figure 2: A transparency view of the ORS TECH spacecraft hardware arrangement (left), stowed solar array configuration (top right), and deployed solar array configuration (bottom right).

1. An electrical power subsystem (EPS) is used to provide multiple voltages for diverse hardware requirements. Four strings of two series hard carbon lithium ion battery cells, commonly used for space application, were chosen to accommodate high peak loads and the needed capacity (Figure 2, 1a). The EPS adapts to a wide range of sun exposure with a peak power-tracking regulator, which optimizes energy collected by the solar arrays (Figure 2, 1b). Power management was able to produce 40-Watts peak power tracking during a period of 10 minutes per orbit.
2. Each of the four double-sided solar arrays (Figure 2, 2a) has 14 triple junction solar cells producing an average power of 7.4 Watts when fully illuminated. The solar arrays are uniquely deployed with innovative release hinge and actuator designs. Spring loaded hinges deploy and twist each solar array to 45 degrees angle in order to maximize power collection at any altitude. In 2013, the CubeSat Design Specification (CDS), revision 12, prohibited the use of any pyro-actuated release mechanisms, which inspired a novel design utilizing thermal expansion properties of two different metals. The outer diameter of the plug is slightly larger than the inner diameter of the cup. This interference holds the plug inside the cup with enough force to survive vibrations experienced during launch. When

the mechanism is activated to deploy, the cup is rapidly heated causing it to expand enough for the plug to pop out and safely deploy the solar array. The reusable nature of the solar array deployment mechanism is favorable for multiple deployment tests.

3. A half-duplex spacecraft transceiver (Figure 2, 3a) operating in the Ultra High Frequency (UHF) band received uplinked commands from the ground station and downlinked telemetry at 1,200 bps to the ground with a 5-Watt transmitter. The antenna (Figure 2, 3b) and the antenna-phasing network (Figure 2, 3c) created crossed dipoles that operate with the ground plane within the solar arrays to provide antenna gain in the spacecraft nadir direction.

4. A highly modular satellite structure was designed to allow ease of access and flexibility while maximizing capacity for subsystems. The packaging serves to mitigate electromagnetic interference (EMI). Bus (Figure 2) and payload (Figure 2) electronics are partitioned into complete insulated enclosures protecting each from any undesirable interference. Additionally, the enclosures are separable which enables bus and payload to be developed and tested at independent locations. Both cavities have removable faceplates providing entry for all board electronics to slide into backplane connectors. The structure secures all contents with a design that endured the launch vibrations of the launch vehicle.

5. Thermal management is implemented to meet the temperature requirements of the bus and payload hardware. Thermocouple measurements will control heaters to actively keep the batteries and payload above minimum temperature specifications during eclipsed orbit. The batteries are thermally isolated from bus electronics with the help of a conductive plate (Figure 2, 5) radiating unwanted heat. Varying optical coatings of silver Teflon and vapor deposited aluminum on Kapton create an effective emissivity that can be adjusted to fit the dynamic environment.

6. Guidance, Navigation, and Control (GNC) components are strategically positioned throughout the spacecraft for accurate measurements and optimum attitude control. A single pitch momentum-bias wheel (Figure 2, 6a) is centered within a cavity in the bus. Solar array embedded magnetic torque coils are positioned passed the lengthwise midpoint of each solar array. This creates a greater moment force due to the distance between the satellites central axis and torque coils when the solar arrays are deployed. The coupled momentum wheel and torque coil systems give the satellite 3-axis nadir-pointing control. Attitude of the satellite is measured by a magnetometer and four coarse sun sensors arranged on a mechanical extension (Figure 2, 6b) located at the nadir end of the satellite which utilizes the spring area of the CubeSat deployer. The mechanical extension maximizes distance between onboard electronics and the magnetometer to prevent erroneous measurements from unwanted EMI. Additionally, two coarse sun sensors are fixed on top and bottom surfaces of each solar array to further determine the difference between direct sun exposure and light reflecting from earth.

7. Satellite position, velocity, and time are provided with precision by a Global Positioning System (GPS) antenna (Figure 2, 7) and receiver daughter board. The GPS antenna with an internal low-noise amplifier collects GPS signals and sends it to the receiver daughter board. The receiver daughter board processes the GPS information.

8. The scalable radiation-hard 32-bit LEON3FT processor[4] was chosen as the main processor for the spacecraft. Two single event latch-up (SEL) immune interface boards, which also provide protection for latch-up susceptible electronics in other subsystems. This processor has been space qualified and was used on the NASA Van Allen Belt Probes (formerly known as the Radiation Belt Storm Probe) mission launched in 2012.

9. Free open-source Real-Time Executive for Multiprocessor Systems (RTEMS)[5] was selected for the real-time operating system (RTOS) which was compatible with the LEON3FT processor. An Operating System Abstraction Layer (OSAL) was able to facilitate the development process through compatibility with existing tools, as well as leverage some heritage code previously developed at JHU/APL for the NASA Solar TErestrial RElations Observatory (STEREO) mission.

ORS TECH Payload

The ORS TECH payload sensor was designed and built by JHU/APL, leveraging existing airborne-based radio technology. Thermal and EMI/EMC mitigations used on the spacecraft bus were also implemented in the payload for the system to work in the rigors of the space environment. The payload was tested in equivalent thermal-vacuum and radiation environment of low earth orbit before integration with the spacecraft bus. Processing of the sensor telemetry was done on the ground, re-using the processing system as the airborne system with some minor modifications for telemetry from low-earth orbit (LEO).

ORS TECH Integration and Test Verification

JHU/APL in Laurel, Maryland performed the spacecraft bus and the payload integration and spacecraft test verification. The ORS TECH spacecraft have passed electromagnetic interference and electromagnetic compatibility tests, mechanical vibration tests, thermal balance tests, and thermal cycle tests. The testing was performed at the Environmental Test Facility (ETF) at JHU/APL[6], which tests spacecraft under conditions as close to the flight environment as possible. The ETF has vibration, EMI/EMC, and thermal vacuum test equipment capable of simulating spacecraft environments from launch to orbital flight. MIL-STD-461 was used for guidance for electromagnetic compatibility and NASA GSFC-STD-7000 (GEVS) was used for guidance for environmental verification. Without knowledge of the actual launch time, the ETF was used to simulate spacecraft deployment in sunlight and eclipse. Figure 3 shows the spacecraft test facilities at JHU/APL.

Additional verification testing of the ORS TECH spacecraft was performed with the ground station, also located on the JHU/APL campus. Mission Operations performed over-the-air day-in-the-life testing with the actual ground station radio and antenna system. The operations team was able to practice spacecraft deployment from the launch vehicle, on-orbit spacecraft checkout and daily payload operations. JHU/APL delivered the ORS TECH 1 and ORS TECH 2 spacecraft for integration with the Nanosatellite Launch Adapter System (NLAS), a 3U CubeSat deployer developed by NASA[7], in August of 2013.

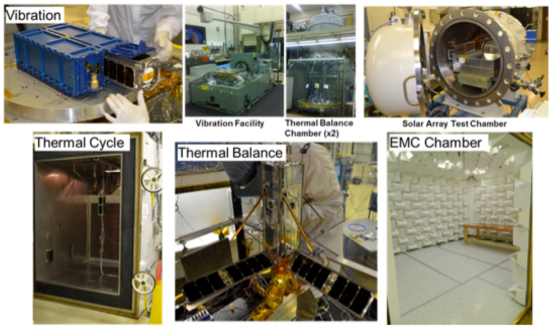

Figure 3 The spacecraft test facility at JHU/APL that was used for verification testing of the ORS TECH spacecraft

ORS TECH Mission Operations

The ORS TECH spacecraft were launched and deployed in November 19, 2013. Spacecraft mission operations were conducted by JHU/APL in Laurel, Maryland. The L3 Technologies InControl^{TM} Satellite Command and Control Software[8] was use for the ORS TECH mission control. The software was used on the Van Allen Probes (VAP) for ground testing and space operations where lessons learned were applied to the ORS TECH mission. The software system organizes commands and records when commands are uplinked to the spacecraft and archives telemetry downlinked from the spacecraft. The operations were scaled down from VAP to ORS TECH.

The ORS TECH ground station was the same system JHU/APL used to study and communicate with the Transit Satellite system[9] (also know as NAVSAT or NNSS – Navy Navigation Satellite System) in the late 2000s. The antenna tracking hardware and software used to track and receive telemetry from the Transit spacecraft was reused for the ORS TECH mission. The ORS TECH ground station consisted of a Yagi antenna, antenna controller, ground transceiver that was almost identical to the spacecraft transceiver, and a computer to plan and execute the mission. Payload sensor telemetry was processed on a second computer. ORS TECH mission operations also leveraged SciBox[10], an end-to-end automated spacecraft planning and commanding system, which was used on the NASA Messenger mission. This planning and commanding system allowed JHU/APL to deliver a ground station to the end-user to 'fly' their spacecraft and plan their own missions. ORS TECH 1 and ORS TECH 2 had a 30-day orbital check out and then moved to a Technology Demonstration phase.

LESSONS LEARNED from the ORS TECH Mission

The ORS TECH spacecraft performed at a high level of capability; the end-user has evidence of the operational military utility of this small satellite. It is important to define the ORS TECH mission as a complete system, i.e., the system includes both the actual spacecraft and the ground operations control center to generate usable data for the end-user. The importance of seeing the spacecraft as part of the whole systems from ground operations through mission execution cannot be over-estimated. ORS Tech 1 and 2 were developed with the complete end-to-end system in mind. The key items learned from the ORS TECH mission that should be applied to future mission:

For JHU/APL, whose experience is with much larger spacecraft, working with the size, weight and power constraints of a 3U CubeSat did not allow for any redundant spacecraft sub-systems. This is a risk that must be accepted when using U-class spacecraft. The size constraints make the thermal design, isolation of electromagnetic interference, and mechanical design critical for the success of the space mission.

At the time of the ORS TECH development, there were little or no CubeSat components with flight heritage that could be used to support the ORS TECH mission. Finding third party vendors with previous space flight experience that were willing to modify their components was also difficult. Development time and cost at JHU/APL and component vendors increased due to the modifications and customizations needed to meet mission requirements. Use existing technology with space flight heritage meeting mission requirements with little or no modification.

A test bed or flat sat or engineering model that functions like the flight system is need to provide early hardware for test and operations to use before launch. After launch the test bed can also be used to debug anomalies and optimize the spacecraft system. Due to cost and schedule constraints, the development of the ORS TECH spacecraft did not use an engineering model (or flat sat). Hardware was not available for testing till late in the development cycle, leaving little time and challenging mission operations to efficiently test and verify the complete system. The lack of an engineering model, or flat sat, drove the use of the ORS TECH 1 spacecraft to function in three capacities: as test bed, engineering model and then flight spacecraft. ORS TECH 1 was also used for the entire in-laboratory developmental testing of the components and all engineering changes were first performed and verified on this spacecraft.

THE SECOND MISSION: RAVAN

The second mission, RAVAN, is funded by the NASA Earth Science Technology Office's In-Space Validation of Earth Science Technologies (InVEST) program. This 3U spacecraft mission is a single satellite demonstration for a possible future Earth radiation budget constellation mission. RAVAN has demonstrated two key technologies that enable accurate, absolute Earth radiation: radiometers with vertically aligned carbon nanotube (VACNT) absorbers and gallium black body phase-transition calibration sources.[11] Although JHU/APL had successfully flown CubeSats with the ORS TECH mission[12], JHU/APL contracted the development of the spacecraft bus and payload, spacecraft integration, environmental testing, launch vehicle integration, and operations to third party vendors. The RAVAN spacecraft was launched on November 11, 2016 and continues to deliver measurements of the Earth's outgoing radiation.

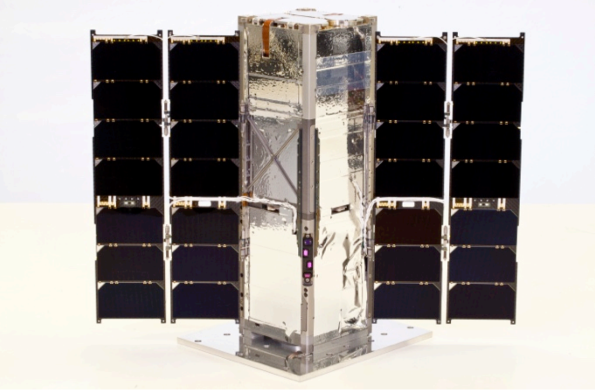

Figure 4 Photograph of the RAVAN 3U CubeSat before launch

RAVAN Spacecraft Bus

The RAVAN 3U CubeSat bus, the XB3[13], was designed and built by Blue Canyon Technologies (BCT), which is based on their XB1 design. The XB3 has 3-axis attitude control with three reaction wheels, three magnetic torque rods, and two star trackers, with a GPS receiver for position and time. For on-orbit nadir-pointing and calibration maneuvers the attitude control requirements are: 0.5° pointing control and 0.1° pointing knowledge. Power is provided by four deployable solar arrays. The battery has more than enough capacity to accommodate eclipse and maintain RAVAN's various attitude orientations and mission modes (see Table 2). Communications use a UHF radio.

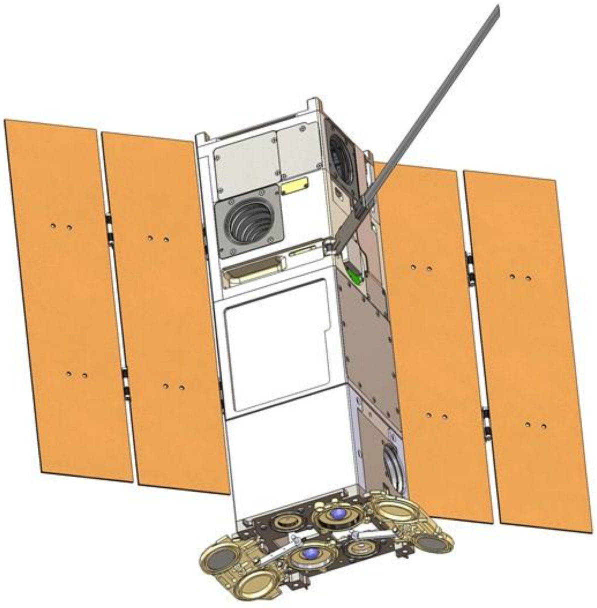

Figure 5: RAVAN 3U CubeSat. The RAVAN payload is the 1U section at the bottom of the figure, shown with doors open. Two star trackers are visible in the upper 1U section, and the UHF antenna extends from the edge of the bus.

RAVAN Payload

The RAVAN payload, developed with L-1 Standards and Technology, comprises four independent radiometers in two pairs, as shown in Figure 6. The primary radiometer pair use Vertically Aligned Carbon Nanotube (VACNT) absorbers; the secondary radiometer pair use a traditional, conical cavity design, for comparison, redundancy, and mission life degradation monitoring. Each pair has a Total channel, measuring all radiation from 200 nm to 200 µm, and a shortwave (SW) channel, which is limited to wavelengths less than about 5.5 µm. The radiometers have a wide field of view (FOV), 130°, to view the entire Earth disk from low Earth orbit. There are no optics between the light source and the radiometer absorbers, apart from sapphire domes over the shortwave radiometers.

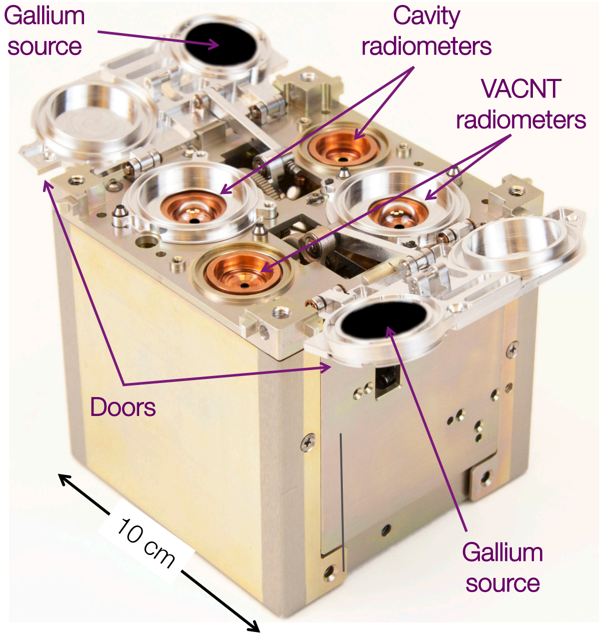

Figure 6: RAVAN flight payload; primary radiometer pair (VACNT absorbers; total and shortwave channels) and secondary radiometer pair (cavity absorbers; total and shortwave channels).

The RAVAN payload has two doors covering the primary and secondary radiometer pairs. The doors protect the radiometers before launch and during commissioning. After commissioning, the doors have been opened and closed as needed. In each radiometer, thermistors monitor the temperatures of the absorber and heat sink. A bridge circuit senses temperature changes due to light absorption. The gallium black bodies lie directly over the Total channels when the doors are closed for calibration. The payload mass is less than 1 kg, draws 1.9 W of power (orbit average), and fits within a 1U volume (<10x10x10 cm^3). The RAVAN payload produces approximately 2.5 MB of science and housekeeping data per day.

RAVAN Integration and Test Verification

Blue Canyon Technologies in Boulder, Colorado performed the XB3 bus and the RAVAN payload integration and RAVAN spacecraft test verification. Tests on the complete RAVAN spacecraft include vibration, thermal vacuum, and launch acceptance testing, and day-in-the-life testing. To meet the delivery to the spacecraft, BCT was unable to test with the full ground station. RAVAN was delivered to Cal Poly for integration with the NLAS 3U CubeSat deployer in July 2016.

RAVAN Mission Operations

The RAVAN spacecraft was launched and deployed on November 11, 2016 into an orbit that is nearly circular, sun-synchronous, and roughly 600 km. RAVAN Spacecraft operations are being conducted by Blue Canyon Technologies in Boulder, Colorado. The first month on orbit was used for commissioning and checking-out the RAVAN spacecraft, during which time the radiometers were protected from spacecraft outgassing. During the first month, the thermal environment of the payload was characterized and the gallium black bodies were tested, exercising them through multiple freeze–melt cycles.

Following the checkout phase, RAVAN began and continues operations comprising continuous nadir Earth observations with interspersed calibration maneuvers, as summarized in Table 2. The CubeSat slews for the solar and deep space views, using the Sun to provide absolute calibration of the radiometers and on-orbit characterization of the radiometer performance. During the operations phase, the RAVAN spacecraft has demonstrated using VACNTs for Earth radiometry.

Table 2: RAVAN Modes of operation

Mode	Configuration	Purpose
Normal	Nadir, VACNT radiometer doors open	Normal Earth data collection
Solar	Point at Sun, doors open	Absolute calibration
Deep Space	Point at deep space, doors open	Offset calibration
Black body Cal	Doors closed	Calibration with gallium black bodies
Comparison	Both doors open	Compare VACNT and cavity radiometers

LESSONS LEARNED from the RAVAN Mission

While the RAVAN CubeSat mission demonstrates an affordable, accurate radiometer that continues to deliver measurements of the Earth's outgoing radiation, there are lessons learned than can be applied to future missions.

With limited launch opportunities, frequency license applications should be submitted as early as possible. The license to transmit from the spacecraft was not granted by the FCC until the last possible day before the RAVAN spacecraft would have been removed from the launch deployer. While the application was submitted over a year before the launch, the FCC provided little or no feedback until the very last day. The FCC and other government regulator agencies need to provide feedback on a predictable timetable, so CubeSat developers can focus on their payload and spacecraft mission.

The ground station and mission operations center at Blue Canyon Technologies were created for the RAVAN mission. As stated above, due to the strict schedule to deliver the spacecraft to CubeSat deployer integration, the full RAVAN ground station was not ready to test with the spacecraft. BCT implemented the Ball Aerospace COSMOS[14], which is an open source satellite command and control system for operations and test. While waiting for RAVAN to launch, over-the-air communications with the ground station were verified using the engineering unit. For further verification, BCT was able to track and receive other CubeSats. With time and resources permitting, use an established ground station and mission operations center and test the complete system: spacecraft with the ground station and mission operations center as much as possible.

The RAVAN spacecraft did not utilize an RF beacon after deployment from the launch vehicle. As BCT worked to establish the complete uplink and downlink between the spacecraft and the grounds station, an RF beacon could have provided short spacecraft status to the ground. While the RF communications with RAVAN is half-duplex in the UHF frequency band, the communications system is able to downlink adequate amounts of radiometer telemetry but more spacecraft telemetry would provide a better picture of the spacecraft performance.

PARTS AND MATERIALS USED ON THE 3U MISSIONS

The traditional approach to parts and materials control on large satellite missions is to employ designated parts and materials engineers that have the prime responsibility for the selection and approval for flight and critical GSE hardware. This is typically done by use of a Parts, Material and Processes Control Board (PMPCB) that develops screening & qualification requirements that cull out infant mortality part failure and identify lot-processing defects. These requirements usually include preparing source control and specification control documentation as well as performing pre-encapsulation inspection and post-procurement destructive physical analysis. For many CubeSat missions, it is atypical for parts and materials engineers to be employed to perform these control functions. For these missions, virtually all parts and materials are treated as "buy and fly", meaning that they are procured from the original equipment manufacturer (OEM) and installed into the next-higher-assembly (NHA) level without any interim or post-procurement processing being performed.

Parts

Typically on large spacecraft (LargeSat), Electrical, Electronic and Electromechanical (EEE) parts are selected for use in the following order of precedence: 1) military-type specification (Mil Spec) level, 2) manufacturer (MFR) high reliability (HiRel) / automotive flow level and 3) industrial/commercial-off-the-shelf (COTS) level.

For the ORS TECH and RAVAN CubeSat missions, the EEE parts selection varied widely, subject to availability and cost constraints. As shown in Table 3, the selection criteria became defined as best-available EEE components given cost and schedule constraints. All part levels ended up being permissible, especially when the part did not fail the project radiation requirements.

Table 3: EEE Parts Counts & Selection Criteria

Mission	Line Item Count	Military Spec Count	MFR HiRel/ Automotive Count	Industrial /COTS Count
ORSTECH	114	66	14	34
RAVAN	178	1	58	119
CAT	394	28	130	236
STEREO (LargeSat)	887	534	118	235
Van Allen Probes (LargeSat)	1460	1050	235	175
MESSENGER (LargeSat)	1757	1069	238	450

Large spacecraft have high part-line-item counts; in comparison, the parts-line-item counts for small U-class satellites are significantly lower as shown in Table 3. This lower part-line-item count dramatically reduces the overall parts cost and reduces the labor associated with delivering a full parts kit to the assembly floor. It also increases the overall system reliability from the perspective of hardware workmanship, as there are fewer potential failure points in the physical hardware.

Derating is the practice of reducing the applied stress levels of EEE part parameters with respect to the maximum stress level ratings of the part. The derated stress levels are established as the maximum levels within the circuit application[15]. Derating lowers the probability of degradation or catastrophic failure occurring during assembly, test and flight by decreasing mechanical, thermal and electrical stresses. The ORS TECH and RAVAN CubeSat missions all used EEE-INST-002[16] as the guideline for performing EEE part derating; this document is the typical industry standard for derating both large satellites and small satellites.

All EEE parts planned for use in flight hardware were reviewed for Government Industry Data Exchange Program (GIDEP) and Alerts and Advisories during all phases of the project. The GIDEP database is a repository for notification of known reliability issues on EEE parts and materials. The ORS TECH and RAVAN CubeSat missions all used the GIDEP database throughout their project lifecycles to stay informed of these issues and how they may affect their own hardware builds. Large satellite missions have employed this same practice.

Materials

Selection of materials consisted of those that were proven to be compatible for use in a conventional low earth orbit (LEO) space environment. Low outgassing materials were selected consisting of those with total mass loss (TML) $\leq$ 1.0% and collected volatile condensable mass (CVCM) $\leq$ 0.1%. Materials typically prohibited from spaceflight use were avoided including cadmium, selenium, zinc, un-plated brass, mercury and its salts, one-part room temperature vulcanizing (RTV) silicone sealants/adhesives cured by reaction with atmospheric moisture, polyvinyl chloride (PVC) polymers (with the exception of Kynar), hookup wire with insulation made from polytetrafluoroethylene (PTFE), fluorinated ethylene propylene (FEP), and other cold flow susceptible fluorocarbons, beryllium oxide and radioactive materials. Pure tin (<3% Lead [Pb] content) was on the list of prohibited materials as well although it was hard to avoid when using COTS level parts. In cases where pure tin content was the only possible choice, the preferred mitigation plan consisted of robotic hot soldering dipping of terminal leads and conformal coating at the assembly level.

FUTURE 3U MISSION: CAT

JHU/APL is leading a third 3U CubeSat mission, CAT, scheduled for launch in 2018 for the United States (US) Department of Defense (DoD). JHU/APL has contracted the spacecraft bus and payload development to third party vendors, while retaining the spacecraft integration, environmental testing, launch vehicle integration, and operations to be done at JHU/APL. Key lessons learned from the ORS TECH and RAVAN missions are being applied to this 3U mission.

Similar to RAVAN, Blue Canyon Technologies (BCT) will provide the 3U spacecraft bus. The updated XB3 leverages the on-orbit flight telemetry and ground test data from the XB3 used on the RAVAN mission. BCT has made improvements to components and upgraded the parts selected. To ease the integration with the sensor, the mechanical, electrical, and software interface to the payload is identical to the RAVAN mission. Even though JHU/APL is not designing and manufacturing the spacecraft bus, lessons from past missions are being used to keep cost and schedule under control.

This future mission will use an engineering model of the complete spacecraft, the XB3 bus and payload, for early hardware test and verification. The integration of the flight spacecraft bus and payload sensor will be done at the Johns Hopkins University Applied Physics Laboratory in Laurel, Maryland. Similar to ORS TECH, this 3U mission will utilize the Environmental Test Facility on the JHU/APL campus for vibration, thermal vacuum, and EMI/EMC performance testing.

Mission operations will leverage the L3 InControl™ Spacecraft Command and Control software. The command and control system has been used on the ORS TECH mission and the Van Allen Probes mission. The Parker Solar Probe will also be using the same command and control system. Test scripts for ground tests will be executed with the L3 InControl™ Spacecraft Command and Control software. Testing in flight-like environments will optimize the command scripting and allow telemetry data to be efficiently processed.

This 3U mission will use the Satellite Communications Facility (SCF)[17] at the Johns Hopkins University Applied Physics Laboratory. The facility was established in 1961 to support the US Navy. The SCF has conducted of 75,000 satellite passes in the last 15 year alone and is capable of supporting L-band, S-band, and X-band communications. This mid-latitude station can support Lowe Earth Orbit (LEO) missions through Deep Space, with a variety of data formats, including TDM and CCSDS.

The mission will utilize a full duplex radio operating in the S-band for RF communications. Unlike the ORS TECH and RAVAN missions, which used a half duplex radio, this mission will be able to simultaneously uplink commands and downlink telemetry. With the limited pass times over the ground station, full duplex communications will utilize every contact with the spacecraft. The radio for this mission can downlink up to 2 Mbps from the spacecraft to the ground. The downlink data rate to be highest used on any JHU/APL small satellite mission.

The mission will re-use the FCC license originally used for an Internal Research and Development (IRAD) project that was not flown. The license is applicable to both the ground station and the spacecraft. Again, JHU/APL is leveraging past work to avoid any cost and schedule increase.

While no post-procurement part level environmental testing, burn-in or qualification testing was performed on parts utilized on the past JHU/APL CubeSat missions. Board level testing will be performed on this mission which included environmental stress screening (ESS) in an unpowered state prior to conformal coat, burn-in for a minimum of 168 hours at the predicted maximum operating temperature for the mission, and at least 500 hours of total powered test time with the last 100 hours to be failure-free.

LESSONS LEARNED APPLIED TO FUTURE U-CLASS MISSIONS

The Johns Hopkins University Applied Physics Laboratory (JHU/APL) continues to look forward and seek opportunities to validate the utility of U-Class Spacecraft Missions as well as point to future improvements that will increase the applicability of this platform towards additional missions in military, scientific, and commercial environments. The following are key lessons learned from the ORS TECH and RAVAN missions that can be applied to future missions.

1. Understand the performance limitations and risks associated with a 3U spacecraft. While launch opportunities are increasing and more resources become available to support these spacecraft, U-class satellites are not replacements for larger multi-sensor satellites.

2. Use existing technologies with space flight heritage and work with companies with space flight experience.

3. Use a 'Flat Sat' or engineering model during the development process to start testing as soon as possible. A test bed which functions like the final system is useful to find any issues early in the development process. The test bed can also be used for ground testing and problem solving while the flight system is in orbit.

4. Test the complete system; the spacecraft with ground station and mission control center. Use as much of the actual hardware and software as possible.

5. Use an established ground station that has previously tracked and communicated with similar or other spacecraft.

6. Use established mission operations command and control systems.

7. Since both spacecraft and payload/sensor telemetry is important, find hardware and processes to downlink as much telemetry as possible. Due to the nature of spacecraft in low earth orbit (LEO), there are few and truncated passes per day over the ground station.

8. Apply for the frequency to transmit at early as possible for mission success. The applicant will need to navigate through the different government organizations (FCC, NTIA, AIRU, and ITU) and the many rules and regulations associated with the frequency license application. Remember the analyses on orbital debris and end of mission disposal needs to be submitted with the application for frequency usage.

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