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SMDC-ONE:

An Army Nanosatellite Technology Demonstration

David J. Weeks
COLSA, Inc.
SMDC-RDT-TP, Von Braun Complex, Bldg 5220, Martin Rd, Redstone Arsenal, AL 35898; (256) 955-0476
david.weeks@smdc.army.mil

A. Brent Marley
Cobham Analytical Services, Inc.
SMDC-RDT-TP, Von Braun Complex, Bldg 5220, Martin Rd, Redstone Arsenal, AL 35898; (256) 955-5702
brent.marley@smdc.army.mil

John R. London III
US Army Space and Missile Defense Command/Army Forces Strategic Command, Technical Center SMDC-RDT-TP, Von Braun Complex, Bldg 5220, Martin Rd, Redstone Arsenal, AL 35898; (256) 955-5287
john.london@smdc.army.mil

ABSTRACT

Our nation has a truly impressive array of space-based capabilities supporting our armed forces. However, much of this support is focused at the strategic and operational levels of war. There are several areas of desired improvement in the space force enhancement mission area at the tactical level of war that could be addressed by small, inexpensive satellites dedicated for use by tactical land warfighters. One of these areas of desired improvement is tactical beyond-line-of-sight (BLOS) communications, including support for ground sensors, text message relay, voice communications, and image or video transmission. Technical solutions to fill these areas of desired improvement should be relatively inexpensive, and more importantly, taskable by tactical users in the area of operations.

New trends in the miniaturization of electronic components are leading to smaller satellites with significant capabilities in the nanosatellite (1-10 kg) and microsat (10-100 kg) classes. For example, the CubeSat standard for nanosatellites now being built by universities around the world is based on tiny cube-shaped satellites with dimensions of only 10cm on a side and weighing about 1 kg. Slightly larger nanosatellite configurations, with multiple cube formats, allowing for missions from low earth orbit with broader scopes are under investigation by organizations such as NASA, Boeing, and the US Army.

One technical approach that could address today's tactical BLOS communications area of desired improvement for the tactical warfighter would be a constellation of nanosatellites in low earth orbit. To investigate the feasibility of such a constellation, the US Army Space and Missile Defense Command/Army Forces Strategic Command (USASMDC/ARSTRAT) is executing the Space and Missile Defense Command – Operational Nanosatellite Effect, or SMDC-ONE, technology demonstration. The key SMDC-ONE demonstration thresholds for success involve designing, developing, building and qualification testing of two nanosatellite units, and acceptance testing of eight flight units within a one-year timeframe ending in April 2009. A custom communications payload will deliver a capability to support simulated ground sensors and text message relay. Communications beyond this level of complexity were not included in this demonstration to reduce schedule risk. SMDC-ONE can help establish the case for inexpensive space force enhancement for the tactical warfighter through relatively inexpensive, rapidly developed nanosatellite constellations.

INTRODUCTION

The United States Army is the largest user of space systems within the Department of Defense. Despite this heavy dependence on data from space, the Army has historically elected to leverage space systems. The last Army-developed satellite, until now, was the Courier 1B, a communications satellite launched on 4 October 1960. The Army has and will continue to depend on existing and future "big space" systems to conduct the full spectrum of combat operations.

As the Army combat regime evolves from a Cold War set piece engagement modality to today's environment of asymmetric warfare and continuous multi-theater operations, a number of single requirement niche operations in localized areas have emerged that are either underserved or not supported at all by current satellites. Unmanned Aerial Vehicles (UAVs) have become ubiquitous in addressing some of these operational gaps, and the Operationally Responsive Space (ORS) Office was formed to focus technologies to meet warfighter needs more responsively with lower cost and more rapidly fielded space systems.

Concurrent with the changing nature of Army combat operations is the rapid advancement of many technologies, particularly in the field of electronics miniaturization, that have opened the door for small, highly affordable satellites designed to perform limited niche missions. These tremendous technical advances were first exploited in this country by universities seeking to rapidly develop satellites and at very low cost for educational purposes. The CubeSat emerged as the standard for many academic institutions seeking to place student projects into space quickly and inexpensively. Although valued greatly by the academic community, CubeSat-class satellites were initially viewed by most traditional satellite developers and users as having little practical value.

One of the major shortcomings of satellites is that individually they do not provide a persistent presence over a specific geographic area of the earth – Keplerian physics demands otherwise. A notable exception of course is geosynchronous satellites, but these satellites are typically very large, very expensive to build and to launch into their requisite orbits, and are severely impacted by electromagnetic radiation attenuation over geosynchronous altitude distances. From a systems standpoint, global persistence can only be achieved by the use of multiple satellites in a constellation. The best example of this kind of persistence is the Global Positioning System (GPS) that is always available to any user worldwide.

Taking all of these realities into account, the CubeSat-class satellite today offers a unique opportunity to address certain mission requirements for the Army. From an individual satellite standpoint, this class of space vehicle can be developed rapidly within the ORS Tier 3 timeline at very low unit cost. Potentially they can be deployed individually to address a specific mission need, although they would likely be in low earth orbit (LEO) and their revisit periodicity would be infrequent. From a systems standpoint, CubeSats can be proliferated inexpensively into constellations that would achieve useful and affordable persistence over multiple regions of interest to the Army. It is important to recognize that a number of possible constellations may not be required by the Army to provide global coverage. Since the Army's geographic focus may not stretch to the earth's poles for many missions, constellations of CubeSats can be limited in number to provide coverage in latitudinal swaths that address specific regions of interest at greatly reduced cost.

Constellations of CubeSats could be sufficiently affordable to allow application against a specific mission need in a limited geographical area. Such constellations would have additional benefits such as being highly survivable, amenable to being frequently refreshed with technology advances due to shorter on-orbit life expectancy, low detection probability, able to leverage manufacturing economies of scale, having good signal strength in LEO, and having the potential for being rapidly reconstituted on a per-unit basis.

Based on the promise that CubeSats potentially held for the Army, and because of urgent requirements gaps that this class of satellite could address, the Army's Space and Missile Defense Command decided in the Spring of 2008 to once again move the Army into the satellite development arena. This paper will describe the twelve-month effort that took a government organization and its industry partner, neither of which had ever developed a satellite, from a standing start to the delivery of eight flight-qualified nanosatellites designed to address a specific warfighter mission need.

OPERATIONAL NEED: BEYOND-LINE-OF-SIGHT COMMUNICATIONS

On today's battlefield, the tactical land warfighter does not always get the exact communications support he or she desires from the existing constellations of large, expensive military and commercial communications satellites in geosynchronous orbits. These large satellites are very effective at providing communications at the operational and strategic levels of war, but less so at the tactical level. Modern tactical-level land combat systems are increasingly dependent on networked communications for command and control (C2) of forces as well as dissemination of intelligence data in text, voice, image and video formats. Often these types of data must be transmitted to users at the tactical level by line-of-sight terrestrial communications links. Line-of-sight communications are often limited by factors such as the distance between units and signal blockage by terrain. Beyond-line-of-sight communications via satellites can overcome many of the disadvantages of line-of-sight communications. Constellations of satellites dedicated to tactical warfighters would greatly benefit command, control and communications as well as intelligence data dissemination to tactical land forces.

There is an emerging niche for satellites focused on tactical missions such as data exfiltration from ground sensors, text message relay, voice communications and image and video transmission. Data exfiltration and text messaging are both fairly low data rate satellite communications applications and are relatively straightforward technologically.

Voice communications via satellite with its higher data rates are more complex technologically. Tactical land warfighters are usually equipped with limited communications systems with relatively low power outputs and low gain antennas. These tactical communications systems are not generally designed for use with geosynchronous satellites at altitudes of 22,300 miles (36,000 kilometers) but would be powerful enough for transmitting to low earth orbit (LEO) altitudes of around 250 miles (400 kilometers). For non-time critical data exfiltration and text relay, a small number of store-and-forward satellites in LEO would suffice. On the other hand, real-time data exfiltration and text relay as well as voice communications would require many satellites in LEO in several orbital planes to provide the necessary persistent coverage.

For voice communications especially, the satellites would probably require a switching capability from satellite to satellite. This switching capability is analogous to the seamless switching from one cell phone tower coverage area to the adjacent area as one moves overland while using a cell phone. The commercial Iridium LEO communications satellite constellation has this capability. However, such a switching capability drives up satellite complexity and cost. Transmissions of images and video via satellite requires even higher data rates which drive higher satellite power level requirements with the attendant increases in satellite complexity and cost.

To be practical in terms of utility to the tactical warfighter, satellites used for beyond-line-of-sight communications must have an intuitive user segment that is simple to use. Ideally any new satellites should simply be interoperable with existing hand-held or mobile communications equipment. The satellites should also be available 24/7 to be truly usable everywhere within a given area. Because a large constellation would be needed, individual satellite unit cost would need to be low, in the range of a few hundreds of thousands of dollars. Finally, the satellites should be responsively deployable and easily replenishable on orbit in accordance with the rapid deployment principles put forth by the Department of Defense's Operationally Responsive Space Office.

TECHNICAL APPROACH: LOW EARTH ORBIT NANOSATELLITE CONSTELLATION

The US Army Space and Missile Defense Command/Army Forces Strategic Command (USASMDC/ARSTRAT) chose to explore the capabilities of the nanosat class of satellites in meeting the needs of the warfighter. The initial focus was on communications with emphasis on data exfiltration; that is, to uplink data of interest from ground sensors and then downlink that data to a site beyond the line of sight from the originating sensor location. While there are military and commercial assets that can and do routinely provide communications from warfighters in one area to another location within or outside that theater, the challenge for the soldier in the field is to obtain the critical data that he or she needs in a timely manner. It would be strongly advantageous for land warfighters to have their own space assets to provide beyond-line-of-sight (BLOS) communications.

The approach that USASMDC/ARSTRAT took for its first indigenous satellite program is to explore the nanosat (0-10 kg) class while using the Cal Poly CubeSat form. The SMDC-ONE program earlier this year completed the construction and testing of one qualification nanosat followed by eight flight nanosats. Each is designed to be deployed from a Poly-Picosatellite Orbital Dispenser (P-POD). The qualification unit underwent rigorous shock, random vibration and thermal-vacuum testing at the prime contractor and NASA locations. Thermal balancing and antenna deployment tests were conducted during thermal-vacuum testing at the prime contractor's location. Radio frequency characterization testing was conducted at US Army facilities. Careful coordination was conducted with Cal Poly, Stanford University and SRI International representatives to ensure conformity with the Cal Poly standards and leveraging of their experiences with CubeSats.

Choice of the CubeSat Form

Nanosats were selected as the appropriate satellite mass class for several reasons. These lightweight payloads have numerous piggy backing opportunities and invite the development of a low-cost launcher designed for nanosatellites. Such a launcher could offer responsive insertion of CubeSats into desired orbits within a matter of days or even hours given pre-approved trajectories and range readiness.

CubeSat standards greatly facilitate the integration of these satellites with most US launch vehicles. The Minotaur I and Falcon I vehicles have already been used to launch CubeSats from the Wallops Flight Facility on Virginia's Eastern Shores and from the Reagan Test Site in the Marshall Islands. Another reason for using CubeSats is their relatively low-cost for development and launch. Low mass and volume force an early system approach. Payload mass has traditionally had a high correlation with development cost for spacecraft. Final integration of the CubeSats with the launch vehicle can be performed in a matter of weeks or even days.

Universities have performed a tremendous service in their CubeSat development programs. Not only are they providing hands-on experience for their students but are training up the next generation of aerospace engineers who will develop new and improved technologies as well as discover new applications for these very small satellites.

Table 1: Academia Involvement in CubeSats (partial listing)

Institutions with CubeSat Involvement		
Arizona	Arizona State	Auburn
Boston Univ.	California-Irvine	Cal Poly
Central Florida	Colorado Space Grant Consortium	Cornell
Dartmouth	Florida	Hawaii
Illinois	Iowa Space Grant Consortium	Kansas
Kentucky Consortium	Louisiana	Michigan
Montana State	San Jose State	Santa Clara
Stanford	Texas A&M	Thomas Jefferson High School for Science & Technology in Virginia
Washington		

CubeSats have now been developed at many universities and even high schools (see Table 1) and by many nations (see Table 2). These tables are not exhaustive but give an indication of the extent of the CubeSat playing field.

The United States Government has also elected to play a role in the CubeSat arena including those listed below in Table 3. The federal government is looking at those cases where smaller might be better. Classes of very small satellites allow opportunities for low-cost involvement, experimentation, relatively low-cost for development and fairly inexpensive rides to space. As with any piggybacking into space, you go where the primary payload is headed and you go when the primary payload is ready and under any conditions that the primary payload levies.

Table 2: International Involvement in CubeSats (partial listing)

Nations with CubeSat Involvement		
Belgium	Canada	Columbia
Denmark	England	France
Germany	Holland	Italy
Japan	Norway	Poland
Romania	South Korea	Spain
Switzerland	Turkey	

Table 3: US Government Organizations Involvement or Strong Interest in CubeSats (partial listing)

Government Organizations with CubeSat Involvement		
Aerospace Corporation	Air Force Academy	Air Force Research Laboratory
Air Force Space and Missile Systems Center	Army Space and Missile Defense Command/Army Forces Strategic Command	Defense Advanced Research Projects Agency
NASA Ames Research Center	NASA Goddard Space Flight Center	NASA Marshall Space Flight Center
Naval Post Graduate School	Naval Research Laboratory	National Reconnaissance Office
National Security Agency	National Science Foundation	Operationally Responsive Space Office
Office of the Secretary of Defense (Pentagon)		

University CubeSat program lessons learned and commercially available Pumpkin, Inc. CubeSat kits for early orientation are leveraged. Going into low earth orbit (LEO) may often mean low altitudes with relatively short orbital lifetimes. Short orbital lifetimes may be sufficient for experimentation. For SMDC-ONE, the design life is one year on orbit while the minimum success criteria is six months. Short lifetimes provide opportunities for performance improvements and technology refresh between some of the launches.

Within industry, Boeing has been involved for several years now and has a system still in orbit after over two years in space. Many in the government are waiting to see when nanosats prove to be commercially viable. In the meantime they are skeptical, but cautiously await early results from government CubeSat programs. Overall, government interest in these satellites is escalating.

The SMDC-ONE Design Approach

SMDC-ONE took the approach of finding a design solution somewhere in between what most universities adopt, where the student learning experience may be paramount, and the traditional Department of Defense and NASA standards involving high standards of quality assurance and documentation. Still, no shortcuts were taken on configuration management or documenting each action taken on the satellite units and circuit boards utilized commercial-off-the-shelf parts.

Early usage of a mass simulator and a stereo lithography assembly (SLA) were highly leveraged by the prime contractor, Miltec Corporation, (see Figure 1). Both units were in demand by various parts of the SMDC-ONE team. The SLA was particularly helpful in determine cable lengths and routing.

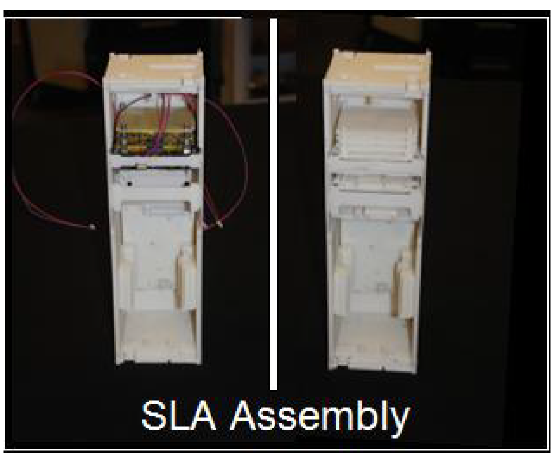

Figure 1: Stereo Lithography Assembly of the SMDC-ONE Satellite

Major satellite components are depicted in Figure 2 below. A gyro module is also in the spacecraft but is not used by any controls (it was added as an experiment).

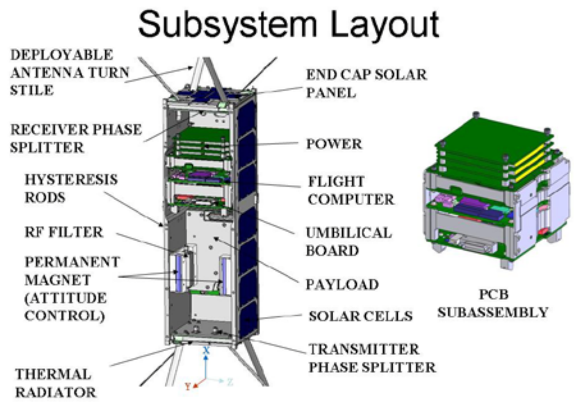

Figure 2: SMDC-ONE Subsystem Layout

SMDC-ONE Environmental Testing

Two qualification units were built and tested in a rigorous fashion. Qual Unit #1 passed shock qualification levels at NASA's Marshall Space Flight Center without issue (see Figure 3). However, random-vibration testing at Miltec's Iuka Mississippi facility shook loose a discrete component on a space environment-designed board provided by a vendor. That component was then carefully staked more fully on all other existing boards. Qual Unit #1 was then converted to a back up unit while awaiting a replacement board as the component was completely separated from the board. With improvements made, Qual Unit #2 became the lead qualification unit and underwent shock testing, random-vibration testing and thermal-vacuum testing.

Figure 3: Shock Testing at NASA Mashall Space Flight Center

During random-vibration testing, a real-time clock module lost electrical connectivity with its battery (see Figure 4). The module was then carefully potted on Qual Unit #2 as well as on all the other units (Flight Units 1-8 and Qual Unit #1) before qualification testing resumed.

Figure 4: Random Vibration Testing at Miltec's Iuka, MS Facility

Thermal balancing was performed during thermal-vacuum conditions to verify on-orbit predictions (see Figure 5). With a fully qualified spacecraft design, the flight units began acceptance testing for random-vibration and thermal-vacuum conditions.

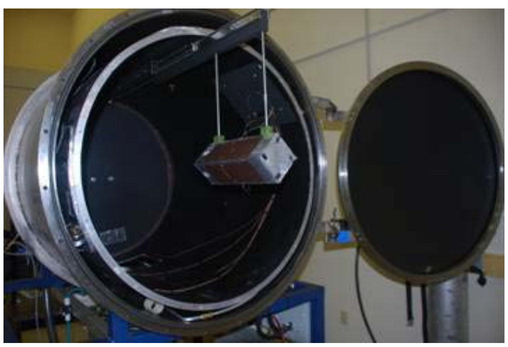

Figure 5: Thermal-Vacuum Testing at Miltec's Huntsville Facility

SMDC-ONE uses a custom UHF-VHF transceiver. The antenna radiation patterns were identified through testing at the Army's Aviation and Missile Research, Development and Engineering Center (AMRDEC) Unconventional Beam Office test facility. Operating frequencies have been requested through the Army Spectrum Management Office. Of course, frequency allocation is a complex process and was not yet established at the date of this writing.

SMDC-ONE Concept of Operations

The objective of the first flight demonstration involves a single SMDC-ONE satellite which will receive its tasking from the Forward Operating Base (FOB) or Command and Control (C2) station as shown in Figure 6. The early SMDC-ONE satellites do not have on-board GPS, so the tasking and timing information will be provided from the C2 station after preliminary on-orbit checkout of the satellite occurs. The program is planning to have two C2 stations, one at USASMDC/ARSTRAT Headquarters in Huntsville, AL and the other at USASMDC/ARSTRAT's Battle Lab in Colorado Springs. The first demonstration consists of simulated sensor data transmitted from one or both of the C2 stations. The tasking data and other data files will be received by the satellite (as its ground track covers Huntsville and/or Colorado Springs), stored on-board, and then transmitted to the C2 station(s) as directed.

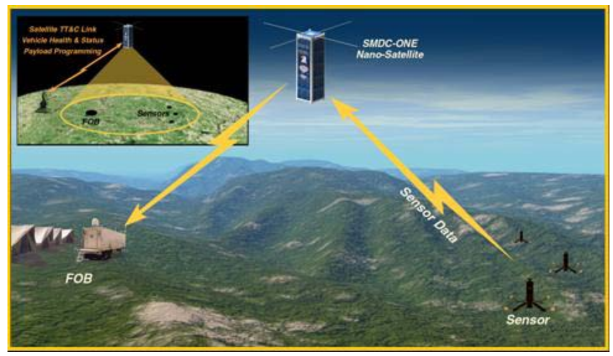

Figure 6: SMDC-ONE Operational View 1 (OV-1)

On some orbits the ground track will cover both C2 stations which are separated by 1200 miles. A text message will be transmitted from the first station in the ground track and quickly relayed to the second station. In some cases the ground track will first cover Huntsville while in others, Colorado Springs will come into satellite view first.

After initial on-orbit checkout of the satellite by the prime contractor (Miltec) and USASMDC/ARSTRAT personnel is completed, testing and experiments will be conducted by the Space and Missile Defense Future Warfare Center's Battle Lab. Both ground segments (Huntsville and Colorado Springs) will be used in the checkout and experimentation phases.

Schedule

Schedule was a primary driver in delivering SMDC-ONE. The USASMDC/ARSTRAT Commanding General directed in April 2008, that the SMDC-ONE nanosatellites would be built and the command had twelve months to build and test the satellites. Twelve months is a short period of time when working within federal government and aerospace industry strictures. Procurements and contracts consumed valuable time but on April 28th, 2009 the satellites were delivered to USASMDC/ARSTRAT by Miltec. Following that presentation, the nanosats remained at Miltec for battery discharge monitoring, software upgrades and small improvements to ensure spacecraft reliability.

Lessons Learned

There were many lessons learned during this development program. These included:

- Difficulty of working through the International Traffic in Arms Regulations (ITAR) – some components were supplied from an overseas vendor; when testing failures revealed issues, ITAR restricted the program from providing specifics to the vendor which would have helped the vendor to provide higher quality components. If possible, find domestic suppliers as ITAR issues consume time and funds.
- Early prototype boards are highly desirable.
- Early SLA models and mass simulators are also very beneficial.
- Environmental testing will likely uncover new issues (success-driven test schedules are not likely to work).
- Identify and prioritize requirements/objectives early and gain agreement from all stakeholders.
- If at all possible, find local vendors for spinning the circuit card assemblies with populated components.
- In a 9-12 month development period, there is precious little time for subcontracts – start early and be persistent in getting subcontracts awarded.
- Have an expediter to get purchase orders and subcontracts through the procurement system.
- Quality assurance and configuration management is important though it does slow things down.
- Work early on qualification and acceptance test documents (plans and procedures) with customer buy-in.
- When working with CubeSats and P-PODs, work to the standards, not the measured volume within the P-POD.
- Ensure that the stakeholders have a common and consistent set of expectations.

Future Plans

As for future plans, the program is planning a Block II upgrade which would include:

- Reaction wheels for increased platform stability
- On-board GPS
- Software defined radio on PC-104 cards for increased mission flexibility and low-volume usage
- S-band for data uplink and downlink (to include short video clips)
- UHF capability (retained from block one)
- Multiple satellites for the next flight demonstration

SMDC-ONE DESIGN

Miltec leveraged an existing space vehicle development contract with the Army's Space and Missile Defense Command for SMDC-ONE. Though Miltec had an extensive heritage in the missile industry, this was this first effort in satellites.

A stakeholder within USASMDC/ARSTRAT had pre-identified the communications element vendor due to operational experience, so efforts began immediately to bring the Pericle Communications Company under contract. This same stakeholder also identified the 3-U CubeSat form with the P-POD deployer as the best choice for this technical demonstration. It was also recommended that Miltec utilize Cal Poly and Stanford as consultants to leverage their CubeSat and P-POD experience and knowledge. The design approach was to keep the design as simple (yet robust) as possible. Originally it was thought that all eight SMDC-ONE nanosatellites would be launched together. Later the first ride materialized, providing room for a single SMDC-ONE spacecraft. At the onset of the program, it was assumed that the selected orbit would support at least a year on-orbit of operational life. Early objectives of the SMDC-ONE program are shown in Table 4 below.

Schedule was a strong driver for the USASMDC/ARSTRAT Commanding General. By the Preliminary Design Review, which was conducted about five months into the year long development cycle, an original program objective, S-band communications, had to be pushed to future versions of the spacecraft due to time constraints.

To help keep things simple, canted turnstile antennas were selected for the design. There are four VHF transmitting antennas on one end of the satellite and four UHF receiving antennas on the other end. To keep integration as simple as possible, the P-POD deployer is being used. Originally designed for approximately 3 kg mass, the satellite was allowed to grow to 4 kg in order to extend operational life on orbit.

The custom transceiver has good performance and should be able to relay simulated ground sensor (GS) data files including images to the C2 station for the first demonstration of a single SMDC-ONE satellite. Other files including text messages can also be sent within theater. Also, the satellite's electrical power system has significant margin.

Table 4: SMDC-ONE Program Objectives

Mission Objectives	Minimum Success Criteria	Reality
Demonstrate ability to rapidly design and develop militarily relevant low-cost spacecraft	Design, develop & deliver 8 SMDC-ONE satellite systems within 12 months with hardware cost ≤ $350k each	Eight flight units were delivered in a year with hardware costs of less than $350k each. Follow up work continues on the satellites while awaiting launch.
Receive packetized data from multiple Ground Sensors (GS). Transmit that data to ground stations within the SMDC-ONE ground track.	Receive GS signal on two or more SMDC-ONE satellites and successfully relay that signal to a deployed ground station	GS data will be simulated for the first demonstration flight by using GS-like data files on a laptop computer.
Provide real-time voice and text message data to and from field deployed tactical radio systems	Not required for mission success	Text message data from a ground station laptop will be uplinked to the satellite and then downlinked. The originating program stakeholder decided deployed tactical radios were not necessary for the demonstration.
Demonstrate SMDC-ONE operational life of 12 months or longer	Demonstrate an on-orbit operational life of 6 months or longer	Initial provided orbit appears to be a fairly short duration orbit.

The ground segments are now under development and should be delivered to their operational locations by the time the 2009 Small Satellite Conference in Logan, Utah begins (10-13 August 2009). Data exfilration appears to be an excellent application for these nanosats.

CONCLUSIONS

Though yet to fly, the SMDC-ONE technology demonstration will help establish the case for inexpensive space support to the tactical warfighter through relatively low-cost and responsively developed nanosatellites and ground segments. Though low-cost, these nanosatellites should be reliable spacecraft for life on orbit of up to two years. Areas of further development which would greatly benefit nanosatellites are increased electrical power and a propulsion system. Though SMDC-ONE does not employ a propulsion system, constellation station keeping will require a low-mass/volume propulsion system sufficient for two-year life on-orbit. Development of custom transceivers greatly drive up the cost of the flight and ground segments. Hardware costs are not the primary driver in either development or production of nanosatellites if components are customized. Simple designs should reduce labor costs and thereby greatly contain overall nanosat cost. Twelve month development schedules may drive satellite performance tradeoffs.

Low-cost nanosats give up long life on orbit with their normal design life of one to two years. Reliability may be somewhat lower than more expensive satellites as nanosats normally do not have hardware redundancy or elaborate software schemes to accommodate single event upsets or other space environmental effects. However, these extremely lightweight satellites are associated with quick, low-cost development cycles, relative ease in catching a ride to orbit, low-cost operations on orbit, and the potential to exfiltrate sensor data and get it to the warfighter. Appropriate constellations of nanosats in low earth orbit can provide a high degree of persistence for the warfighter, which he or she can depend upon, much as the GPS is mostly taken for granted today. The presence of a proliferated constellation of relatively short life nanosatellites allow for technology refresh opportunities and are problematic to adversaries who might want to eliminate nanosat support to the warfighter.