U.S. Army Small Space Update

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ABSTRACT

In December 2010, the U.S. Army flew its first satellite in 50 years, the SMDC-ONE CubeSat. Placed in a very low orbit, the first SMDC-ONE mission lasted only 35 days but enjoyed great success in demonstrating the viability of CubeSats to perform exfiltration of unattended ground sensors data and serve as a communications relay between ground stations over 1000 land miles apart. The success of SMDC-ONE helped shape the U.S. Army's Space and Missile Defense Command's (SMDC) programmatic goals for finding new and innovative ways to implement space applications and technologies that aid the warfighter. Since 2010, SMDC has flown ten additional CubeSats including the three SMDC Nanosatellite Program-3 (SNaP) CubeSats currently on orbit (launched October 2015). This paper addresses several SMDC satellite-related development efforts including SNaP, Army Resilient Global On-the-move SATCOM (ARGOS) Ka-band communications microsatellites, Kestrel Eye (an imaging microsatellite), Kestrel Eye Ground Station (KEGS), Common Ground Station (CGS) for all future Army small satellites, supporting technologies including Small Business Innovative Research (SBIR) efforts, the Concepts Analysis Laboratory, SMDC Space Laboratory, the ACES RED effort and earlier responsive launch vehicle activities. Several of the lessons learned from previous as well as ongoing satellite activities are also covered.

INTRODUCTION

Under the leadership of Dr. Wernher von Braun and Major General John Medaris, the Army, in conjunction with the Jet Propulsion Laboratory, developed and orbited America's first satellite, the 14 kg Explorer I, in January, 1958, using a modified Jupiter-C rocket (Juno 1) developed by the Army Ballistic Missile Agency (ABMA) at Redstone Arsenal in Huntsville, Alabama. Data from Explorer 1 led to the discovery of the radiation belts around the Earth. Other satellite firsts achieved by U.S. Army satellites include store-and-forward data (Explorer III, 1958) and satellite communications (SCORE, 1958). In October 1960, COURIER 1B proved to be the last satellite developed and operated by the U.S. Army. In that same year, President Dwight Eisenhower directed the transfer of the ABMA core team to become the Marshall Space Flight Center.

In April 2008, the Commanding General of the U.S. Army Space and Missile Defense Command/Army Forces Strategic Command (USASMDC/ARSTRAT and hereafter referred to as SMDC) directed the development of eight flight nanosatellites within 12 months.[1] That feat was accomplished in April 2009 and 19 months later, the first of those satellites was on-board the second Falcon 9 launch vehicle at Launch Complex 40, Cape Canaveral Air Force Station.

In December 2010, the SMDC orbited and successfully operated the Army's first satellite in 50 years, a 4 kg, 3U nanosatellite dubbed the Space and Missile Defense Command - Operational Nanosatellite Effect (SMDC-ONE). This nanosatellite demonstrated the viability of Army CubeSats for communications relay and data exfiltration from unattended ground sensors and ended the long drought of Army space efforts.[2] Since the SMDC-ONE launch in 2010, ten SMDC 3U CubeSats have flown to low earth orbit (LEO) with varying degrees of success and all focused on providing communications capabilities.

Currently, operations continue on the latest of these satellites, three orbiting CubeSats designated as SMDC Nanosatellite Program (SNaP-3) under an Office of the Secretary of Defense (OSD) Joint Capability Technology Demonstration (JCTD). The next scheduled launch of an SMDC satellite is the Kestrel Eye Block IIM, slated for a December 2016 launch. This satellite has a mass of around 50 kg including an optical payload to provide digital imagery at about 1.5 meter Ground Sample Distance (GSD). SMDC is also developing an advanced communications satellite, designated as the Army Resilient Global On-the-move SATCOM (ARGOS), to provide improved communications for the ground tactical warfighter.

SMDC is working to a space technology roadmap which includes development of earth sensing and advanced communications small satellites. Consequently, current programmatic goals for SMDC include developing global communications coverage for the warfighter, enabling near real-time low resolution imagery collection and dissemination, and finding new and innovative ways to implement space applications and technologies that offer enhanced or new capabilities to the warfighter. This paper will discuss some of the past, present and future satellite efforts, as well as supporting systems and technologies, that SMDC is utilizing to achieve these goals.

SMDC NANOSATELLITE PROGRAM (SNaP)

The purpose of the SNaP program is to demonstrate orbital tactical communications for the disadvantaged warfighter while maturing small satellite capabilities and components. Objectives include demonstrating beyond-line-of-sight communications, on-orbit use of encryption, data exfiltration from unattended ground sensors (UGS), and nanosatellite propulsion. The current generation of SNaP 3U CubeSats has a mass of approximately 5.3 kg and utilizes deployable solar panels and antennas, a modified MAI-400 Attitude Determination and Control System (ADACS), an R134a refrigerant cold gas propulsion system, and an encryption unit. These satellites were developed by General Atomics – Huntsville (formerly Miltec Corporation).

Figure 1: SNaP-3

Three identical SNaP satellites, collectively designated as SNaP-3, were launched on October 8, 2015, as a secondary payload on a United Launch Alliance Atlas V rocket. Individually, the satellites are designated as Alice, Eddie and Jimi. First contact was made with Alice and Jimi on the first pass over the Huntsville, Alabama, ground station on the evening of October 8. First contact with Eddie occurred on the morning of October 9. Contact was lost with Alice and was not reestablished until March 2016. Thus, the planned 3 month on-orbit checkout period proceeded with only Eddie and Jimi.

During the checkout period, it was discovered that the satellites, Eddie in particular, were experiencing several reboots per day on average. Analysis of the telemetry data determined a main contributor to be insufficient power to the flight computer due to the ADACS unit repeatedly rejecting GPS position updates. The cause was traced to an internal delay period which flagged the new GPS data as outdated. A work-around was instituted whereby the ground station sent good position data to the satellite during each contact when reboots were noted. Additionally, errors in the pointing algorithms caused the reaction wheels to saturate at 10,000 rpm, thus preventing the satellites from maintaining the planned attitude control which further exacerbated the power issue.

The abnormally high reboot rate impaired contact with the satellites during the checkout period, thereby limiting checkout opportunities. However, the work-arounds developed allowed several systems to be successfully tested and most checkout objectives to be met.

With the completion of the on-orbit checkout period, the technical demonstration period began, spanning from February 22 to March 18, 2016. The purpose of the technical demonstration was to assess SNaP-3's technical capabilities, accomplish a set task list (analog voice, digital voice, and texting) in a limited period of time and assess the readiness of the constellation for an operational demonstration. Because of Alice's continued inactivity during this period, the technical demonstration included only Eddie and Jimi.

Near the end of the technical demonstration period, contact was reestablished with Alice and telemetry indicated a healthy satellite. Regular communications resumed which enabled a test of the encryption system to be performed on the third SNaP-3 satellite. This test was successful and marked the third on-orbit SNaP-3 spacecraft to successfully use this particular encryption system.

Table 1 summarizes the operations performed during this period. The same technical issues that hampered the on-orbit checkout period limited the amount of tasks completed. However, positive results from the technical demonstration supported the decision to proceed with a limited operational demonstration.

Table 1: Technical Demonstration Results

Task	Setup	Mode	Antenna	Eddie	Jimi
1	Baseline	Analog	Tracking	24-Feb	25-Feb
2	Baseline	Digital FSK	Tracking	N/A	25-Feb
3	Baseline	Text	Tracking	N/A	25-Feb
4	UGS	***	***	Gateway Failure	Gateway Failure
5	Unobstructed	Analog	Man Portable	29-Feb, 4-Mar, 5-Mar	27-Feb, 4-Mar
6	Unobstructed	Digital FSK	Man Portable	4-Mar	27-Feb, 4-Mar
7	Unobstructed	Text	Man Portable	28-Feb	28-Feb
8	Unobstructed	Analog	Whip	4-Mar	4-Mar
9	Unobstructed	Digital FSK	Whip	Mode Lock Failure	4-Mar
10	Wooded	Analog	Man Portable	8-Mar	8-Mar
11	Wooded	Digital FSK	Man Portable	Mode Lock Failure	Mode Lock Failure
12	Wooded	Analog	Whip	8-Mar	8-Mar
13	Wooded	Digital FSK	Whip	Mode Lock Failure	Mode Lock Failure

The limited operational demonstration occurred between April 4 and April 8, 2016. This demonstration involved two teams located over 420 ground miles apart: one team located in Huntsville, Alabama, which included SMDC employees and soldiers from the 53rd Signal Battalion and the Future Warfare Center; and the second team located in Mayport, Florida, which included SMDC employees, a soldier from the 53rd Signal Battalion, and Navy sailors. These tests used the same man-portable, non-tracking antennas as was used in the technical demonstration. During this test, over-the-horizon voice communications were established in analog mode separately through Alice and Jimi.

Following the completion of the limited operational demonstration, Jimi was commanded to execute two separate propulsion events. Satellite pointing difficulties discussed earlier prevented predictable alignment of the thrust vector, thus changes in the satellite's orbit could not be effected in a controlled manner. However, analysis of the telemetry data showed an expected spike in the current drawn from the battery indicative of heating element activation in preparation for the event. Data also showed that the satellite roll rates and ADACS reaction wheel speeds changed indicating forces had been applied slightly offset from the satellite's center of mass. Based on these data sets, it can be concluded that the propulsion events occurred. SNaP-3 operations will continue through the end-of-life to retrieve housekeeping and status data and to further test capabilities.

Overcoming technical issues proved to be a challenge but the SNaP JCTD demonstrated most capability objectives. Lessons learned from the SNaP-3 operations will be applied to current and future SMDC space system efforts.

KESTREL EYE PROGRAM (KE)

Tactical, near-real-time imagery is required by the warfighter. Today, in-theater tasking of an imaging satellite to take an image of a designated ground object of interest and receiving the image during the same satellite access (pass) is important to the warfighter in achieving mission success. The purpose of the Kestrel Eye program is to develop a small, low cost, visible imagery satellite demonstrator to directly address this requirement at a lower unit cost than traditional space assets.

Figure 2: Kestrel Eye IIM

The current KE program began as a KE Block I proof-of-concept or pathfinder. Derived from the KE Block I design, a KE Block II concept improvement was developed. In 2012, the Army, in conjunction with the Office of the Secretary of Defense (OSD) JCTD program, initiated the Kestrel Eye Block II as an electro-optical microsatellite-class imagery satellite to support the tactical warfighter. Two contractors were selected to build second-generation KE satellites, designated KE Block IIA (Spaceflight Industries) and KE Block IIM (Maryland Aerospace Incorporated). As a JCTD, the KE program is teamed with OSD, the Combatant Command (COCOM) sponsor - U.S. Pacific Command (USPACOM), and transition agent - the Army Program Executive Office (PEO) Missiles and Space.

KE is scheduled to demonstrate its capability in the second quarter of FY 17. The primary objective of the demonstration will be to task the satellite to take an image. An independent evaluator will assess the military value of the KE demonstration. KE will demonstrate the critical technologies required by an operational system. When the military utility and concept of operations (CONOPS) are verified through experimentation, an acquisition transition decision will be made.

The intent of KE is to demonstrate a tactical space-based imagery microsatellite. A KE satellite constellation would provide dramatically lower unit cost than typical space based assets. With this low unit cost, large numbers of satellites can be procured enabling the system to be dedicated to the tactical warfighters.

Key advantages of Kestrel Eye include:

• Smaller size and greater number than traditional satellites: affordable, persistent presence.
• Graceful degradation: no single launch or satellite failure in the constellation causes complete loss of service.

As of this writing, the KE IIM satellite (developed by Maryland Aerospace Inc. (MAI)) is well into integration and test. After launch, the KE satellite will spend a period of time on the ISS awaiting Japanese Experiment Module (JEM) airlock scheduling before deployment. During the first two months on-orbit, the satellite checkout operations will be conducted, culminating in a technical demonstration. KE capabilities will be exercised in various scenarios such that the independent assessor can make a military utility evaluation. If KE is successful in the evaluation, then transition plans will be fully developed and implemented.

Current plans for the KE IIA (developed by SpaceFlight Industries) satellite are pending review. Prior to selection for flight to the ISS, KE IIA was designed with components (propellant, propellant tankage, and battery cells) not easily adapted for meeting human rated space requirements. Other options are under evaluation for use of the KE IIA satellite and its components.

KESTREL EYE GROUND STATION (KEGS)

The original ground station for KE was developed to support the singular KE Block I satellite and was intended to be used in a laboratory setting. A targeting utility was demonstrated early in the KE Block I program with hardware-in-the-loop and the Kestrel Eye Dynamic Simulator (KEDS), which allowed the satellite imaging capability to be demonstrated, promulgating the vision for KE. As stated earlier, under the KE JCTD two contractors were selected to build the second generation KE satellites. Each contractor chose slightly different approaches to provide comparable capability. The approaches were not completely backwards compatible with the KE Block I, creating some challenges in designing a ground station compatible with all Kestrel Eye satellites. Refinement of architecture requirements and feedback from representative user forums in 2013 and 2014 helped shape the ground station requirements and use cases. The main requirements for the ground station were to enable the user to easily choose a target of interest (point-and-click) and receive the satellite image during the same satellite access time (pass). In summer 2014, the KE team began work on developing the KEGS, incorporating the design upgrades, architecture differences and user feedback.

Figure 3: First integrated KEGS (foreground) and GATR-TRAC® (background) test to demonstrate tracking an X band satellite in LEO - January, 2016.

KEGS hardware consists of a small two-man transportable ground station. Figure 3 shows an early version of KEGS.

KEGS software was developed jointly between the two satellite contractors and SMDC engineers with the former focusing on satellite interactions (i.e. commanding and telemetry) and the latter focusing primarily on the user interface software (i.e. targeting and mission planning). This government-contractor blend has resulted in greater understanding on both sides of the development as well as a natural peer review. Both contractors developed satellite flight computer emulators that are beneficial for software development efforts and reduce software integration risks. This approach resulted in an Air Space and Missile Defense Association Technical Achievement Award for a Government Team in January 2016.

The high level of integration and teaming on this program has improved the risk posture of the KE JCTD and KEGS. The architectural design supports both KE Block II satellites and provides a good platform to demonstrate their utility in the intended applications. The lessons learned and skills developed in support of this effort are being directly transitioned into SMDC's Common Ground Station (CGS) effort, which will be discussed later in this paper.

Mobile LEO Tracking Ground Antenna

Increasing investments in LEO small satellites, Unmanned Aerial Systems (UAS), and related capabilities by military and commercial customers are pushing tracking antenna capabilities to the point where traditional space-ground segments do not exist. A rugged, easily deployable tracking antenna is needed to utilize these new capabilities.

Current deployable ground stations are massive, typically truck or trailer mounted and require special handling equipment and specially trained personnel to operate and maintain. Tactical units cannot utilize the aforementioned LEO and UAS capabilities without ready access to them via an organic, tactically deployable ground station that incorporates a steerable antenna. This antenna must be ruggedized to survive the rigors of the deployed environment.

GATR-TRAC® is an inflatable tracking antenna supporting transportable ground station applications that directly addresses these issues. GATR is under contract to mature and ruggedize the GATR-TRAC® antenna (nicknamed the All-terrain Inflatable GATR or ALLIGATR) that will retain GATR's lightweight, portable attributes while meeting the intent of applicable environmental considerations found within MIL-STD-810. This antenna's rugged design for military utility will be assessed and demonstrated in concert with the KE JCTD program and with other available satellites in order to prove out advancements to Technology Readiness Level (TRL) 8 and readiness to directly enter programs-of-record**.** GATR-TRAC® is shown in Figure 3. The antenna is scheduled to be delivered in August 2016.

COMMON GROUND STATION (CGS)

SMDC is developing small satellite systems to address Army capability gaps and provide greater capability to Army operational units. To date, these satellite systems have unique, proprietary, and dissimilar Command and Control (C2) and Mission Management (MM) systems. To reduce cost and increase commonality, SMDC is developing a common command and control/mission management (C2/MM) solution known as the Common Ground Station for its families of small satellites.

The primary objective of CGS is to unify the C2 elements, thereby reducing development time and cost, minimizing risk, supporting concept of operations (CONOPs) testing, and supporting multi-user mission planning and test execution. CGS is envisioned to facilitate the creation of additional ground architecture elements which can be leveraged to support future operational satellite constellations. Additionally, CGS will coordinate satellite operations via a comprehensive mission planner to ensure the most efficient satellite utilization and to serve more customers.

SMDC has partnered with the Naval Research Laboratory (NRL) to provide the Government-off-the-shelf (GOTS) Neptune® C2 and Virtual Mission Operations Center (VMOC™) MM software. The Neptune software provides a framework with a core set of reusable components forming the foundation of a command, control, and monitoring system used for spacecraft and ground equipment development, integration, test, and operations. The VMOC application will receive, manage, and synchronize mission support requests and apply prioritization and apportionment as determined by the SMDC Commander. The VMOC application is accessible from any site with a web-connected workstation with Public Key Infrastructure (PKI) validated authentication. NRL is supporting software development and integration for the SMDC C2 development program maximizing existing world-wide C2 infrastructure and architecture. Initial Operating Capability is planned for June 2017.

ARMY RESILIENT GLOBAL ON-THE-MOVE SATCOM (ARGOS)

ARGOS is a LEO communication satellite system designed to provide beyond-line-of-sight support to the Warfighter Information Network-Tactical (WIN-T) for Brigade Combat Team (BCT) operations, voice and text to Army Tactical Radios, and UGS data exfiltration.

ARGOS has three primary objectives. The first is to support the WIN-T on–the-move capability for BCT operations using the Ka-band. Second, ARGOS will support BCT and below operations in ultra-high frequency (UHF) via Army Tactical Radio equipment. Third, in addition to UHF voice and data communication over tactical radios, ARGOS will support UGS data exfiltration in both Force Protection and Intelligence, Surveillance, and Reconnaissance (ISR) scenarios. ARGOS has teamed with WIN-T and the Communications-Electronics Research, Development, and Engineering Center (CERDEC) to ensure compatibility of space and ground segments of the Ka band mission, and with the Army Research Laboratory for the UGS mission. The intent for integration of Army Tactical Radios with UHF is to require no modification to the current Project Manager Tactical Radios (PM TR) equipment. ARGOS is currently contracted with the Johns Hopkins Applied Physics Laboratory (APL) to develop system requirements and provide an initial concept design for both objective and demonstration units. Upon completion of the design phase, solicitations for production of the demonstration system will be posted with the end of FY 2019 as the projected launch date.

The Army has identified the need for increased capabilities for beyond-line-of-sight communications for its tactical users at increased distances. Also, there is the need to provide increased capacity and assure communications in a degraded environment. There are also areas that are not currently covered by SATCOM that require support.

WIN-T Increment 2 introduces a high-capacity on-the-move networking capability for combat formations (to include Battalion and Company leaders) as well as provides network operations interoperability infrastructure within their headquarters elements. Increment 2 provides communications interoperability for ground-based Army units fielded with this high-capacity tactical network.

The SMDC Space Division is analyzing the ability to support WIN-T Increment 2 with a LEO spacecraft and payload, while CERDEC is analyzing necessary upgrades to software and modems on a WIN-T demonstration set of equipment.

PM TR enables tactical communications by providing a range of products capable of terrestrial and celestial communications. SMDC has already demonstrated the ability to launch a satellite into LEO and communicate using the PRC-117 and PRC-152 radios without any modification to the radios. These radios are out of the PM Handheld, Manpack and Small Form Fit. ARGOS will continue this effort by increasing support to numerous users, thus demonstrating the ability to support BCT operations. The intent is to directly address gaps with beyond line-of-sight communications for dismounted soldiers. ARGOS is continuing analyses to determine if other radios from PM Airborne, Maritime Fixed Station and PM Mid-tier Networking Vehicular Radio can be supported as well.

ARGOS will use SMDC's Common Ground Station (CGS) for command and control of the ARGOS constellation. APL engineers are currently working with the CGS team to ensure compatibility.

ARGOS demonstrator satellites are envisioned to be launched around the 2020 timeframe.

SUPPORTING TECHNOLOGIES: SMALL BUSINESS INNOVATIVE RESEARCH (SBIR)

Nanosatellite to Standard Army Handheld, Phase II (Army SBIR Topic A12-067)

Nanosatellite to standard army handheld radio communications show tremendous promise to address the Army Forces Command Operational Needs Statement by providing beyond-line-of-sight UHF communications and high bandwidth S-band backhaul for disadvantaged users, time critical communications capability, non-invasive exfiltration of Unattended Ground Sensor data, increased communications capacity in current radio networks (i.e. more users), and reduced reliance on commercial communications satellite service.

Despite improvements to military UHF communications enabled by SMDC-ONE, SNaP and SWIFT™ Software Defined Radio (SDR), the need for increased bandwidth and channel capacity continues to grow. Integrating nanosatellite communications into the WIN-T Ka-band architecture is projected to increase channel capacity and reduce current network burden, resulting in large improvements in the number of users supported. Under the Phase I and Phase II SBIR program, Tethers Unlimited, Incorporated (TUI) has engaged in the research required to provide high analog bandwidth, precise timing, and high processing throughput in UHF and S bands to SMDC for nanosatellite communications applications. Results of the Phase II include a prototype state-of-the-art baseband processor, a SWIFT™ SDR product, and a novel deployable range compensating antenna. This program directly supports SMDC's mission of developing innovative nanosatellite scale communication solutions to address warfighter needs.

A second Phase II program beginning in 2016 will advance and mature the baseband processor, develop error correction techniques, develop a prototype Ka band transceiver daughter card for the SWIFT-SDR product and refine antenna pointing methodology in support of ARGOS. This program is valuable to a wide audience of military users on the WIN-T network. Additionally, this innovation directly supports missions requiring high instantaneous bandwidth processing capability. The base Phase II program focused on fulfilling communication gaps between dismounted soldiers. The need for this Phase II program stems from requirements to address technology gaps identified in support of BCT communications. Army Program Office WIN-T and other restricted customers could immediately benefit from the proposed research. The innovation of enhanced baseband processing, Ka band transceiver prototype development, and antenna pointing is a critical need for realizing the benefits of high bandwidth, multi-user Ka band communications for both military and commercial applications.

ElectronicVeil (Army SBIR Topic A14-072)

As the DoD has become increasingly dependent on the use of mobile computing platforms to conduct mission operations, the need for improving security in an environment that includes commercial mobile devices has grown. Key device level security issues facing mobile computing platforms include network authentication, data protection, malware defense, and mobile ad hoc networking (MANET). The focus and priority of this topic is seeking innovative software architectures for mobile ad hoc networking to ensure secure communications in a complex space network environment.

The desire for self-organizing, self-forming, and scalable multi-hop mobile ad hoc networks poses significant security challenges due to the wireless and distributed nature. Applications and operating systems installed on mobile devices are subject to malware, spyware, or unexpected functions such as tracking user actions or sending private information to outsiders. Malicious activities could disrupt Army networks and compromise sensitive information.

Finally, current mobile devices and software architectures are limited by their processing capability for executing complex encryption algorithms or mission data intensive computations. Preliminary research assessments highlight the availability of next generation device/component technologies and outline novel architecture designs with potential to significantly improve network security. Of particular interest are Android-based platform solutions with multiple processors. Secure software architectures are being sought that fully utilize multiple processors within these devices and across a mobile ad hoc network to increase security, robustness, and computation capability.

New innovative solutions are required in the form of secure software architectures for mobile ad hoc networks to protect applications and data within a complex space network environment from being exploited or exfiltrated from advanced threats. SMDC has contracted Quickflex, Incorporated to develop ElectronicVeil under an SBIR Phase II program. ElectronicVeil is a cost-effective, high-assurance military-secure mobile computing platform which combines data integrity, configurable security policies, and micro-attestation among devices on a MANET without reduction in the features or functionality of the mobile computing platform. Phase II completion is scheduled for May 2018.

Redundant High Bandwidth Communications (Army SBIR Topic A16-079)

Small satellites (and constellations) in LEO have increasingly shown military and commercial value for the sensors and data they can provide. While the Department of Defense use of small satellites for earth sensing is increasing, commercial companies are also interested in the capabilities made possible by small satellites. However, as the sensor payload capability increases, the ability of currently available small satellite transmitters to send large amounts of data to the ground are strained. This problem is typically exacerbated by the short line-of-sight contact windows over ground stations.

Additionally, if the main communications link is experiencing interference or an outage typical in congested spectra, critical contact opportunities might be missed. A redundant high bandwidth communications link easily adaptable for commercial and government use is highly desired. Therefore, a redundant communications link (transmit) providing high data rates in spectra allocated for government use in Ka band and moderately high data rates in spectra allocated for government use in X band is desired. SBIR Topic A16-079 in DoD solicitation 16.1 is aimed at addressing this problem. Source selection is ongoing at the time of this writing with expected awards in summer 2016

SUPPORTING TECHNOLOGIES: BROAD AGENCY ANNOUNCEMENT (BAA)

Reliable Expandable Satellite Testbed (REST)

Small satellites present an enormous opportunity for cost savings over the traditional spacecraft design paradigm. Traditionally, in spacecraft design, single, high dollar spacecraft are tested exhaustively to push that failure rate as close to zero as possible, driving up cost. Conversely, if numbers of low cost satellites can be built and tested, then a failure rate can be derived from the population.

In this relatively new area of low cost spacecraft, the failure rate has been very high (estimated at about 34 percent, biased higher by failures of university CubeSats).[3] This low failure rate is unacceptable for a military system intended to augment or replace key capability where reliability, mission assurance, and dependability are crucial.

The ability to launch numbers of satellites in quick reaction and with frequent refresh rate is extremely attractive – provided the satellites perform reliably and consistently. The ability to increase reliability will allow organizers to effectively plan and execute missions with flexibility. In order to accomplish this vision, the failure rate must be driven down to more acceptable levels. High failure rates can essentially be attributed to three main areas: a lack of systems engineering rigor by non-traditional spacecraft developers; the use of Commercial-Off-The-Shelf (COTS) components insufficiently vetted for space qualification and functional testing; and the deliberate lack of redundancy in order to minimize the impact of size, weight and power (SWaP) and cost on small satellites.

SMDC, under the Department of Defense Rapid Innovation Fund BAA, is developing an expandable hardware-in-the-loop (HWIL) capability that can be utilized during all phases of spacecraft development and mission. This capability will include event simulation, environmental stimulation, improved modeling fidelity, incremental inclusion of additional flight subsystems, comprehensive test case coverage, and aid in accurate diagnostics. These are all aimed at driving down technical, cost and schedule risks as well as increasing mission assurance in small satellite programs while maintaining consistency within the small satellite cost paradigm. The goal is to be generic, tailorable, and exportable for standardization and usable across multiple satellites. The contract is expected to be awarded in summer 2016.

CONCEPTS ANALYSIS LABORATORY (CAL)

The CAL mission includes performing research, advancing technologies and developing the science and engineering (S&E) workforce of the SMDC Technical Center. Newly hired engineers and scientists and college interns are employed in the CAL for approximately two to three years to develop competencies in space, directed energy and missile defense related technologies.

The goal is to develop an engineering workforce and future leaders who are technically proficient and have hands-on experience enabling more informed decision-making as they progress through their careers. Personnel also participate in conducting distinguished visitor tours and outreach events to promote education in the Science, Technology, Engineering and Math (STEM) areas. CAL personnel learn the importance of hands-on experience early-on for the S&E workforce.

The CAL provides value by providing in-house analyses, hardware and software design, testing and fabrication, operations and test support. Specifically, the CAL's contributions to space technology development include ground station operations, ground station software development, satellite coverage and lifetime analysis, and antenna design, testing and fabrication. Currently, the CAL facilities include: a lab area with lab benches, 3D printers and a circuit board mill; a satellite ground station with attached cleanroom; collaborative office area and a large meeting/classroom with media wall. The CAL will house and provide personnel to support the CGS through ground station software development and operations. The CAL will also support the new Space Lab and ACES RED discussed later in this paper. CAL engineers are instrumental in performing on-orbit operations of all SMDC satellites, the most recent being the SNaP-3 satellites. The CAL played a crucial role in SNaP-3 initial hardware assessment and on-orbit checkout by operating the ground station and performing pass planning. Analysis of telemetry was used for anomaly determination and diagnoses. Software was also developed to assist with operations. Examples include an orbital propagator used in determining antenna pointing angles and radio Doppler corrections, a log database management tool, and plotting tools for telemetry data. CAL engineers performed detailed testing of satellite communication capabilities, resulting in several successful voice and text beyond-line-of-sight communications between both local and long-distance (over 400 ground miles apart) operators. Figure 4 shows the CAL ground station during a distinguished visitor tour.

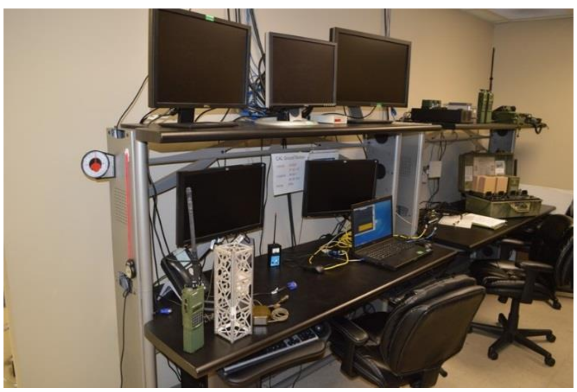

Figure 4: CAL ground station

The CAL is currently building a 3 meter tracking dish antenna system (Figure 5) in support of the KE program. The structural and mechanical designs have been completed while the electronics boards for power management and data handling are being designed and manufactured in-house on a circuit board mill. All associated software for sensing and actuation is being coded by government engineers. The in-house work should result in significant cost savings over a commercial tracking dish procurement. The antenna will be permanently mounted on a SMDC roof top and can be used to support programs besides Kestrel Eye.

Figure 5: LEO tracking antenna

CAL engineers used rapid prototyping techniques to develop 3D printed helical antenna forms. Rapid prototyping enabled precise tuning of antenna parameters. These techniques have also enabled the development of a monopulse tracker where precise phase measurements of the incoming communication signal are used to track the satellite. The monopulse tracker is expected to improve satellite communications due to its greater precision than open loop tracking of the ephemeris.

The CAL provides quick turn simulation and analysis support. Utilizing primarily the Analytical Graphics, Incorporated (AGI) Systems Tool Kit® (STK) and MATLAB®, CAL engineers develop tools and perform a variety of analyses for systems in all phases of development from conceptual to on-orbit. This rapid analysis capability has a powerful impact on programmatic decisions and shapes new research and development efforts. See Figure 6.

Figure 6: CAL analysis area

U.S. ARMY SMDC SPACE LABORATORY

Current and future Army Space Science and Technology (S&T) personnel need hands-on design and testing experience in order to adequately evaluate future space technology gaps, milestones, goals, and objectives; and to prepare space technology investment strategies and roadmaps. In-house research is needed to develop, determine, and drive goals and objectives for future Space S&T programs that also support the present projects.

While the programmatic efforts are developing the near-term operational capabilities, there are occasional technology gaps in the S&T demonstration efforts require technology maturation and risk reduction experimentation, research, and development. It is the goal of the Space Laboratory to identify these technology gaps and perform experiments to fill them, mature the technology, or reduce technical risk.

Present SMDC satellite developments rely heavily on nanosatellite technologies and innovative applications. While many CubeSats have flown in space to date, most of these spacecraft were custom built with little flight heritage translating from one flight to the next

The Space Laboratory is currently in Phase I of a two-phased effort to address the needs of Army Space development efforts as discussed above. Phase I is developing a hardware and software in-the-loop small satellite design, test, and simulation bench known as a "Flat-Sat". Figure 7 shows a (compressed) diagram of the Flat-Sat. The test apparatus is broken up into benches that correlate with subsystems or systems that are natural components of a spacecraft. There are five benches:

1) Dynamics Bench – a 3-axis rotational apparatus to test ADACS and Reaction Control System (RCS) concepts of 3U CubeSats;
2) Structures Bench – a torsion, tension, compression, and impact analysis apparatus for CubeSat architectures;
3) Thruster Bench – a 1U CubeSat containing an RCS cold gas thruster simulator;
4) Systems Bench – Command and Data Handling equipment and SDRs, connecting all other benches in complete satellite simulations; and
5) Constellation and Mission Planning Bench – a complete ground station and mission planning simulator with HWIL capability used to determine viability of various constellation mission concepts. This bench is connected to the Redstone Space Operations Center – Testbed (RSOC-T).

The RSOC is the operations center within the CAL used to operate all SMDC satellites and will eventually incorporate the CGS. The RSOC-T is composed of various elements including the Constellation and Mission Planning Bench employed to develop and perform experiments with various configurations in the quest for small satellites with upgraded capabilities and reliability. The expected completion date of the Flat-Sat is the end of FY16.

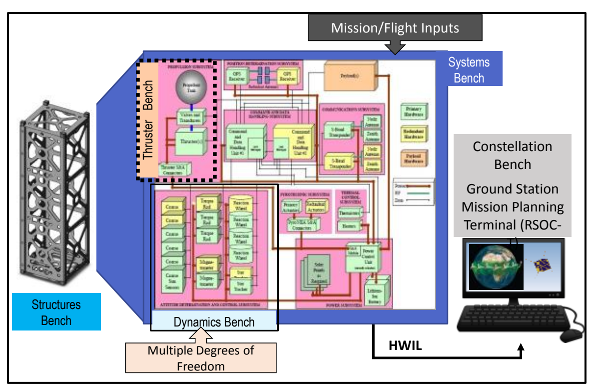

Figure 7: U.S. Army SMDC Space Laboratory "Flat-Sat" Architecture

Phase II of the Space Laboratory effort will identify specific programmatic technology development and maturation needs and then design single, very specific small spacecraft flight experiments to mature technologies and identify and reduce risks of the larger program missions. Phase II is known as Army Cost Efficient Spaceflight Research, Experiments, and Demonstrations (ACES RED). The ACES RED program is currently identifying and prioritizing a set of singular technologies for development and flight testing. Table 2 shows a notional list of technologies being planned for the program while Figure 8 gives a notional timeline and illustrates the transition schedule for the flight experiments. The goal is to fly on rideshare opportunities at least one flight per eighteen to twenty month cycle. These experimental spacecraft will be built in-house at SMDC's Space Laboratory. Table 2 indicates notional missions for the ACES RED program. TRLs will be developed for each element.

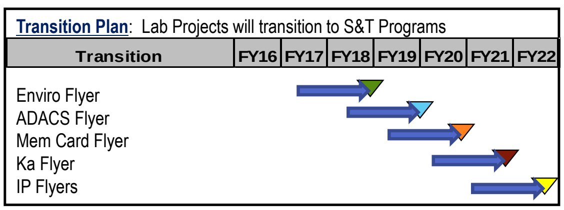

Figure 8: Notional Flight Experiment Schedule for ACES RED

Table 2: Notional Missions for ACES RED Program

Spacecraft Flight Test	TRL	OBJ TRL	Technology Objective	Status
Environment/ GPS Flyer			Measure drag, lift, fields, and rad as well as GPS performance at LEO to improve TLEs	Concept
ADACS Flyer			Test and fully evolve ADACS standard set	Concept
Memory Card Flyer			Fly large sample space of memory cards to choose future standard	Concept
Ka Radio Flyer			First Ka band radio test	Concept
Formation IP Flyers			Detach routers on orbit and pass IP between sats	Concept

Figure 9 illustrates Space Lab and ACES RED strategy integrated with SMDC's larger roadmap for space technologies. The concept for the lab is to identify, analyze, simulate, test, and fly nanosatellite concepts and feed the results of the missions back into the larger efforts, which are intended to mature technologies, reduce technical (and therefore programmatic) risk, and possibly drive down mission costs. The first ACES RED flight is planned for 2018.

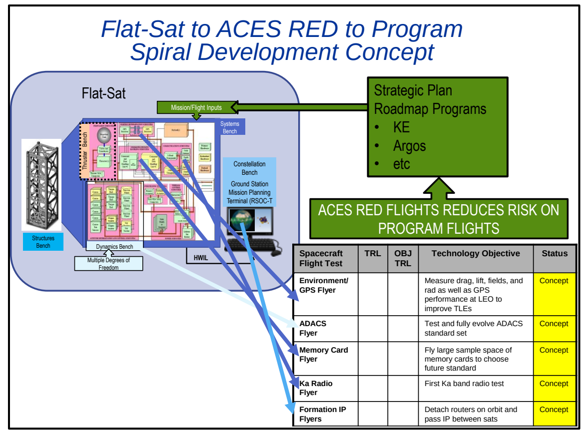

Figure 9: ACES RED concept for feeding larger Army Space program needs

RESPONSIVE LAUNCH

Multipurpose NanoMissile System (MNMS) Program

In 2006 the SMDC Technical Center identified a need to support the deployment of military nanosatellites using a very low cost, responsive space launch system. This was based on the emerging military utility of these nanosatellites operating in constellations, coupled with similar findings by SMEs at DARPA. However, such a system did not exist. SMDC identified some characteristics that this type of launch system would likely have, including the employment of low cost materials, a low part count, and a very simple design. During 2007 it became clear that additional funding would be forthcoming to SMDC in FY08 targeted specifically for the development of such a launch vehicle. SMDC, in the interest of moving quickly to establish a contract vehicle to design and build this small launch vehicle, employed a task order contract. COLSA Corporation in Huntsville was the only bidder, and a task order was established with Authority To Proceed (ATP) occurring in February 2008. Orion Propulsion, also of Huntsville, was a subcontractor to COLSA and the program's technical lead. Thus, the Multipurpose NanoMissile System (MNMS) Program was initiated.

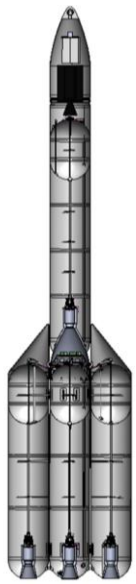

Figure 10: MNMS Model

The MNMS vehicle as proposed was a three stage stainless steel launch vehicle, with the first two stages using Nitrous Oxide and Ethane and the third stage having both a liquid and solid propellant option. The vehicle was controlled in flight using liquid injection thrust vector control, thus avoiding gimbal systems. Roll control was achieved using a cold gas system. The vehicle used one engine per stage segment, although the first stage was clustered, as shown in Figure 10. The engines avoided the need for turbomachinery by using a novel pressurization system called VaPak. Leveraging the work done during DARPA's AirLaunch QuickReach program that did much pioneering work in VaPak and of which Orion Propulsion was a part, MNMS baselined VaPak for at least the first two stages of the vehicle. VaPak uses autogenous pressurization by allowing the saturated propellants in each tank to bootstrap pressurize as the propellants are depleted.

The first stage engine (20,000 lbs. thrust) was successfully tested horizontally at a commercial test site west of the Huntsville Airport. These hot-fire tests were of relatively short duration (<10 seconds) due to propellant supply limitations. Test operations then shifted to the Redstone Test Center in the spring of 2010. For these tests, a complete first stage simulator with engine was mounted in a vertical orientation on the test stand. This gave the program the capability of full 120 second duration burns in a flight-like configuration. The testing incrementally increased in duration until a successful 60 second burn was achieved on June 18, 2010 (Figure 11). This turned out to be the last hot-fire test of the program due to several factors. Almost all of the Congressional Add funding had been expended, the task order Period of Performance was ending, and a high priority Missile Defense Agency (MDA) program required the use of the test stand.

Figure 11: MNMS Engine Test (June, 2010*)*

A new MNMS task order was established in August 2011 using the Concepts and Operations for Space and Missile Defense Integration Capabilities (COSMIC) Task Order. Quantum was the prime contractor with Dynetics and COLSA as subcontractors. Dynetics had fully acquired Orion Propulsion in the spring of 2011. Although a new task order was put in place, there was very little funding available to move the program forward. SMDC's Technical Center sought other sources of funding which led to the beginnings of the SWORDS program.

Soldier-Warfighter Operationally Responsive Deployer for Space (SWORDS)

In February 2012, the Soldier-Warfighter Operationally Responsive Deployer for Space (SWORDS) was selected by OSD as a new JCTD program. In the spring of 2012 a new task order was developed through COSMIC that matched the SWORDS JCTD requirements and period of performance. Bids were submitted from the two COSMIC primes, BAE and Quantum. Quantum was subsequently selected and their team constituted the SWORDS contractor team. Quantum's two subcontractors were KT Engineering and Teledyne Brown Engineering (TBE). KT Engineering was the vehicle concept originator and overall technical lead while TBE led in manufacture and heavily supported propulsion testing.

SWORDS was proposed as a technology demonstrator for low cost launch vehicle development that focused on innovative manufacturing techniques to achieve low recurring costs. The design employed liquid oxygen and liquid methane as propellants, which were pressure-fed into the engine combustion chamber. This approach avoided the need for complex and expensive propellant feed systems such as turbomachinery. The SWORDS vehicle concept called for three stages, each of which was powered by four engines. Each engine was independently throttleable, and in-flight steering of the vehicle would have been achieved by varying the thrust of engines to induce thrust vector moments to the overall vehicle. The engine nozzles were canted inboard at specific fixed angles on each stage to balance between required thrust vector control moments and an optimized thrust vector through the vehicle's center of gravity. This use of thrust magnitude steering avoided the requirement for complex mechanical engine or thrust steering systems. The overall vehicle concept was proposed by KT Engineering. An image of the SWORDS concept is shown in Figure 12.

Figure 12: SWORDS

The manufacturing of the vehicle depended on the use of thin-wall stainless steel propellant tanks, similar to the design approach used by General Dynamics for the Atlas ICBM. However, the wall thickness of the tanks would be considerably greater than the Atlas tanks, because the SWORDS vehicle propellants were to be pressure fed. Welding of steel joints would be achieved by resistance spot welding techniques. Other key design and manufacturing features called for the use of non-aerospace COTS hardware and components when possible and decomposing single functions into multiple identical components to achieve economies of scale in manufacturing and procurement.

The SWORDS JCTD proposed the use of surplus Peacekeeper ICBM fairings with in-flight tractor motor removal. This approach saved the program the expense of developing a unique fairing system, although the Peacekeeper fairing was much heavier than required by SWORDS.

The SWORDS team included program oversight from OSD Acquisition, Technology and Logistics (ATL) at the Pentagon, program and technical management by

Army SMDC, and major technical contributions from NASA's Marshall Space Flight Center (MSFC), Kennedy Space Center (KSC), Ames Research Center (ARC), and Langley Research Center (LaRC). The operational management and assessment planning was provided by US Pacific Command with support from 1st Air and Space Test Squadron at Vandenberg AFB. The transition management and planning was the responsibility of the Army Program Executive Office (PEO) Missiles and Space organization.

The SWORDS program formally began in May of 2012. Wind tunnel testing of the vehicle design was successfully accomplished at MSFC, under the direction of LaRC. Ground system design and development was led by KSC. KT Engineering executed vehicle design and engine system integration at their facilities in Madison, Alabama. A test stand at MSFC was refurbished to support SWORDS first stage engine testing. Guidance and control software development was led by ARC.

The program vehicle and ground launch systems achieved a significant level of design maturity between May 2012 and March 2014. However, difficulties in achieving low cost propellant tank manufacturing, a critical element in achieving the program cost goals, greatly impeded vehicle development and test progress. This problem, coupled with other unanticipated vehicle design and program execution complexities and costs, led to the decision by SMDC and OSD leadership to descope the program in March 2014 to only an engine technology development effort. A short duration hot-fire test of the SWORDS first stage heat sink engine was successfully executed in late September 2014 at MSFC. Because of dwindling funds, the engine program terminated at the end of September 2014. Figure 13 captures a hot-fire test of the SWORDS engine at MSFC.

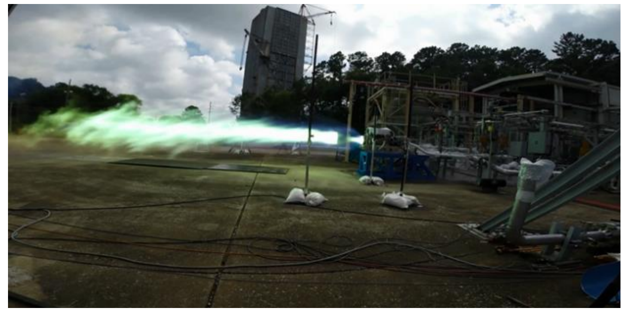

Figure 13: SWORDS Engine on Marshall Space Flight Center Test Stand (September, 2014*)*

Future plans focus on leveraging other Government and commercial small satellite launch vehicle efforts. Finding an affordable, timely ride to a desired orbit is still a huge bottleneck to the execution of satellite programs. The Army is unable to shoulder the financial responsibility for full-scale development of appropriately sized launch vehicles but strategizes with other U.S. Government organizations to support the best opportunities for access to affordable, responsive access to space.

CONCLUSIONS

SMDC has become increasingly interested in the utility of small satellites to benefit warfighters. To date, the primary interest areas have been imaging and communications, including data exfiltration of unattended ground sensors. Army Science and Technology (S&T) funds for these efforts have been steadily increasing over the past few years as greater numbers of officers and managers have recognized the potential of these small satellites. Persistent coverage is key for operational systems and in LEO that means tens if not scores of small, affordable satellites in a constellation. Satellites must get to orbit to be useful and to that end, the Army is collaborating with others to provide rideshares and to encourage the development of new small launch vehicles. The Army Space and Missile Defense Command's Space and Strategic Systems Directorate continues to work to a technology roadmap to assure the needs of Army warfighters are met in the future.

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- NASA Langley Research Center
- NASA Marshall Space Flight Center
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- US Southern Command (USSOUTHCOM)
- US Special Operations Command (USSOCOM)

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