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SMALL SATELLITE INITIATIVES: BUILDING ON SUCCESS

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ABSTRACT

The successful flight demonstration of the ORS TECH 1 and ORS TECH 2 triple (3U) cubesats has further established the operational mission applications that small satellites can cost effectively execute for the Civil, National Security, and Intelligence communities. Determining the tradeoff between large, multi-instrument observatories, and smaller, inexpensive single or narrowly purposed systems, is a key to efficient future space utilization in a heavily cost constrained environment. The ORS TECH 1 & 2 nanosatellites were designed, built, and operated by The Johns Hopkins University Applied Physics Laboratory. These pathfinder systems represent prototypes of a broader Multi-Mission Nanosatellite (MMN) architecture that APL has developed, which is now being deployed across other 3U, 6U, and 50 kg “Express” class initiatives. Although successfully able to complete their operational mission requirements, these small satellites are not without their respective limitations. Understanding the optimal size, price point, and mission utility combination is discussed in this paper. Through the course of significant design and investigation, APL has identified mission sets where a spatially or temporally distributed system may provide disruptive value beyond the acknowledged reductions in development cost, schedule duration, and barriers for access to space. This paper will address the technical, performance, and programmatic elements of utilizing nano- and small microsatellites to serve in the emerging roles as replacement functionality or augmentation to larger traditional science and military space missions.

Keywords: Nanosatellites, ORS Tech, Operationally Responsive Space, Express, CubeSat

1. INTRODUCTION

1.1 More With Less

The path toward achieving economical, reliable high performance, and accelerated satellite development has been long and difficult. The idea of accessing space became a reality in the late 1950s causing an explosive growth of development in military and scientific capabilities. During this time, advancement in mission capacity was priority; not cost or schedule. While military space technology remained secret and mainly engaged with the Cold War, the National Aeronautics and Space Administration (NASA) successfully demonstrated increasingly complex scientific space missions. Space systems matured into large complex multi-mission satellites as launch vehicle technology increased carrying capacity. While the importance and challenge of maintaining a space presence was paramount, a shift in the focus of the space industry towards low cost, quick development spacecraft, spurred a revisit to smaller satellites and missions. Continuing the advancement of space technology with less funding led to a variety of economical launch vehicle developments and increased usage of commercially available components.[1]

With the end of the Cold War and growing public concern with expensive space missions, NASA introduced the Discovery Program in 1992 under the Faster, Better, Cheaper initiative to demonstrate low cost interplanetary exploration with small satellites. Even though Faster Better Cheaper was not always better, ten missions proved great success including the first mission, launched in 1996: Near Earth Asteroid Rendezvous (NEAR), developed by Johns Hopkins University Applied Physics Laboratory. While NASA abandoned Faster, Better, Cheaper after a couple of embarrassing failures, many priceless lessons were learned that have improved modern space program development for military and science. An imperative demand to deliver highly capable new military space assets to increase battlefield support comes in the form of small spacecraft using a flexible approach by program design and management.

1.2 Small Satellites

Many early space satellites are considered small satellites. Satellites were constrained to be small because launch vehicles at that time were modified sub-orbital rockets not specifically designed to enter space with large payloads. In 1958 the first successful United States space satellite, Explorer 1, was an 8.32 kg payload and launched to perigee 358 km by a Juno I rocket having a maximum payload capacity of 11 kg. Since then, many different launch vehicles have been developed to accommodate a variety of payload capacities ranging over 5 tons. Mass of a satellite is directly related to a large component of program cost, the launch vehicle. An estimated launch cost of $20,000 per kg drives many programs to design small satellites.[2]

Modern small satellite mission capabilities are far beyond their predecessors. Satellite subsystems adopt consumer electronic designs, much like the cell phone, to reduce size of components and deliver increased processing at low power. Availability of commercial off the shelf parts (COTS) plays a large role in making small satellites more appealing. COTS components for nanosatellites are emerging, but, are mostly of academic research quality.

1.3 Supporting Intelligence, Surveillance and Reconnaissance

As depicted in Figure 1.1, small satellites are capable of demonstrating new technology to support military missions. Intelligence, Surveillance, and Reconnaissance (ISR) is a critical key to nearly all United States military operations today. Recently, ISR technology gave the United States President, Barack Obama, the ability to observe the execution of Bin Laden in real time. ISRs challenge is the ability to gather and communicate information quickly in order to assist strategic or tactical decisions. A sophisticated network of remote sensors can be deployed in concert at sea, ground, air, and space. Space-based ISR sensors have the distinct advantage of accessing areas of interest without needing permission. Space systems have yet to compete with the quick-response deployability that sea, ground, and air based ISR sensors provide since satellite launches are notorious for requiring many weeks or months of preparation.

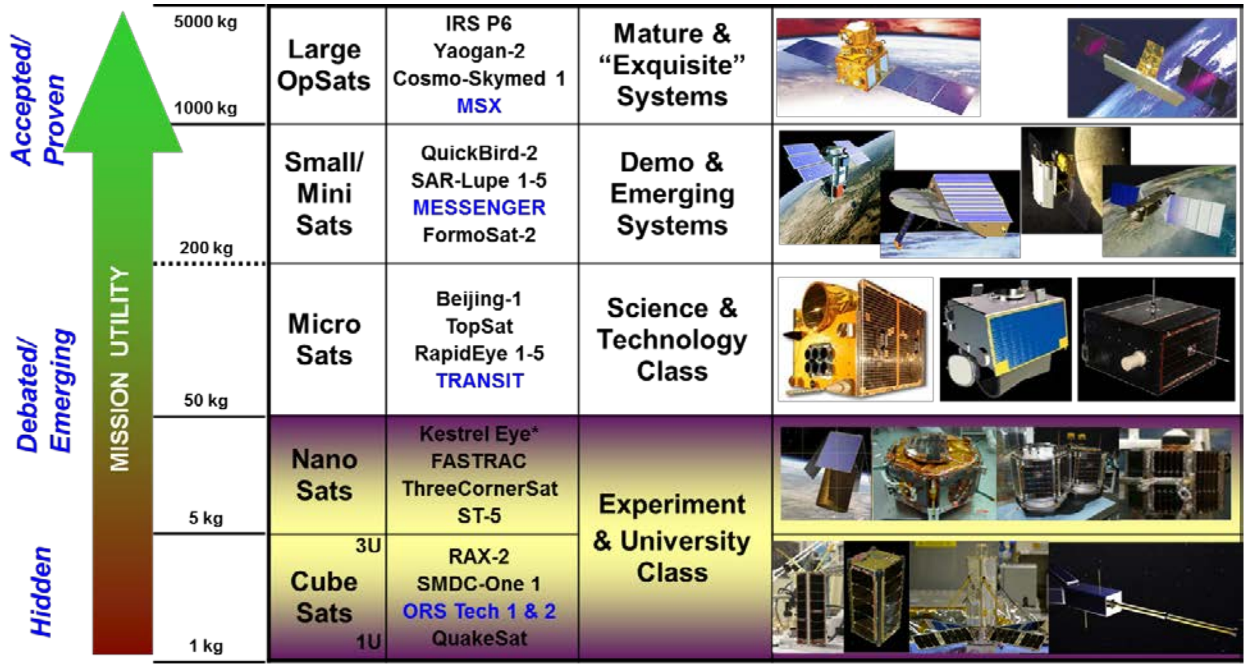

Figure 1.1: The mission utility of nano- and microsatellite class missions is now rapidly emerging as enabling technologies and successful flight demonstrations are performed (satellites built and operated by JHU/APL in blue).

2. SINGLE SENSOR SATELLITE

2.1 The SensorSat

Unlike large mission satellites that typically carry multiple instruments, any satellite carrying a single-instrument payload can be considered a SensorSat. Single-sensor satellites are more likely to develop within one to two years due to their simplicity.[4] SensorSats avoid the design complexity of interference between multiple instruments such as calibration, size, temperature, and power requirements. The reduction of interfaces enables a greater potential to be standardized and mass-producible. A SensorSat opens flexibility to program management and resources as well. Figure 2.1 compares size, complexity and schedule of a few satellites developed by the Johns Hopkins University Applied Physics Laboratory.

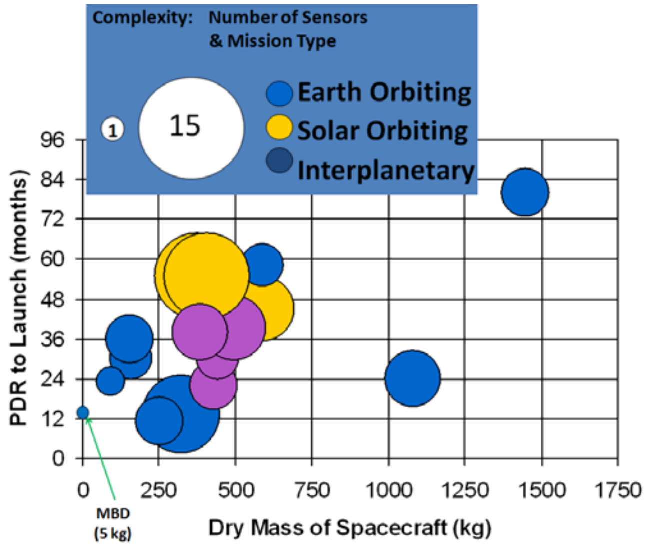

Figure 2.1 Comparison of a few satellites built by the Johns Hopkins University Applied Physics Laboratory contrasting size, complexity, and time to launch

2.2 SensorSat Mission Capability

Depending on mission requirements, there is a large variety of remote sensing instruments with wide ranges of capability available. A SensorSat can consist of a downsized payload taken from older technology to a payload with cutting edge technology. SensorSat mission capabilities are improving as a result of affordability to develop and demonstrate new technology within a shorter time scale. SensorSats can be developed with flexibility due to the simplicity of design and mission.[4] Because of this, a large constellation network of SensorSats is not only easily achievable but also feasible to cost and schedule. Many deployed SensorSats would have the ability to detect and produce multidimensional data in ways one large multi-instrument satellite cannot. A constellation would provide continuous or near-continuous access with the ground.

Some missions may require continuous or near continuous satellite coverage. Launching a constellation into orbit formations is not an easy task. Long formations of satellites orbiting along the same path like a ring circling earth called a train formation, may need multiple launches from different launch site locations in order to deploy correctly. Based on general physical and technological limitations, the number required to achieve continuous coverage approaches 80 satellites at an altitude of 500 km, which equates to an overwhelming cost and schedule. CubeSats have the advantage of attainable cost and schedule that may enable constellation missions previously deemed unfeasible. Continuous coverage coupled with assured access will be a revolutionary key to providing commanders on the battlefield instantaneous and persistent real time information. The results would greatly improve tactical and strategic decision making, as well as create new efficient protocols authorizing the decisions being made. Mission uniqueness and complexity limits the ability to utilize standardized designs. National security space organizations, such as the Operationally Responsive Space (ORS) Office, have set out to improve space to ground support. Implementing standardization is just one piece of the puzzle, where ORS is seeking to strike a pragmatic balance to mission assurance in order to permit "rapidly deploying capabilities that are 'good enough' to satisfy warfighter needs across the entire spectrum of operations, from peacetime through conflict."[5]

3. THE CUBESAT

A standardized miniature satellite specification called CubeSat, developed by California Polytechnic State University and Stanford University, was developed in 1999 to affordably gain access to space for scientific and educational research. Even though the CubeSat market has been dominated by academia, there are many demonstrated characteristics desired by commercial and military applications. CubeSat specifications standardize the size and mass of the spacecraft reducing overall project development and launch cost.[6] The most utilized CubeSat standards are a 1U and a 3U; 10 cm cube shaped picosatellite weighing up to 1 kg shown in Figure 3.1 and a 34 x 10 x 10 cm rectangular shaped nanosatellite weighing up to 5 kg shown in Figure 3.2. A CubeSat chassis can be fabricated from the ground up or simply purchased off the shelf from a vendor.

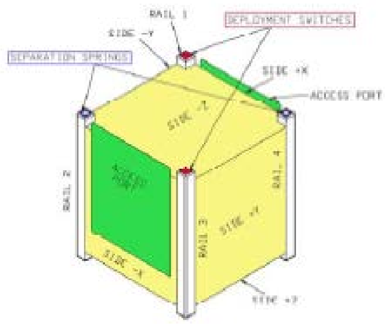

Figure 3.1 Isometric view of a 1U CubeSat

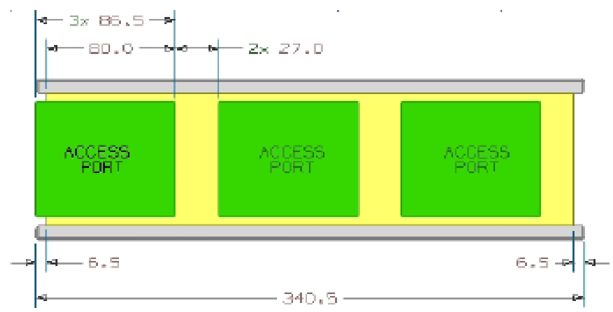

Figure 3.2 Side view of a 3U CubeSat

Similar to the cost benefits utilized in common consumer product designs, uniformity of space systems is highly sought to reduce cost and development time. The CubeSat Design Specification (CDS) has laid the groundwork for true standardization of satellite designs. Originally developed to bring satellite and mission design to the academic level, the CDS has opened the door to developing a satellite to CubeSat standards instead of requiring integrating with specific launch vehicle design constraints. The reduced overall end-to-end development and launch costs make CubeSat an excellent platform to demonstrate non-proven space flight technology designs in actual space environment. CDS coupled with the standardized plug-and-play-like CubeSat deployer increases opportunities to access space.

Figure 3.3 Poly-Pico Orbital Deployer (P-POD)

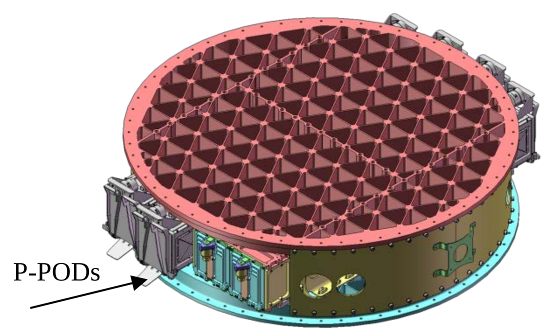

Figure 3.4 The Loadpath Engineering Cubestack Wafer can accommodate up to eight P-PODs or equivalent dispensers.

The CubeSat deployment mechanism is a standardized box that carries the satellite during launch and safely deploys it into orbit. Many CubeSats have been deployed by the Poly-Pico Orbital Deployer (P-POD) shown in Figure 3.3.[7] A single P-POD is able to accommodate three 1U space vehicles or a single 3U system. Multiple adaptations of CubeSat deployers have been developed to increase the number of satellites deployed per launch as well as integration with a variety of launch vehicles. CubeSat deployer specifications allow easy integration with launch vehicle designs. There are many variations of how the deployers integrate with the launch vehicle, as shown in Figure 3.4.[8] CubeSats are typically stowed on launch vehicles as secondary payloads.

The standardized CubeSat launcher has been integrated with different launch vehicles as rideshares.[7] A rideshare is a secondary payload that is a passenger on a primary payload launch. Rideshares benefit all parties involved. Due to a shared launch cost among all payloads rideshares are increasingly common. A launch cost of $20k per kilogram or more is currently estimated[2] and is a driving cost constraint for commercial, academic, and military access to space. With rideshares increasing[9], CubeSats can begin to take advantage of relatively low cost opportunistic launches.

The military has interests in utilizing all the CubeSat has to offer. True responsive space assets are highly desired by the military. Additionally, satellites that can be owned and operated by a single commander while on the battlefield. Instead of the need to reserve time or schedule a mediator to provide information gathered by a satellite, a commander will have private assured access to the satellites capabilities. Military missions in a 3U platform are emerging as their capabilities continue to expand. The standard 3U platform has become an accepted platform to build an operational satellite mission design relevant to ISR. Among the advantages CubeSat stands to provide for military applications, there are limitations that cannot be overlooked. Identifying appropriate and inappropriate missions for CubeSats is largely governed by the size constraints. Fitting all of the subsystems required for critical military mission operation into such a small platform requires compromise at the price of less power for avionics, thermal control, and radio communication and reduced accuracy of attitude control. The lower amount of power generation requires extreme micro management of subsystem operation and storage. With the expertise and skill to manage such a balancing act of a satellite design, 3U missions will someday bring the military store and forward communications, missile warning, weather prediction, ground imaging, tracking, jamming, and interception of intelligence at a reasonable price. Even though current COTS component companies continue improving their hardware designs, operational military CubeSats may require complete ground up development to support higher mission complexity.

4. ORS TECH / MULTI MISSION BUS DEMONSTRATION

Figure 4.1 The JHU/APL Multi Mission Bus Demonstration, also known as ORS Tech 1 and 2.

Responding to the needs of our US Government sponsors for smaller spacecraft to more effectively utilize access to space, JHU/APL has created a flexible and modular, Multi-Mission Nanosatellite (MMN) spacecraft architecture for low-cost execution of critical missions[11]. Under a pathfinder effort, two initial 3U prototype CubeSats were designed and built. To provide the desired combination of nanosatellite mission performance and reliability, JHU/APL developed an innovative system approach using a multi-department team that leveraged the technical insight and experience of the Laboratory's broad range of activities.

As described in Table 1.[10], all the critical subsystems driving large mission satellites have been scaled to fit within a 3U CubeSat form factor with analogous capability[9] enabling ORS Tech SensorSats to reliably support an operationally relevant DoD mission. The design implications of this approach limited the program's options of applicable COTS components or heritage hardware qualified for the task without modification. In response, an innovative approach to flexible development from the ground up was adopted yielding novel mechanisms and electronics and the confidence in a sound design. Nearly every facet of the ORS Tech SensorSats is deliberately designed to permit payload mission performance at any altitude and orbit.

Table 1. Comparison of ORS Tech to a Typical Satellite

Metric	ORS TECH	Example Satellite	Ratio
Mission (Two SVs)	$10M (ROM)	$400M	1:40
Number of Instruments	1	11	1:11
Volume	3,400 cc	71,000 cc	1:24
Mass Limit	5 kg	1,600 kg	1:320
Power (Orbit Average)	6 W	350 W	1:58
Attitude Control HW Elements	1 wheel (momentum) and 4 pairs of torque coils	4 reaction wheels and 8 thrusters	2:4
Number of Active Deployments	4	14	1:3.5
Telemetry Data Storage	2 MB	16 GB	1:8,000
Number of C&DH Systems	1	1	1
Number of Telecomm. radio	1	1	1
Project Duration	14 months	60 months	1:6

ORS Tech SensorSats have passed electromagnetic interference and electromagnetic compatibility tests, mechanical vibration tests, thermal balance tests, and thermal cycle tests assuring its robust design. The ORS Tech bus is an opportunistic design with a launch from anywhere capability and versatile subsystems to support third party built payloads with a wide range of mission requirements.

Details about the innovating design of the ORS Tech SensorSat are provided below:

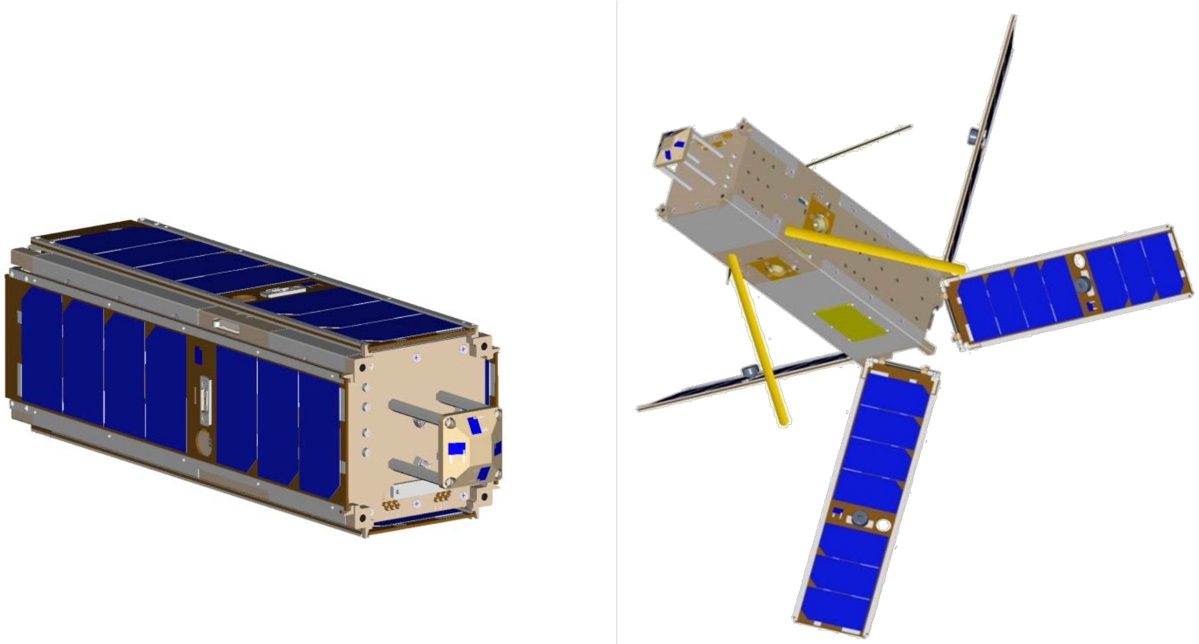

Figure 4.1 Stowed (left) and deployed (right) operational configurations of the ORS Tech space vehicle.

1. A versatile electrical power subsystem (EPS) is used to provide multiple voltages for diverse hardware requirements. Lithium ion battery cells, commonly used for space application, were chosen to accommodate high peak loads and the need for capacity. The EPS adapts to a wide case of sun exposure with a peak power-tracking regulator, which optimizes energy collected by the solar arrays.
2. Four double-sided 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. CDS prohibits the use of any pyro-actuated release mechanisms, which inspired a novel design utilizing thermal expansion properties of two different metals.
3. A half-duplex low-power transceiver spacecraft operates in government UHF band. Both the antenna and deployed solar arrays work together communicating telemetry and command with the ground.
4. Two highly modular satellite structures were developed to allow ease of access and design flexibility while maximizing capacity for subsystems. The packaging serves to mitigate electromagnetic interference (EMI) ensuring optimum electrical hardware performance. Bus and payload (Figure 4.1) 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 at independent locations. Both cavities have removable faceplates providing entry for all board electronics to slide into backplane connectors. The ORS Tech structure secures all its contents with a solid design that will endure several cases of launch vibrations based on varying deployer mounting locations in different launch vehicles.
5. A thermal management subsystem is implemented to meet the temperature requirements of the certain bus and payload hardware. Thermocouple measurements will control heaters to actively keep the batteries and payload above minimum temperature specifications during eclipsed orbit. Varying optical coatings 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 is centered within the bus. Solar cell embedded magnetic torque coils create a rolling moment force 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 coarse sun sensors arranged on the solar arrays and at the sun facing end of the satellite.
7. A Global Positioning System (GPS) receiver provides satellite position, velocity, and time. GPS data is analyzed on board the satellite before communicating its calculations to the ground.
8. The radiation-hard 32-bit LEON3 processor was chosen for its scalable processing capability. 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 Probes mission, built by JHU/APL, which launched in 2013.
9. A flatsat model was used to integrate and test without worry of requiring permission. The Software team took advantage of every opportunity available to run test software. A Real-Time Executive for Multiprocessor Systems (RTEMS) was selected for the real-time operating system (RTOS). RTEMS is a free open source solution that works on many CPU architectures, including the LEON 3. An Operating System Abstraction Layer (OSAL) allowed for the reuse of a small amount of heritage based software developed for previous space mission (STEREO). Development tools for LEON 3 already existed and were utilized for ORS Tech.
10. Rigorous end-to-end environmental testing was used to confirm the design functionality and performance across all mission modes and environments (see Figure 4.2).

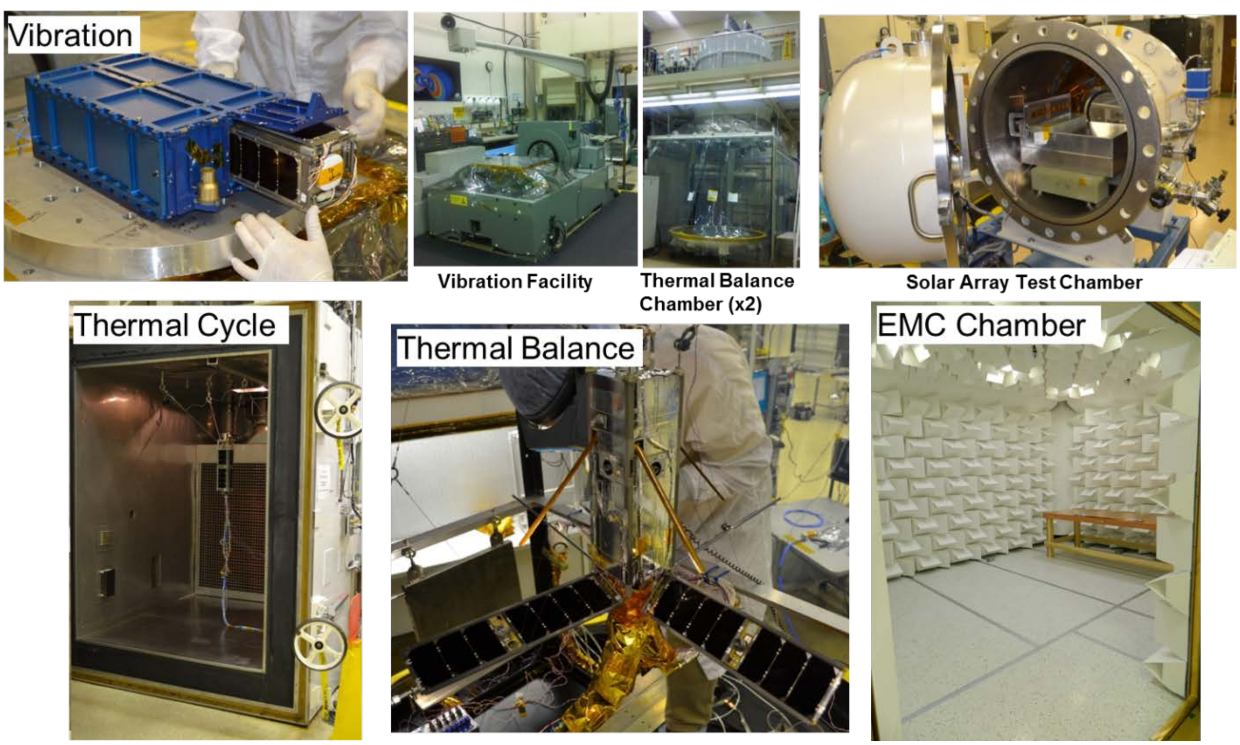

Figure 4.2 Complete testing of the ORS Tech 1 & 2 space vehicles was performed to ensure design integrity, workmanship, functionality, and operation across all launch environments and mission phases.

5. ORS TECH 1 & 2 LAUNCH AND EARLY OPERATIONS

As shown in Figure 5.1. the two ORS Tech 1 & 2 space vehicles were launched at 2015 EST on Nov. 19, 2013 as part of the Operationally Responsive Space (ORS) Office ORS-3 Mission[12]. The Minotaur I launch vehicle delivered the 28 nanosatellites into an approximately 500 km x 40.5°circular orbit in accordance with a deployment approach JHU/APL helped conceptualize through independent modeling and simulation support[13]. Given the favorable proximity to JHU/APL of the NASA Wallops Flight Facility where the ORS-3 mission launched from, contact was successfully made with both vehicles on the first overflight pass of the Master Gateway at JHU/APL approximately 100 minutes after launch. Both systems were fully commissioned into nominal mode over the course of the first week, demonstrating strong power margins, benign thermal behavior, stable pointing, and dependable communications between the satellites and ground. As planned, the mission operations were transitioned to highly automated, near lights-out function in the early January timeframe.

Figure 5.1 The ORS Tech 1 & 2 space vehicles were launched as part of the Operationally Responsive Space (ORS) Office ORS-3 mission that successfully deployed 28 nanosatellites on November 29th, 2013 into LEO.

6. SUMMARY

The continuation of feasible responsive space technology research and development is vital to carry military intelligence to the next level of operation. To prepare for the challenges imposed by future adversaries there is need for a new dynamic approach yielding reliable technology at attainable costs and schedules. Supporting the United States military on the battlefield with instantaneous information is at its highest demand. Strategic and tactical decisions must be in the hands of operatives in action on the battlefield. The answer will come in a smaller economical mission focused package, beginning with the standardized 3U and extending to 6U and larger 75 kg "Express" class systems. These SensorSats have great potential of becoming the persistent modular network of a responsive space asset infrastructure. It has been over 50 years since the first successful United States satellite launch and while the technology has progressed tenfold since then, there still remains many challenges to overcome. Comparatively, the CubeSat standard was introduced little more than one decade ago and much of its potential has yet to be realized. Increasing participation and the ability to deploy large numbers in a single launch will enable CubeSat to advance faster than ever before.

The two 3U ORS Tech SensorSats have now been qualified to support DoD payloads that will revolutionize the mission area and truly provide an operationally relevant capability. The current sociopolitical environment of constrained resources drives these small SensorSats to be utilized beyond their initial objectives. Johns Hopkins

University Applied Physics Laboratory has designed, built and operated over 70 spacecraft and 200 instruments contributing to more than 70 years of work devoted to space science. The organization has a history of engineers and scientists with the skills and knowledge to create innovative disruptive technology. It is proud to be at the forefront of another with its development of the ORS Tech mission.

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