Army Decade in Space

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ABSTRACT

In the twelve short years since the announcement of the SMDC-ONE satellite initiative by Lieutenant General Kevin Campbell, then Commanding General of U.S. Army Space and Missile Defense Command (SMDC), SMDC has put in place an active program of satellite technology development and a Low Earth Orbit Investment Strategy that holds great promise for providing low-cost, responsive data from space as the next major evolution in technology to enable Multi-Domain Operations for the Army of 2028 and beyond. The first fruits of that initiative were seen ten years ago with launch and successful mission of the first SMDC-ONE satellite. This small satellite strategy has gained traction with Army and DoD leadership who embrace the small satellite paradigm. This paper discusses Army progress and lessons learned in the past ten years of small satellite efforts, discusses relationships with other organizations and looks forward to potential capabilities enabled by technology advancements and innovative partnerships.

INTRODUCTION

"All military operations today are affected by space-based communications, imagery, positioning and location support, missile warning, and related capabilities. As the Army transforms itself for the future, space will be essential for achieving the information dominance necessary for the advanced, full-spectrum Army operations of tomorrow," (Lieutenant General Joseph M. Cosumano Jr. circa. 2003, then commander of the U.S. Army Space and Missile Defense Command).

The U.S. Army had a prominent role in the nation's early space endeavors, launching America's first satellite, Explorer 1 in 1958, until relinquishing that role in the 1960s to the U.S. Air Force and to NASA. Subsequently, the U.S. Army became a voracious user of space-based data, developing a heavy dependence on military and commercial space systems for communications, command and control, reconnaissance, and weather information. [1]

The U.S. Army pioneered the use of Satellite Communications (SATCOM) with the Synchronous Communication (SYNCOM) satellite service used in the Vietnam War. Later, DESERT SHIELD and DESERT STORM exposed tactical users to the value of multi-spectral imagery, GPS position/navigation, satellite weather, ballistic missile warning, and satellite communications (SATCOM). In 1997, the Army established a major command, the U.S. Army Space and Missile Defense Command (SMDC), to serve as its proponent for space and national missile defense and overall integrator for theater missile defense.

In 2006, SMDC was at a crossroads. SMDC had historically been largely focused on missile defense technology development, but its role was evolving due to the establishment of the Missile Defense Agency. SMDC began to focus on technology developments in other mission areas. At this same time, the Congressionally mandated Operationally Responsive Space Office was about to stand up, driven by the recognition among many in the DoD that U.S. military space systems needed to move away from a largely strategic focus to become more tactically germane. Finally, the revolution in microelectronics and microcomputers fueled by the cell-phone industry created a perfect storm of opportunity for the Army to re-establish a tactically relevant satellite development capability after a hiatus of almost 50 years.

SMDC adopted the paradigm that very small satellites brought many great advantages to the table: They were low cost, could be developed and built rapidly, packed an enormous amount of capability into a small package, could be deployed in large numbers for coverage persistence and survivability, and had relatively short orbital life which enabled frequent technology refresh. Thus, began the Army's return to space system development, albeit a small initial step but with hopes for greater things in the future.

SMDC's first foray into larger than nanosatellite development was the Kestrel Eye satellite program, later designated Kestrel Eye Block I. The program had initially been a DARPA seedling, but was transferred to SMDC because it was viewed as more of a novel application of technology than a novel technology. For SMDC this was not an issue; providing a low-cost effect for the ground component warfighter was of paramount importance.

At about the same time Kestrel Eye was transferred from DARPA, SMDC initiated a new small launch system as a partner program to Kestrel Eye. It was reasoned that Kestrel Eye, due to its small size, would need a dedicated low-cost small launch vehicle to place it into a variety of specified orbits. At the time very few small satellites were being considered for any use other than university-based experiments, and there was no demand for a small booster to launch them to a specific orbit. So, the Multi-purpose Nano-Missile System, or MNMS, program was initiated to provide a dedicated, responsive, and low-cost launcher for Kestrel Eye.

In 2008, an urgent real-world need emerged that could be addressed by a small satellite operating to detect unattended ground sensor signals. LTG Campbell announced the SMDC-Operationally Nanosatellite Effect (SMDC-ONE) program at a speech given during the 2008 National Space Symposium.[2] After LTG Campbell's April 2008 speech, SMDC-ONE quickly eclipsed Kestrel Eye Block I and MNMS in development rapidity due to its much higher priority.

One year to the month from LTG Campbell's announcement, eight flight-ready satellites were delivered. The first of these SMDC-ONE satellites was launched aboard the second flight of SpaceX's Falcon 9 rocket in December 2010. It is interesting to note that it took longer to await a launch than to build the satellite. Ultimately, SMDC is grateful to the National Reconnaissance Office (NRO) for providing that first launch and many others to follow, thus playing a key role in providing the Army access to space for its burgeoning line of small tactical satellites.

Since the SMDC-ONE launch in December 2010, 11 additional SMDC smallsats have flown in Low Earth Orbit (LEO) with varying designs for multiple missions. The most complex mission to date and the Army's largest satellite since COURIER 1B in 1960 was an imaging satellite called Kestrel Eye Block II, a more capable successor to the Kestrel Eye Block I, launched in August 2017. Kestrel Eye Block II was deployed from the International Space Station by astronaut Mark Vande Hei, a retired Army colonel. Other projects have explored applications of sensing and communications technologies, low cost small satellite components, Hardware-in-the-Loop and other innovative technology experiments and demonstrations.

Through these SmallSat missions and the lessons learned the Army has developed the Army Tactical Space Strategy.[3] The Army Tactical Space Strategy is designed to provide tactical land component forces with space-based capabilities (Communications, Intelligence, Surveillance, Reconnaissance, Surveillance, Target Acquisition (RSTA), and Assured Positioning, Navigation, & Timing (APNT)) to the Commander for Battlefield Situational Awareness and to aid in the targeting process in support of force projection and maneuver during Multi-Domain Operations (MDO).

The Army Tactical Space Strategy will extend the Army's ability to sense at deep ranges, and enable Beyond-Line-of-Sight (BLOS) tactical network and communications capability using commercial space, military satellite communications, LEO tactical communications, DoD/Intelligence Community (IC) enterprise investments, and commercial remote sensing mega-constellations

This paper will take a brief look at the different Army SmallSat missions and related technology developments over the last decade and share their key lessons learned. Lessons that provide the foundation of the Tactical Space Strategy. Additionally, a look forward to where the Army is heading in the decades to come as we look forward to the next major evolution of Army SmallSat capabilities to enable MDO for Army of 2028[4].

COMPLETED PROJECTS

SMDC-ONE SERIES

SMDC-ONE was the first Army satellite in 50 years. In 2008, USASMDC developed eight nanosatellites as part of the Army's effort to develop an operationally responsive space capability under the direction of LTG Campbell (Figure 1). Program Manager Mr. John London and his team within the SMDC Technical Center Responsive Space Division led the rapid development of these nanosatellites using an industry partner with no prior spacecraft experience to address an urgent need. By taking a non-traditional approach to space platforms and a moderate tolerance for risk these Army nanosatellites were ready for launch within one year of LTG Campbell's direction.

Figure 1. SMDC-Operational Nanosatellite Effect (ONE) spacecraft

The first of these units would launch within 19 months of delivery. An additional five SMDC-ONE spacecraft would go on to support Army missions while the remaining two were provided in a spirit of collaboration to support Navy small satellite efforts.

The maiden launch of SMDC-ONE occurred in December 2010 aboard a Falcon 9 test flight as a secondary payload. SMDC-ONE was one of several secondary "CubeSat" payloads launched on the mission (Figure 2). SMDC-ONE was the second longest lasting of the payloads, remaining in orbit for 35 days.

Figure 2. Satellite dispensers containing SMDC-ONE and payloads seen immediately after Dragon separation

SMDC-ONE earth station operators collaborated with other earth station operators and developed the techniques necessary to establish contact with small satellites deployed in a cluster. After successfully establishing contact during the initial on-orbit window, operators utilized all available information including antenna beam-width, spectrum tools, and orbital propagators to identify and track SMDC-ONE. These techniques would be used in later missions, reducing object identification from weeks to days.

SMDC-ONE provided valuable telemetry data, demonstrated the retrieval and relay of Unattended Ground Sensor (UGS) data, and relayed data files (text and images) between ground stations located at Redstone Arsenal, AL, and Colorado Springs, CO. Contact between the Ground Station at SMDC Huntsville and SMDC-ONE was made on the first orbit and maintained between the satellite and ground stations on every orbit except one during the orbital life. That one exception was due to operator error. The maiden SMDC-ONE accomplished all mission objectives and after 35 days on orbit, SMDC-ONE re-entered Earth's atmosphere.

Subsequent Communications Demonstrators

In September 2012, two additional SMDC-ONE spacecraft were launched as auxiliary payloads on National Reconnaissance Office Launch 36 (NRO L-36) aboard an ATLAS V launch vehicle. The auxiliary payload mission on NRO L-36 was known as Operationally Unique Technology Satellite (OUTSat). For this mission, the SMDC-ONE platform was modified to have the capacity for voice relay between terrestrial tactical radios. The two modified SMDC-ONE satellites launched on OUTSat were manifested as SMDC-ONE 2.1 (Able) and SMDC-ONE 2.2 (Baker). The primary mission objective for these modified SMDC-ONEs was to demonstrate added voice relay capability through a LEO nanosatellite using military standard radios, which had never been done before.

During the one year on-orbit demonstration, both Able and Baker successfully demonstrated that nanosatellites could support tactical communications using standard military radios such as the AN/PRC-117G and AN/PRC-152 within a local area (Redstone Arsenal for this demonstration).

Both Able and Baker successfully executed the Over the Horizon (OTH) voice relay mission utilizing the repeater mode of the radio. Repeater mode was demonstrated 50 out of 51 times onboard Able. There were nine repeater mode tests attempted with Baker, with discernible voice heard each time.

While path loss due to range was the largest initial concern for repeater performance, it was discovered through testing that the limiting factor was decreased contact duration due to lack of Doppler compensation. Through on-orbit testing and independent bench testing the tactical radios have been shown to tolerate approximately +1.5 kHz of frequency offset. The tactical radios commonly deployed do not have the capability for Doppler correction due to velocity of LEO satellites. One possible solution, which would limit modifications to military radios, is then to force the spacecraft to pre-compensate. Without Doppler correction it is only possible to have 1 to 2 minutes of discernible voice per satellite pass.

These lessons learned and the relay limits would be the basis for the following SMDC Nanosatellite Program (SNaP) demonstrations.

Thanks to the spacecraft's extended on-orbit demonstration, operators were able to broadcast the Army Song prior to the Army-Navy Football game. Final contact with Able occurred 15-months after deployment.

In November 2013, an SMDC-ONE bus hosting an Air Force payload was launched as a secondary payload onboard a Minotaur 1 as part of the Operationally Responsive Space-3 (ORS-3) mission. The Operationally Responsive Space Enabler Satellite (ORSES) represented a joint effort between SMDC and the ORS office. The mission for ORSES was to demonstrate a new protocol, called LEOPARD, and validate the KI-55 Type-1 Cryptographic device for spacecraft. The LEOPARD protocol was designed to allow data transfer between ground terminals and LEO satellites without a priori knowledge of either asset's position. Although ORSES launched and operated successfully, it failed to demonstrate either of its mission capabilities due to a loss of satellite communications a few days after launch. Some aggressive technical risks were taken that proved to be too large for the program without sufficient time to adequately test. The lessons learned during this mission would drive wider power margins and more robust end-to-end testing with flight hardware.

In December 2013, two legacy SMDC-ONE satellites, SMDC-ONE 2.3 (Charlie) and SMDC-ONE 2.4 (David), were launched onboard the NROL-39 alongside two next generation satellites, SMDC Nanosatellite Program (SNaP) and Tactical Satellite-6 (TacSat-6), as part of the Government Experimental Multi-Satellite (GEMSat) mission. The mission for Charlie and David was to extend the ultra-high frequency (UHF) SATCOM experimentation and demonstration of Able and Baker. After successful initial contact and two weeks of telemetry collection, ground operations were shifted to prioritize SNaP and TacSat-6 contacts. This decision was driven by the limited resources including availability of ground operators and two operational ground stations. Contact was never re-established with Charlie and David. Charlie and David represented the last of the SMDC-ONE class spacecraft that would be launched.

Lessons Learned

Telemetry collection on SMDC-ONE was limited to a choice between being 'telemetry positive' or 'telemetry deep'. These limits were due to hard-coded sample rates, sequential data indexing, space-to-ground data links (max 10 kb/s), and limited ground stations. The maiden SMDC-ONE was telemetry positive, only sampling health sensors once per hour (or so) on-orbit. While this allowed for the ability to fully capture the satellites health on-orbit it was under-sampled and insufficient to re-create on-orbit conditions, gauge performance, or analyze faults. Telemetry rates for subsequent SMDC-ONE spacecraft were dramatically increased to ensure that most sensors were sampled every 5 seconds. This meant much more data was available on-orbit, but since downlink rates were not improved, much of that data had to be left on-orbit. Operators would query the sequential index and then request expanded data around high priority events (e.g. communications relay demonstrations) or faults. While this style was not ideal, it did inform the follow-on SNaP design to timestamp telemetry index to allow for easier operator querying.

Within the SMDC-ONE family of spacecraft the payload radio was directly tied to raw bus power. The payload radio was able to pull from either the battery or raw solar panel voltage thanks to the radio's internal power controller. This allowed the payload radio to operate even after complete failure of the flight computer (FC) and Electrical Power System (EPS) Controller card. The SMDC-ONE flight computers were prone to on-orbit resets and all experienced total flight computer failure within months of on-orbit operation. The SMDC-ONE spacecraft were a simple design with no redundant systems, without active attitude determination and control (ADAC) systems and relied on sun-pointing to maintain positive power budget. The FC provided for telemetry collection, EPS allowed for eclipse operations, but the spacecraft could (limitedly) function with only solar panels and the payload radio; therefore, space hardening was primarily focused on these components. These design considerations allowed all SMDC-ONE spacecraft to be able to continue on-orbit demonstrations despite the loss of key subsystems.

Satellite operations proved to be as much of a challenge as ensuring an operational spacecraft. A fault attributed to a functional satellite due to ground issues is an expensive opportunity loss. Original SMDC-ONE ground stations utilized custom SATCOM terminals and commercial antenna positioners adapted with custom controllers. The selected antenna controller was quickly observed to be overloaded by the weight and center of gravity offset of the antenna assembly and was traded in favor of a commercial solution widely used by the amateur radio community. In the following OUTSat operations, operators observed shorter than expected contacts with higher than anticipated noise floors. The noise floor was determined to be due to bleed-over from the ground station transmitter into the ground station receiver. This issue was present in the original mission but became problematic due to the increased orbital altitude versus the maiden launch (300 km nearly circular to approximately 540x760km). Changing the ground radio's internal filters increased average contact duration dramatically from 3-4 minutes to 8-10 minutes.

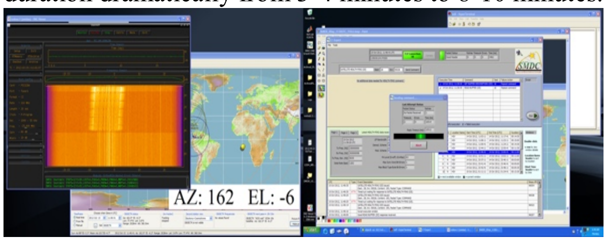

Figure 3. SMDC Earth Station Screens from 15 October 2012 contact with SMDC-ONE Baker

These four missions represented the U.S. Army's return to space after a 50-year absence and commitment to provide research and development of space-enabling materiel solutions. The success of these missions has encouraged the development of multiple new Army space technologies as well as increased industry investment.

SNaP3

Two launches of SNaP (NRO-L39/GEMSAT, NRO-L55/GRACE)

SNaP was approved in August 2011 as a Joint Technology Demonstration (JCTD) Program with a mission to provide BLOS communications to disadvantaged users at the squad level utilizing existing fielded low-power, hand-held squad radios with no in-theater infrastructure. SNaP leveraged the lessons learned from the SMDC-ONE program and expanded the role of CubeSats from technical demonstrations into a platform with operationally relevant capabilities.

Three SNaP spacecraft were all manifested for the NROL-39 GEMSat Rideshare. Schedule slips and issues during testing resulted in only a single SNaP-1 being delivered in time for launch. SNaP-1, TacSat-6, SMDC-ONE 2.3 and SMDC-ONE 2.4 launched successfully on 5 December 2013. After a successful on-orbit insertion, SNaP-1 was not contacted until 6 January 2014 when the spacecraft experienced near full sun on-orbit conditions (high beta). It was discovered that the spacecraft went into power saver mode during initial de-tumble maneuver. Due to high momentum in the vehicle the spacecraft was never able to de-tumble leaving it unable to maintain sun-tracking. Contact was lost shortly after the end of on-orbit full sun conditions.

Due to the limited number of rideshares opportunities at the time, the SNaP program became too schedule-driven not allowing time for a system engineering design approach with rigorous requirements verification and testing. A second phase of the program was established that implemented a number of lessons learned and was less tolerant of risk, principal among the new rules was that the project would not be schedule driven. Additional lessons learned applied to the second phase were the use of entry/exit criteria for major milestones, embedding government personnel with the prime contractor to understand issues as they occur, the establishment of an Independent Review Team (IRT) (which continues to support SMDC projects today), increased rigor in testing, systems engineering and risk management, and a process to ensure senior level management attention, risk adjudication and approval for launch.

Three SNaP Phase 2 spacecraft (Alice, Eddie, and Jimi) were successfully launched as secondary payloads on 8 October 2015 on the NROL-55/GRACE mission, another ATLAS V launch. Initial contact was made with Alice and Jimi on the first available pass visible to Redstone Arsenal ground stations while initial contact with Eddie was made on 9 October. During this mission, the SNaP spacecraft successfully completed all mission objectives. This included successfully relaying BLOS voice communications between two users with PRC-152 tactical radios using man-portable and standard whip antennas (in unobstructed and obstructed skies) between Redstone Arsenal and other BLOS locations, relaying text communications between PRC-117 and PRC-152 tactical radios and successfully demonstrating an encrypt/decrypt test of the KI-55 on all three satellites. The KI-55 is a 2013 NSA-approved type 1 encryption device developed for use on small satellites. This was the first successful demonstration of the KI-55 in space.

Responsive Launch (MNMS, SWORDS)

In 2008, SMDC embarked upon building a small orbital launch vehicle with then Orion Propulsion, Inc. The effort was called the MNMS. MNMS culminated in a successful static hot-fire test of the first stage in 2011, after which SMDC took on an even more ambitious launch vehicle project known as Soldier-Warfighter Operationally Responsive Deployer for Space (SWORDS). SMDC was joined by four NASA centers in the development of SWORDS – Marshall Space Flight Center (propulsion testing, wind tunnel testing, and other functions including various analyses and integration of the contributions of the other NASA centers), Ames Research Center (avionics), Kennedy Space Center (operations), and Langley Research Center (analyses). The lead contractor was KT Engineering, which designed the launch vehicle and built the 65,000 pound thrust modular engine that could be produced for about $1.25 per pound of thrust. At the time, the engine was the largest Liquid Oxygen-Methane engine ever hot-fired and remains the lowest cost per pound of thrust large rocket engine ever produced. The engine was successfully tested at the Marshall Space Flight Center in September 2014 before the Army decided to stop development of small launch vehicles and to instead leverage the rapidly maturing small launch vehicle commercial industry.

Kestrel Eye Block II

The Kestrel Eye (KE) concept started in 2005 when Maryland Aerospace, Inc. approached the DARPA regarding the creation of a microsatellite program to provide tactically relevant images to the warfighter. DARPA initiated the program and then transitioned it to SMDC in 2007. SMDC started the Kestrel Eye Block I program in 2008 and the Kestrel Eye Block II Joint Capability Technology Demonstration (JCTD) program in 2013.[5]

The objective of Kestrel Eye Block II was to aid the warfighter by shortening the time from a warfighter request for imaging to the image delivery to the requesting warfighter. This was accomplished by designing a system in which the satellite could, within a single pass: 1) be tasked by the warfighter to take an image 2) take the requested image and 3) downlink the image to the warfighter.[6] This concept is illustrated in Figure 4.[5] To achieve the responsiveness goals, the program pursued the development of a portable, two-part ground system. First, the Kestrel Eye Ground System (KEGS) consisted of a transportable set of equipment for communication with the satellite. Second, GATR Technologies (now a division of CUBIC Corporation) developed a tracking platform for the GATR 2.4-meter antenna to make the GATR-TRAC antenna capable of tracking satellites operating in LEO. As with KEGS, the GATR-TRAC antenna is transportable, which enables the entire ground system to be deployable and allows the warfighter to operate the system in the field. While this operational description discusses a single satellite, the mission of the Kestrel Eye Block II demonstrator was to prove the program objective with a single satellite as a first step to developing a constellation. A constellation of satellites was the ultimate goal as a constellation of low-cost satellites in LEO provides for persistent coverage and graceful degradation where the loss of any individual satellite does not disrupt the overall mission.[5]

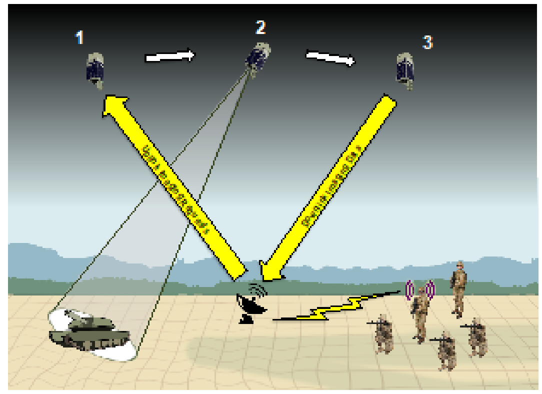

Figure 4. Kestrel Eye Block II Mission Concept

As an imaging satellite, Kestrel Eye Block II centered on the imaging payload. This consisted of a 10-inch telescope developed by Harris Corporation, an industrial commercial off-the-shelf (COTS) camera, and a COTS frame grabber capable of capturing the images from the camera and formatting them as a NITF file. The telescope and camera provided a 1.5 m ground sample distance when operating from the mission design altitude of 500 km. The NITF image format provided for the dissemination and analysis of Kestrel Eye Block II-produced images through tools widely available in the DoD.[5] Like the mission concept, the technical design of Kestrel Eye Block II was based upon filling the mission objective of providing tactically relevant images to the warfighter in a responsive timeline.

On August 14, 2017, Kestrel Eye Block II was launched to the International Space Station (ISS) aboard the Falcon 9 CRS-12 mission. Once all deployment criteria were met, Kestrel Eye Block II was prepared for deployment from the Japanese Experiment Module. The deployment occurred on Oct. 24, 2017. A picture of the deployment of Kestrel Eye Block II from the ISS is shown in Figure 5.[5] Of particular excitement to SMDC, was the Kestrel Eye Block II was deployed by NASA Astronaut Mark Vande Hei, a recently retired U.S. Army colonel from SMDC.[6] After deployment, the satellite went through a series of checkouts culminating in the opening of the aperture door and subsequent imaging on April 28, 2017[7]. From that point, Kestrel Eye Block II was able to meet the command's objectives, provide Soldiers an opportunity to operate it, and to participate in operational demonstrations to evaluate its utility. Overall, the Kestrel Eye concept established that using microsatellites to obtain rapid situational awareness for the warfighter was valid.[8]

Figure 5. Kestrel Eye Deployment from ISS

ACTIVE PROJECTS

Army Cost-Efficient Spaceflight Research Experiments and Demonstrations (ACES RED)

ACES RED is an ongoing flight experiment and demonstration effort to test phenomena, technologies, and concepts for future Science and Technology (S&T) projects that support the U.S. Army Space S&T Roadmap Programs. To date, there are two flight experiments, ACES RED #1 or the Attitude Determination and Control System (ADCS) Flyer, and ACES RED #2

ACES RED #1 is roughly a 3-U cubesat-sized satellite bus containing several experimental payloads. It was designed, fabricated, and tested by SMDC Technical Center engineers from the Concepts Analysis Laboratory. This experiment's primary mission is to gather data on and verify the long-duration performance of COTS technologies in a space environment. The goal is to lower costs for future Army space programs by identifying COTS technologies that are suitable for use in future Army satellites. The primary payload of ACES RED #1 is the Maryland Aerospace MAI-400 ADCS. Other payloads include FPGA-based flight computers, low-cost flight computers (Avnet PicoZed, Atmel microcontroller), global positioning system, low-cost star-tracker, and various internal vehicle diagnostic sensors. [9,10]

ACES RED #1 was launched to the ISS aboard the SpaceX Falcon 9 Commercial Resupply Services 17 mission on May 4, 2020. As a participant in the Department of Defense Space Test Program (STP), ACES RED #1 was integrated on the STP-H6 pallet, which provides the ground team with experiment and reliable reference data for a minimum of one year after being mounted to the ISS.[10, 11]

ACES RED #2 is currently in the development phase of the program and is scheduled to launch in November 2021, again as a part of a DoD Space Test Program mission, STP-H7. ACES RED #2's primary mission is similar to that of the first ACES RED, which is to demonstrate and space qualify COTS hardware, though this time the hardware being tested is for advanced communications rather than ADCS. The primary payload aboard ACES RED #2 is modified COTS hardware that will be used to demonstrate quasi-quantum key distribution and quantum indistinguishability in space.

Several other ACES RED missions are planned for the upcoming decade to expand on the knowledge and experience gained through the ACES RED #1 and #2 missions.

Harbinger

In 2016, SMDC entered into a Cooperative Research and Development Agreement (CRADA) with York Space Systems in Denver, CO, to design and build a low-cost, rapidly developed 150kg-class satellite. York teamed with ICEYE of Finland and integrated ICEYE's high-resolution state-of-the-art imaging Synthetic Aperture Radar (SAR) to demonstrate small satellite near real-time image tasking and collection. The satellite launched successfully in May 2019 aboard a Rocket Lab Electron launch vehicle from Mahia, New Zealand, courtesy of the Space Test Program at Kirtland AFB, NM. Currently, the satellite bus is performing nominally with image tasking and pointing exercises being performed by York Space using an onboard low-resolution optical camera while a SAR payload to bus communication issue is being worked. York Space developed an easy to use graphical user interface (GUI) as an application for smart phones, tablets, and computers, demonstrating real-time satellite tasking and return of state-of-health data from remote locations.

CURRENT PROJECTS

Gunsmoke

Gunsmoke is a capability under development for tactical warfighter situational awareness. Gunsmoke will demonstrate the utility of providing actionable targeting data for long-range precision fires direct to the warfighters. There are two variants of the Gunsmoke effort: J and G. The J variant is a formal Joint Capability Technology Demonstration (JCTD) and will be in a 3U cubesat form factor. The G version is more capable and will be in a 6U cubesat form factor.

Lonestar

Lonestar is a capability under development for space-based situational awareness to the tactical warfighter. Lonestar is a 6U cubesat form factor.

Synthetic Aperture Radar (SAR)

SAR is a capability in development to provide all-weather/all-lighting imaging capability from smallsats in LEO to tactical military users, featuring the direct downlink of data to a remote ground terminal. SAR enables BLOS and long-range precision fires for reconnaissance, surveillance, and target acquisition (RSTA) operations with the ability to operate in denied areas, supporting Multi-Domain Operations.

Next Gen SAR is developing an end-to-end SAR test bed under an Other Transaction Agreement with the Defense Innovation Unit (DIU). This advanced SAR satellite to be employed in the testbed with an objective of shortening the time frame for sensor-to-shooter support.

Tactical Geospatial Intelligence (TacGeo)

TacGeo is a capability being developed to provide an electro-optical/infrared (EO/IR) satellite supporting tactical land component forces. The TacGeo satellite and its supporting elements will demonstrate low-latency EO/IR imagery traceable to rapid delivery to the warfighter. TacGeo has mission objectives of being capable of daylight imaging operations with sufficient resolution and precision to support identification and geolocation of operational level ground targets, being capable of nighttime collects with sufficient resolution to provide battlefield situational awareness to ground commanders, and being capable of direct payload tasking from operational level commanders and direct tasking and downlink through a remote ground terminal commercial standard interface and existing military terminal interfaces.

Polaris

Polaris is a capability being developed to provide tactical land component forces with space-based capabilities enabling Battlefield Situational Awareness and aid in the targeting process in support of force projection and maneuver during Multi-Domain Operations. Polaris provides tactical units with accurate and reliable information in A2/AD or degraded environments.

Sensor to Shooter

The Army is developing Sensor-to-Shooter (S2S) prototypes to enhance mission effectiveness of military personnel and supporting platforms for enhanced targeting systems to enable rapid and responsive multi-layer S2S capabilities for tactical application. The prototype system(s) include technology maturation in the multiple complex and inter-related areas including enabling decision support systems, multi-layer sensor management, dynamic and autonomous taskings and battle management displays and situational awareness (SA). This includes information needed to operate and manage multiple layers to include High Altitude Layer (HAL) and Tactical Space Layer (TSL) capabilities on tactical timelines required to defeat A2/AD targets in contested Multi-Domain Operations. These systems can reduce the timeline for Tasking, Collection, Processing, Exploitation and Dissemination (TCPED) of data to/from multi-layer sensors. These systems will employ data analytics, machine learning, and reasoning to expedite discovery and delivery with high confidence to enable mission execution.

Battle Management Command and Control (BMC2)

During the early years of the previous decade, SMDC satellite programs featured unique ground control designs and architectures for each program. During that time, relatively inexpensive UHF control system antennas and single frequency tuned radio systems were the norm for existing and planned projects. SMDC-ONE thru Kestrel Eye Block II all had dedicated, purpose-built ground systems. Over time, advancements in Software Defined Radios (SDRs), more properly defined as modems, as well as the movement to non-UHF frequency bands drove programs to employ more expensive and capable SDRs and dish antennas. In 2014, SMDC made the decision to pursue the goal of a “common” ground system to be used and reused by successive programs. Consideration and study of the viability and feasibility of available commercial services and Other Government Agency (OGA) support ultimately resulted in SMDC procuring several proven commercial radio systems for conducting operations. In 2017, the SMDC Technical Center established the Payload Demonstration Laboratory (PDL) to provide support to Army LEO S&T small satellite programs as a critical enabler to the capability they demonstrate and also help reduce the risk associated with individual ground station development. The PDL supplies proven commercial ground control software and SDR capability and access to multiple antennas in the S- and X-bands. This supports a primary goal, which is the elimination of the need for each project to develop its own ground station architecture thus freeing budget and focus for the payload development. The PDL plans and conducts on-orbit payload demonstration in support of SMDC Small Satellite programs, as well as conducting pre-mission checkouts, hardware and software validation, and ground control training.

In conjunction with the Redstone Arsenal Garrison, SMDC designed and developed an antenna complex on Redstone Arsenal (Figure 6), which was completed in May 2019. This complex provides a direct connection from the PDL to the antenna for the SMDC small satellite command and control and payload data downlink. Near term plans include the network connection to an OGA network providing several geographically diverse antenna positions as well as development of an offsite antenna location owned by SMDC. This design and near-term plan supports the initiative of providing low-cost, responsive data from space.

Figure 6. Redstone Arsenal Antenna Complex

The PDL will also assist in demonstrating data routing possibilities in simulating direct commands from the tactical site as well as data downlink and distribution. This will demonstrate viability of the ground control station providing information into existing Army networks to be ingested into Army systems.

OTHER DEVELOPMENTS

The interests of Army Space in the last decade have focused primarily on the communications and imaging demonstrations. In addition to these full smallsat missions there have been substantial advancements in Army space-related efforts that have either not yet flown or were commercialized outside the Army. The Army has developed leading-edge capabilities in smallsat class Radio Frequency (RF) and optical communications to include intersatellite and ground-based systems. These can be integrated to work with space systems as well as optical and quantum communication methods. Additionally, there has been substantial research and development done in propulsion systems, articulation of solar arrays, phased arrays, and testbeds for small satellites.

LABS AND PEOPLE

SMDC LABS

In 2015 the Space and Missile Defense Command's Technical Center was designated a Science and Technology Reinvention Laboratory (STRL).[12,13] A significant purpose of the STRL is the performance of research, development, or engineering by employees of the Department of Defense. This designation allows the Technical Center a number of additional authorities and flexibilities for enhanced recruiting and maintaining personnel to staff the labs that are established to support SMDC mission areas.[14] It also provides a mechanism to fund basic and applied research, technology transition, workforce development, and laboratory infrastructure. Brief descriptions of each of the labs that support SMDC's space mission are provided below.

Concepts Analysis Lab

The Concepts Analysis Lab (CAL) is a lab that is staffed primarily by engineers who are very early in their career, typically right out of college. The CAL performs research and engineering projects in support of all of SMDC's mission areas and provides the engineering talent needed to conduct SMDC's on-orbit operations. CAL personnel provided operational support for SMDC-ONE, SNaP, and Kestrel Eye. Given that the satellites operated in LEO, operations occurred day and night with personnel rotating to support the mission. Operations included general contact and state-of-health checks for the satellite, mission planning and tasking, and training operators.[11] Additionally, CAL is engaged in the space mission of SMDC through model and simulation (M&S) support using tools such as Systems Tool Kit (STK). This engagement supports the space mission in two primary ways. First, the STK mission performed by the CAL increases the understanding of space-related concepts in junior engineers and scientists within the Technical Center. In conducting the M&S mission, junior scientists and engineers gain an understanding of orbital mechanics, parameters that effect mission performance, and the functional aspects of subsystems and payloads. This increases the technical competency of SMDC and the ability to perform future space missions successfully. The CAL has grown in capability to support the space mission through M&S support to actual or conceptual missions. The CAL has provided M&S support to on-orbit programs by evaluating pass opportunities (quality and duration) and payload test opportunities to inform mission planning and system evaluation. These analyses have provided information on the feasibility of proposals, mission performance of different constellation architectures, and identification of potential ground station locations.

In addition to M&S and mission support, the CAL has performed multiple design and development projects. The CAL served as the primary source for personnel to design, fabricate, and perform check-outs of the Warfighter Assisting Low Earth Orbit Tracker (WALT) antenna which served as the primary ground station antenna for Kestrel Eye operations.[16] A picture of the WALT antenna is shown in Figure 7. The CAL also performed the design, fabrication testing and delivery of the first ACES-RED experiment, which at the time of writing, is mounted to the ISS collecting data on the performance of non-space-rated COTS hardware in space.

Figure 7. WALT Antenna

QuEST

The Quantum Entanglement and Space Technology (QuEST) lab was established in 2018 to research and demonstrate quantum sciences applications for U.S. Army sensing and communicating capabilities. The Quantum Entanglement and Space Technology or QuEST lab was established in 2018 to research and demonstrate quantum sciences applications for U.S. Army sensing and communicating capabilities. This lab is a collaborative effort between the University of Alabama-Huntsville (UAH) and SMDC and employs a multidisciplinary workforce comprising physicists, engineers and computer scientists. The QuEST lab's current major focus is planning for and developing payloads for upcoming ACES RED #1 and #2 missions.

Position, Navigation and Timing (PNT) Resiliency Lab (PRL)

The PNT Resiliency Lab (PRL) concept was established in 2017 to rapidly assess and develop new technologies, techniques, and prototypes that provide assured PNT to the warfighter and improve navigation warfare capabilities (NAVWAR). The PRL reached initial operating capability in 2019, establishing the ability to simulate, characterize, and develop innovative technologies that assure PNT resiliency to the warfighter.

The PRL increases the effectiveness of the warfighter by providing an efficient, lower cost alternative to expensive field testing for programs/efforts related NAVWAR and assured PNT. Outfitted with state-of-the-art simulation and test equipment, the PRL can conduct evaluation and research of the latest techniques and technologies that can provide an advantage to the warfighter. The PRL is an enabler to the smallsat capabilities by providing a way to rapidly identify and implement improved technologies and validate system requirements. As an example, the PRL provided simulation and test expertise to the Lonestar program to help improve and implement key technical elements and algorithms.

Payload Demonstration Lab (PDL)

The Payload Demonstration Lab concept was established in 2017 to centralize the Command, Control and Telemetry ground infrastructure into a common and shared architecture among SMDC Technical Center small satellites and payloads. The PDL reached initial operating capability in March 2019, establishing it as a critical enabler to the small satellite capability and reducing the risk associated with individual ground station development.

The PDL plans and conducts on-orbit payload demonstration in support of SMDC small satellite programs, as well as conducting pre-mission checkouts, hardware and software validation, and ground control training.

The PDL consists of a primary control node located in the SMDC headquarters and is connected to the Redstone Arsenal Garrison-owned, SMDC-designed and -developed antenna complex on Redstone Arsenal. This complex provides a direct connection from the PDL to the antenna for the SMDC small satellite command and control and payload data downlink.

The PDL will also serve as the communication connection hub to other external networks to add geographical diversity as well as increased contacts for satellite programs.

Figure 8. PDL Team conducting operations during the first pass of Kestrel Eye on orbit

Figure 9. PDL Team installing first antenna in support of Kestrel Eye

Reliable Expandable Satellite Testbed (REST)

The Army developed REST as an operationally relevant hardware-in-the-loop (HWIL) and software-in-the-loop (SWIL) system tailorable and scalable from component to constellation. The testbed allows for rapid definition of mission concepts and tests space technology for tactical application. The framework is built on a highly precise, high fidelity simulation that can include different combinations of components and/or subsystems. REST was designed through a DoD Rapid Innovation Fund Broad Agency Announcement (BAA) that allowed for the system to be developed by the contractor and delivered to SMDC. It was delivered to SMDC in early 2019. Since then, engineers in the CAL have been trained on the system and are gaining the knowledge needed to support future tests. This capability allows in-house large- or small-scale testing of smallsat systems for tactical applications with the goal of increasing mission assurance and reducing risk.

SUMMARIZE ARMY DECADE IN SPACE

The SMDC-ONE launch in December 2010 was a pivotal achievement, demonstrating that small satellites have tactically relevant value to the Army. Subsequent missions gained momentum with the tipping point achieved on the Kestrel Eye Block II mission. It is finally well accepted that small satellites can be a useful and viable tactical layer supporting the national defense. Through these smallsat missions and the lessons learned the Army developed the Army Tactical Space Strategy nested within and supportive of the National Defense Strategy (NDS).[3]

SMDC is the Army Force modernization proponent for space, high altitude (HA) and ground-based midcourse defense (GMD). Two of SMDC's missions are to provide research and development of materiel solutions as well as combat development solutions in support of the prompt global strike and air and missile defense missions; and conducts mission-related research and development. Over the past decade, SMDC has conducted science and technology research to demonstrate space-based technologies capable of being operated on small satellite constellations in LEO for tactical defense applications. Capabilities include ISR, Battlefield Management Command and Control (BMC2), communications, and assured PNT supporting Army combat operations in contested MDO. Other projects develop smallsat LEO payloads to aid in the targeting process to enable rapid and responsive sensor-to-shooter capability.

CONCLUSION

The character of war has changed. Where the fight occurs, how forces fight, what doctrine applies, and what weapons are needed all change over time. The Army is facing the rise of great power competition. The introduction of precision-guided munitions, the internet, and widespread and prolific use of computers, information technology and space-based systems enabled the change. In the future, new technologies such as hypersonics, artificial intelligence, supercomputing and robotics will accelerate the change. The Army of 2028 and beyond must be ready to deploy, fight, and win decisively against any adversary, anytime, and anywhere, in a joint, multi-domain, high-intensity conflict.

In the future operational environment, adaptable peer adversaries will employ innovative combinations of conventional and irregular forces to challenge U.S. operations in every domain, to include the space domain. Potential adversaries are investing in technologies to achieve overmatch against U.S. systems. Potential adversaries are also expanding the battlefield geographically because the effects of their multi-domain capabilities are less bound by geographic and time constraints and extend the range in which formations are under threat.

According to the 2018 National Defense Strategy the main emphasis and focus for U.S. forces are threat actors who combine traditional operations, hybrid strategies, and asymmetric warfare tactics with new technologies and capabilities that prevent, stall, or complicate the U.S. ability to bring forces to bear thereby permitting adversaries to achieve their political objectives. Irregular operations will allow adversaries to operate at times and places of their choosing, often in concert with proxies, terrorists, or criminal activities, operating within the "Gray Zone" at a level below the threshold of warfare to target the will of a national population or the decision-making apparatus of a nation-state or an international organization/alliance. This challenges U.S. forces' ability to shape the strategic and operational environments in opposition to adversarial activities, and again, may present an unfavorable cost-benefit equation to U.S. political leaders.

The Army lacks sufficient protected tactical communications; assured PNT; deep sensing and rapid, responsive long-range targeting capabilities; and advanced processing to support tactically responsive operations in the new contested operational environment. The future of warfare is characterized as faster and at longer ranges; is more destructive; targets civilians and military equally across the physical, cognitive, and moral dimensions; and if waged effectively, secures its objectives well before actual battle is joined.

Currently, the Army's organic sensors lack the range, persistence, accuracy, survivability, and timeliness sense and understanding across the depth and breadth of the multi-domain battlespace to reveal threat intentions, strategies, capabilities, and tactics of a peer adversary. Technical advancements in low-cost, small satellite technology has opened a new domain for tactical units to benefit from space assets. The advances enable a future Tactical Space Layer to provide protected high-bandwidth, low latency communications, near-real-time Multi-Domain Intelligence (MDI), complementary PNT, and Sensor-to-Shooter solutions to equip the MDO-Capable Force by 2028 and the MDO-Ready Force by 2035.

The Army's LEO Space Strategy approved by the Vice Chief of Staff of the Army and the Undersecretary of the Army in August 2018 was designed to provide tactical land component forces with the Tactical Space Layer capabilities to enable battlefield situational awareness and understanding and aid in the targeting process in support of force projection and maneuver during MDO. The LEO Space Strategy will extend the Army's ability to sense at deep ranges and enable BLOS tactical network and communications capability using commercial space, military satellite communications, LEO tactical communications, DoD & Intelligence Community enterprise investments, and commercial remote sensing mega-constellations.

Tactical Space Layer capabilities will provide deep area sensing and rapid targeting systems that will be available in daylight, night, and poor weather to land component commanders and weapons platforms. An objective Tactical Space Layer architecture will incorporate artificial intelligence and machine learning to the maximum extent possible for distributed mission execution, reduced Soldier burden, automated constellation management, and enable rapid Sensor-to-Shooter capabilities.

Technology demonstrations like DARPA's Blackjack program will showcase the ability to create a highly networked, resilient, and persistent DoD capability to provide over-the-horizon sensing, signals, and communications to hold ground, maritime, and air domains under constant custody. The Space Development Agency's (SDA) layered architecture will operationalize the Blackjack demonstration and provide viable warfighter persistence to support MDO.

The Army's multi-domain formations will possess the combination of capacity, capability, and endurance, which generate the resilience necessary to operate across multiple domains. The Army will need Ground Stations capable of leveraging the SDA-layered architecture and other space-based sensing sources to provide near-real time information to fires systems across the battlefield in a modular, scalable form factor supporting formations from Brigades to Corps. These expeditionary and mobile ground stations will enable cross-domain fires with Artificial Intelligence (AI) shorten kill-chains and provide assured access to current and future National, Commercial, and multi-Service, space-based assets.

All Army formations will have the capability to conduct independent maneuver, employ cross-domain fires, and maximize human potential. The combination of these capabilities will allow both offensive and defensive operations in contested spaces against a near-peer adversary. Finally, Army formations will be able to converge capabilities in all domains to optimize effects to overmatch the enemy through cross-domain synergy including the space domain. The Army will rely on future space-based systems as outlined in the paper as part of a modernized organization ready to deploy, fight, and win decisively against any adversary, anytime and anywhere, in a joint, multi-domain, high intensity conflict.

The U.S. Army has been a voracious user of space-based data, developing a heavy dependence on military and commercial space systems for communications, command and control, reconnaissance, and weather information since the 1970s. Army Space will continue to play a strong role supporting the Army's modernization to an MDO-Ready force by 2035. Continued S&T investments to maximize the Army's return on space capabilities will provide the foundation for long-term overmatch against near-peer adversaries. Convergence, a key tenant of MDO, is the rapid and continuous integration of capabilities in all domains that optimizes effects to overmatch the enemy through cross-domain synergy and multiple forms of attached all enabled by mission command and disciplined initiative. Army space forces will continue to modernize to maximize space support to convergence in MDO. Lastly, Army Space will continue to innovate with joint and interagency partners to ensure future sensors have the range, persistence, accuracy, survivability, and timeliness to enable long-range precision fires to accurately identify and engage targets within tactical timelines.

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