Abstract for

18^{th} ICCRTS

"C2 in Underdeveloped, Degraded and Denied Operational Environments"

For paper entitled:

C2 of Next-Generation Satellites

Topics:
Topic 7: Architectures, Technologies, and Tools
Topic 3: Data, Information and Knowledge
Topic 1: Concepts, Theory and Policy

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Space systems have come to be used so extensively that it is almost impossible to imagine tomorrow's military operating without the strategic, operational, and tactical advantages that they offer. In the words of then-Deputy Secretary of Defense William Lynn, "Space systems enable our modern way of war. They allow our warfighters to strike with precision, to navigate with accuracy, to communicate with certainty, and to see the battlefield with clarity." Assured command and control (C2) of space systems is the assumption underlying the provision of these capabilities.

While nanosatellites are a promising area of development, their assured C2 strained at best due to communications shortfalls. A reliable, secure, low-power cross-link would allow many space missions to be conducted by nanosatellites, while reducing the program cost. We will show how this can be achieved leveraging the MUOS constellation to create a "cross-link" for nanosatellites, which would allow them to provide a resilient capability with an affordable price tag.

C2 of Next-Generation Satellites

Perspective

Since the launch of Sputnik I in 1957 ushered in the dawn of the space age, space activities have transformed from a novel symbol of national power into vital drivers of political, military, technological and scientific developments. The United States has exerted a leadership role in space capabilities, which have become inseparably linked to our national security, providing "the United States and our allies unprecedented advantages in national decision-making, military operations, and homeland security."[1] They undergird modern military concepts and operations, providing essential position, navigation and timing (PNT) data, reliable communications, and robust intelligence, surveillance and reconnaissance (ISR) information. Each of these three capabilities is itself an enabler of modern combat operations, but together they are even more valuable. The complementary employment of these capabilities fundamentally undergirds the U.S.' ability to command and control its military forces – an ability that is increasingly revealed as our nation's most powerful strategic advantage in the face of growing asymmetric threats and the rise of near-peer competitors.

Although the United States has long enjoyed a leadership role in the space domain, we cannot assume that this advantage will automatically continue. As described in the *National Security Space Strategy*, the space domain is becoming increasingly contested, congested and competitive. The U.S.' space assets are at risk from intentional adversary actions as well as unintentional man-made threats and natural occurrences. Moreover, these issues are exacerbated by the constrained fiscal environment faced by the nation and the DoD, which will pose a significant challenge to space-related research and development as well as the fielding of new capabilities.

In short, sustaining the United States' advantage in the space domain has never been so crucial to our national security, or so seriously challenged on so many different fronts simultaneously. In order to adapt to this changing environment – and continue to dominate it – the United States cannot simply pursue the same approaches that have been successful for the past 50 years. Novel concepts and capabilities are required. Among the most promising is the rise of CubeSat technology – standardized, affordable nanosatellites able to perform space missions that have traditionally only been performed by large satellites and satellite constellations. CubeSats represent a game-changing technology; however, while their payloads and busses have seen enormous investment and development, CubeSats will only fulfill their enormous potential if a low-cost command and control (C2) capability is available to operate them.

Strategic Environment

The "Three C's"

[1] *National Security Space Strategy* (Washington, D.C., Department of Defense and Office of the Director of National Intelligence), January 2011.

As outlined in the *National Security Space Strategy*, the strategic environment is driven by three trends – the space domain is becoming increasingly congested, contested, and competitive as more nations and non-state actors recognize its advantages and pursue their own space and/or counterspace capabilities. The congested nature of the space domain is the simplest issue to quantify. In stark contrast to the handful of nations operating in space 50 years ago, today there are over 60 nations and government consortia that own and operate satellites – not to mention the plethora of commercial and academic satellite operators.[2] As a result of their activities, the Joint Space Operations Center (JSpOC) currently tracks approximately 22,000 man-made objects in orbit that are ten centimeters or larger, of which about five percent (1,100) are active payloads or satellites, eight percent (1,760) are rocket bodies, and the vast majority – 87 percent, or 19,140 – are debris and inactive satellites.[3] In addition, there may be as many as hundreds of thousands of additional pieces of debris that are currently too small to track. Each of these objects has the potential to damage satellites in orbit, as in the 2009 collision between a Russian government Cosmos satellite and a U.S. commercial Iridium satellite. Not only does this risk of collision threaten national space capabilities, but it also vastly increases the overall quantity of orbital debris – the 2009 collision was estimated to create approximately 1,500 new pieces of trackable space debris.

The space domain is becoming increasingly congested in terms of the electromagnetic (EM) spectrum usage as well. The 1,100 active satellites and payloads noted above have generated intense demand for EM spectrum bandwidth, which is expected to increase exponentially in the coming years.[4] In fact, as many as 9,000 satellite communications transponders are expected to be in orbit by 2015.[5] As the number of transponders increases, so too does the risk of radiofrequency interference.

In addition to this congestion – and partly as a result of it – the space domain is also becoming increasingly contested. The U.S. can no longer unquestioningly rely upon assured access to its space assets. Rather, these assets are subject to a growing array of risks from those wielding counterspace capabilities. Kinetic anti-satellite weapons remain a challenge, as they were during the Cold Era. However, the most likely threat today to U.S. military space systems is not one of physically shooting them down, but rather of nonkinetic effects, such as electronically jamming GPS and communications signals. These tactics are relatively low-cost options for states seeking an asymmetric advantage against United States forces.

While the range of threats has increased, the threshold for wielding these weapons has decreased. During the Cold War era, the use of anti-satellite weapons was perceived to be a harbinger of a nuclear

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[2] See William J. Lynn, "A Military Strategy for the New Space Environment," *The Washington Quarterly*, Summer 2011.
[3] United States Strategic Command, "Factsheet: USSTRATCOM Space Control and Space Surveillance," May 2012. Accessed at: <http://www.stratcom.mil/factsheets/USSTRATCOM_Space_Control_and_Space_Surveillance/>.
[4] *National Security Space Strategy* (Washington, D.C., Department of Defense and Office of the Director of National Intelligence), January 2011.
[5] Ambassador Gregory L. Schulte, Deputy Assistant Secretary of Defense for Space Policy, "Statement Before the House Committee on Armed Services, Subcommittee on Strategic Forces," March 15, 2011. Accessed at: <http://www.defense.gov/home/features/2011/0111_nsss/docs/Schulte_HASC_Testimony.pdf>.

first-strike, as the space domain was inextricably linked with the issue of nuclear escalation. However, as the national government's and military's use of space has expanded beyond launch detection and missile tracking, the use of counterspace weapons – particularly nonkinetic ones – has been lowered, with several nations having employed them for political purposes and incorporated their use into conventional military doctrine.

Lastly, the strategic environment is competitive, and expected to become more so in future. Many of the 60 nations mentioned earlier that currently operate satellites rely on their own national aerospace industries to do so. Although the United States continues to enjoy technical leadership in the development of space systems, its share of global satellite manufacturing has steadily decreased since the end of the Cold War, as the expertise among these other nations has increased.[6] Advanced technologies have proliferated; as one example, the U.S. Air Force-operated Global Positioning System (GPS) is a capability that has been or soon will be replicated by Europe's Galileo, Russia's Glonass, China's Beidou, Japan's Quasi Zenith and India's Regional Navigation System. In additional to national competition, the competition from and among industry has also increased, as space-enabled services have become commercially available. However, an encouraging step on this issue was taken in January 2013 with the passage of the FY2013 National Defense Authorization Act (NDAA), which included a long-awaited satellite export control reform provision.[7] This reform will help to bolster the competitiveness of the U.S. space industrial base, while also better protecting the U.S.' most sensitive technologies.

Budgetary Complications

These shifts in the strategic space environment towards an increasingly congested, contested and competitive landscape are occurring amid a U.S. budgetary "drawdown," which has reduced the ability of the U.S. to simply increase its space investments in order to adapt to the changing environment. The current challenges facing the U.S. defense budget is two-fold; there are the cuts stemming from the Budget Control Act of 2011, and the issues resulting from ongoing Continuing Resolutions rather than defense budgets.

The Budget Control Act of 2011 (BCA) was signed into law on August 2, 2011.[8] The BCA contained several components, including discretionary defense spending caps and an automatic defense spending cut (also known as sequestration or the "trigger"). The defense spending caps reduced the total amount of funds which could be appropriated for defense over the period of FY 2012 to FY 2021. In addition to these caps, the BCA built in an automatic sequestration provision. Under this provision, if Congress was unable to enact a total budget reduction plan of $1.2 trillion dollars over the period FY 2012 to FY 2021, automatic cuts would start in FY 2013 that would cause defense spending to be cut by an

[6] Satellite Industry Association, "State of the Satellite Industry Report," September 2012. Accessed at: <http://www.sia.org/wp-content/uploads/2012/10/EXTERNAL-2012-SIA-SSIR-Presentation-Final-Version.pdf>.
[7] Public law 112-239: National Defense Authorization Act for Fiscal Year 2013, Section 1261, "Removal of satellites and related items from the United States Munitions List," January 02, 2013.
[8] Heniff,Bill Jr., Elizabeth Rybicki, and Shannon M. Mahan "The Budget Control Act of 2011," CRS Report R41965.

additional $57.4 billion per year. Congress was unsuccessful in creating a budget reduction plan, and thus the sequestration "trigger" was enacted and went into effect on March 1, 2013. These automatic cuts will result in an 11.5% decrease in funding for the entire defense category during FY 2013.

The defense budget is further complicated by the late passage of defense appropriations bills. For the past 12 years, the DoD has been forced to operate under Continuing Resolutions (CR) for at least part of the fiscal year. In FY 2013, the DoD operated under a CR for the first half of the year that froze DoD base funding at FY 2012 levels. This CR was replaced by the passage of the "Consolidated and Further Continuing Appropriations Act, 2013" on March 26, 2013. This follow-on legislation authorized the DoD to receive funding at levels greater than FY 2012 levels, but was still an overall decrease in funding of roughly $26 billion.

These dual fiscal challenges facing the U.S. defense budget will complicate the future of the U.S.' role in this dynamic space environment – we will not simply be able to throw more money at the problem until it has been solved. Instead, novel concepts and capabilities are needed to provide the U.S. with its own asymmetric advantage in space.

The Plan

U.S. National Government's Plan

The U.S. National Government has been proactive recognizing the need for a new approach to ensure the continuation of its leadership role in the space domain. The FY 2009 National Defense Authorization Act mandated the Space Posture Review (SPR), an assessment of U.S. national security and space policy and objectives conducted jointly by the Secretary of Defense and the Director of National Intelligence. The DoD and Intelligence Community submitted an interim *Space Posture Review* report to Congress in March 2010, and the *National Space Policy* was released by the Office of the White House in June 2010. Following its guidance, the DoD and Intelligence Community released the first-ever *National Security Space Strategy* in January 2011, which concluded the Space Posture Review.

The June 2010 *National Space Policy (NSP)* is President Obama's statement of his Administration's highest priorities for space, and it reflects the U.S.' national principles and goals that will inform the conduct of its space programs and activities. The overarching theme of the document is international cooperation, which is woven throughout the policy. The principles outlined in the *NSP* include the right of all nations to use space for peaceful purposes and to operate space systems without interference, and the concomitant responsibility of all nations to "act responsibly in space to help prevent mishaps, misperceptions and mistrust." It also discusses the U.S.' commitment to deterring aggressive action in space, and defeating these actions if deterrence fails. The specific goals outlined in the *NSP* include the following:

- Energize competitive domestic industries

- Expand international cooperation
- Strengthen stability in space
- Increase assurance and resilience of mission-essential functions
- Pursue human and robotic initiatives
- Improve space-based Earth and solar observation capabilities

U.S. Department of Defense's Plan

In order to ensure alignment with the *NSP*, the formulation of the *National Security Space Strategy (NSSS)* was undertaken after the *NSP*'s release. The *NSSS* was released in January 2011, and represents the first space strategy issued by the DoD. It describes the future strategic environment in the space domain, and then lists the U.S.' national security space objectives as:

- Strengthening safety, stability, and security in space;
- Maintaining and enhancing the strategic national security advantages afforded to the United States by space; and
- Energizing the space industrial base that supports U.S. national security

In order to accomplish these objectives, the *NSSS* also identifies five interrelated strategic approaches. They are to:

- Promote responsible, peaceful, and safe use of space;
- Provide improved U.S. space capabilities;
- Partner with responsible nations, international organizations, and commercial firms;
- Prevent and deter aggression against space infrastructure that supports U.S. national security; and
- Prepare to defeat attacks and to operate in a degraded environment.

U.S. Department of the Navy's Plan

The *Navy Space Strategy* and its associated *Action Plan* were released after the *NSSS*. The *Navy Space Strategy* addresses the Navy Space Community's mission, vision and goals. Although the Air Force is the DoD's Executive Agent for Space, the Navy relies heavily on space systems to conduct its many missions, ranging from low end humanitarian missions to high-end warfare. Specifically, the Navy relies on space systems for critical communications; positioning, navigation, and timing (PNT); missile warning; meteorological and oceanographic data; and intelligence, surveillance, and reconnaissance (ISR) information. Like the *NSP* and *NSSS*, the *Navy Space Strategy* emphasizes cooperation, noting that "Commercial and foreign partner capabilities have become increasingly useful in bridging the gap between requirements and capabilities." The *Navy Space Strategy* sets forth five Strategic Goals:

- Understand the Navy's operational dependency on space and mitigate the impact of risks posed to critical space assets.
- Identify, prioritize, document, and advocate Navy's requirements which are most effectively fulfilled by space capabilities.
- Posture the Navy Space Cadre to leverage current space systems and influence future development.
- Prioritize and fund key Navy space-related science, technology, research, and development efforts to advance operational capabilities.
- Engage with key national and joint space-related entities at all levels to ensure current and future Navy needs and requirements in space are identified, understood, resourced, and protected.

The space domain has remained a core Navy priority, and an updated *Space Strategy* is expected to be released this year.

Forging the Way Ahead with Next-Generation Nanosatellites

The challenge is clear; the U.S. must adapt to – and even dominate – a rapidly evolving strategic environment that is congested, contested and competitive while budgetary pressures severely limit its options. CubeSats – standardized, affordable nanosatellites able to perform space missions that have traditionally only been performed by large satellites and satellite constellations – may hold part of the answer.

The CubeSat program was launched in 1999 as a collaborative effort between Professor Jordi Puig-Suari at California Polytechnic State University (Cal Poly) and Professor Bob Twiggs at Stanford University.[9] The primary mission of the CubeSat Program is to provide access to space for small payloads. Cal Poly has developed the Poly Picosatellite Orbital Deployer (P-POD), a standardized CubeSat deployment system. In order to ensure that CubeSats are standardized and configured to match P-POD requirements, Cal Poly has published CubeSat specifications. A standard CubeSat unit is a 10-cm cube with a mass of no more than 1.33 kg. This basic CubeSat is often called a "1-U" CubeSat, meaning one unit. CubeSats are scalable along only one axis, by 1-U increments. CubeSats such as a "2-U" CubeSat (20×10×10 cm), "3-U" CubeSat (30×10×10 cm) and a "6-U" CubeSat (60×10×10 cm) have been both built and launched. However, the standard P-POD is capable of carrying only three standard CubeSats (or the equivalent), which somewhat limits the development of CubeSats larger than 3-U.[10]

[9] "CubeSat Design Specification, Rev.12," The CubeSat Program, California Polytechnic State University, San Luis Obispo. Accessed at: < http://www.cubesat.org/images/developers/cds_rev12.pdf>.
[10] "CubeSat Design Specification, Rev.12," The CubeSat Program, California Polytechnic State University, San Luis Obispo. Accessed at: < http://www.cubesat.org/images/developers/cds_rev12.pdf>.

CubeSats offer many distinct advantages over their larger traditional counterparts. The key is that they can utilize frequent low-cost launches, rather than very limited, high cost launches. This allows for a higher level of risk tolerance as well as the rapid injection of new technology. In addition, their lower cost and mass (as compared to traditional satellites) allows developers to try many solutions. Together, these attributes result in a "virtuous cycle" of innovation.[11]

Although the CubeSat program was initially comprised of mostly academic and industry participants, government entities have seen their potential and are moving into this space as well. The National Aeronautics and Space Administration (NASA) has established a CubeSat Launch Initiative (CSLI) to provide opportunities for small satellite payloads to fly on rockets planned for upcoming launches. The DoD is also investigating the potential of CubeSats with the Defense Advanced Research Projects Agency's (DARPA's) "System F6" (Future, Fast, Flexible, Fractionated, Free-Flying Spacecraft). The goal of System F6 is to create clusters of CubeSats "linked by ad hoc wireless networks allowing them to autonomously share tasks such as processing, data storage, sensing, communications relay and navigation, while trading off missions if any satellite fails or falls out of orbit."[12] The Army, Air Force, Navy and even Special Forces have each experimented with CubeSat technology. Military CubeSat operators reap an additional benefit beyond cost savings and the ability to upgrade quickly. As space becomes increasingly contested, CubeSats' small size makes them difficult targets to shoot at.

The Navy has seen their potential, and argues that "Beyond state of the art research is needed to drastically reduce the size, weight and power of payloads that have traditionally performed Naval space missions on much larger satellites."[13] In order to meet this requirement, the Navy is seeking to develop novel CubeSat payloads for Naval space missions, including narrowband communications, astrometry, and ocean sensing, among other missions sets.[14]

Challenges to Nanosatellite Operations

Current Communications Limitations

Despite the many advantages they might offer, CubeSats will only be able to realize their full potential if a low-cost command and control (C2) capability is available to operate them. This is a significant challenge, as communications with nanosatellites are limited by a number of factors, both on the ground and in the space vehicle. These factors severely limit the availability of Telemetry, Tracking and Commanding (TT&C), and payload data connection to the satellite. Most often, store and forward communications is the only option for nanosatellites. The lack of reliable communication drives many missions to larger satellites, and therefore higher cost.

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[11] Jordi Puig-Suari, "CubeSat: A Different Path to Space," Presentation at the 3rd Nano-Satellite Symposium, Kokura, Japan, December 12 – 14, 2011. Accessed at: <http://www.nanosat.jp/3rd/sozai_report/Day_2_0404_Puig-SuariJordi_California_PolytechnicState_University/NSS-03-Day_2_0404_Puig-SuariJordi.pdf>.
[12] Paul McLeary, "CubeSats Tapped for Orbital Networks," *Aviation Week,* September 01, 2011. See also DARPA, "System F6," Tactical Technology Office, accessed at: <http://www.darpa.mil/Our_Work/tto/Programs/System_F6.aspx>.
[13] Navy SBIR 2012.2, Topic N122-146, "Novel CubeSat Payloads for Naval Space Missions," May 24, 2012.
[14] Navy SBIR 2012.2, Topic N122-146, "Novel CubeSat Payloads for Naval Space Missions," May 24, 2012.

Most nanosatellites are launched into Low Earth Orbit (LEO) and are only within the line of sight of any given ground station antenna for a few minutes per day.[15] The long times between ground station contacts means data is stale upon arrival. Short communications windows limit data throughput and require well honed operations to make efficient use of each pass. A network of ground stations can be used to increase the number of ground contacts, but this approach increases complexity and cost.

Other factors can also impact the space to ground link. Weather events, both terrestrial and solar, can limit availability of ground sites. Ionosphere scintillation and other anomalies effects can severely degrade the communication link.[16]

Space Segment

Communication link reliability remains a major challenge for current and future nanosatellite missions. A large percentage of CubeSat missions have had a communication failure.[17] There are three general options for the communication solution: developing a custom radio, modifying an existing terrestrial radio for space use, or buying an existing space rated radio for nanosatellites.

Custom radios for individual nanosatellites are at best impractical. Frequently universities use this solution as an academic exercise. Developing a custom radio takes away from the primary mission and in the end degrades the resulting payload product. Modifications to an existing radio take less time than developing a radio from scratch, but this solution is often less robust if the original hardware was designed terrestrial use. The hostile environment of space is not kind to active circuitry. The best solution is to purchase a nanosatellite radio, so that mission developers can focus on the primary payload.

Ground Segment

Ground station manning is a significant cost driver for nanosatellites programs. While smaller satellites reduce the cost of development, materials and launch, the cost of manpower on the ground remains the same, and is a much larger percentage of the overall system cost. To improve the link margin, ground stations often use a relatively large, active pointing antenna. Even if automated, a local technician is required to maintain and troubleshoot any issues at the ground station. Reducing the cost of ground stations would make nanosatellite missions even more affordable. A virtual mission operation center that does not require any customer hardware would simplify the mission development.

MUOS Cross-Link Option

[15] Air University, "Force Support – Air Force Satellite Control Network," Maxwell AFB, 2012. Accessed at: <http://www.au.af.mil/au/awc/awcgate/au-18/au18004a.htm>.

[16] P. Doherty, "Ionospheric Scintillation Effects in Equatorial and Auroral Regions," ION GPS 2000, Salt Lake City, Utah, p. 662-671.

[17] P. Doherty, "Ionospheric Scintillation Effects in Equatorial and Auroral Regions," ION GPS 2000, Salt Lake City, Utah, p. 662-671.

A possible solution is to leverage the Mobile User Objective System (MUOS) to create a "cross-link" for nanosatellites. Once launched, the MUOS satellites will provide UHF communications from geosynchronous orbit. MUOS is intended to support ground, maritime and airborne terminals, however, a nanosatellite could emulate a handheld terminal providing instantaneous communications from any point in LEO using an omni-directional antenna.

MUOS essentially provides cellular phone capability from space. The MUOS network allows data connections to the secure DoD networks including the Secret Internet Protocol Router Network (SIPRnet). If integrated with a capability such as the Naval Research Laboratory's Virtual Mission Operation Center (VMOC), nanosatellites could achieve TT&C and payload data delivery without the use of a dedicated ground station.

Program Executive Office Space Systems and the Space and Naval Warfare Systems Command are developing a prototype MUOS cross-link capability using Small Business Innovative Research (SBIR) funds. The radio for the MUOS cross-link will be one of the smallest space tested software defined radios to date. A High Assurance Internet Protocol Encryptor (HAIPE), currently under development by the Air Force Research Laboratory, will provide the required communications security.

Alternatives To MUOS Cross-Link

There are few existing options for a persistent communication link for a space vehicle in LEO. These solutions are frequently saturated due to existing requirements and often beyond the reach of a smaller nano-satellite mission.

Iridium

"The Iridium satellite constellation provides voice and data coverage to satellite phones, pagers and integrated transceivers over Earth's entire surface. Iridium Communications Inc. owns and operates the constellation and sells equipment and access to its services. The constellation operates 66 active satellites in orbit to complete its constellation and additional spare satellites are kept in-orbit to serve in case of failure.[18] Iridium is a viable communication solution for a small satellite data link. However, there are three issues that must be considered before using Iridium as the primary communication links: the satellite must be at a lower altitude Iridium, the satellite must be in a relatively similar inclination to mitigate the Doppler Effect, and the overall cost of transferring the data must be within the mission's budget.

[18] H. Boiardt and C. Rodriguez, "The Use of Iridium's Satellite Network for Nano-Satellite Communications in Low Earth Orbit," Aerospace Conference, 2009 IEEE , vol., no., pp.1-5, 7-14 March 2009.

The Iridium constellation, orbiting at approximately 760 km altitude, 86° inclinations,[19] was designed as an earth communication system and therefore the antenna radiation pattern is aimed towards earth. The first limitation for a nanosatellite mission planner is the fact that the altitude must be significantly lower than 760 km, or the connection quality of service would be very spotty. If the mission requires for the nanosatellite to be at a similar or higher orbit, communication to the Iridium constellation is impossible. Another problem with using Iridium is the concern that if the space vehicle is not in the same plane as one of the Iridium satellites, the Doppler shift becomes increasingly difficult to compensate due to a large relative velocity. The cost of transferring data is also significant with Iridium. After the mission has purchased both space vehicle and ground hardware, there is a per bit cost for transferring data over the lifetime of the mission.

AFSCN

The Air Force Satellite Control Network (AFSCN) provides "force support, the ability to sustain forces, [which] includes the space mission of on-orbit support for satellites. During the entire life of any satellite or military space system, from prelaunch checkout to on-orbit operations, there is a requirement for constant control, support, and direction of the satellite and its assigned mission … Satellite command and control is the essential mission of the AFSCN. To accomplish this complex task, various control centers are organized to integrate incoming and outgoing satellite control data for decision making. The complexity of the AFSCN mission increases with the number of active satellite missions. Supporting resources of the AFSCN consist of leased and allocated communications, and host-base-provided facilities and utilities."[20]

The main issue with AFSCN support to nanosatellite missions is the saturation of the AFSN resources. The nanosatellite mission would need to compete with existing priorities, and growing number of nanosatellites would quickly strain AFSCN capacity.

TDRSS

The Tracking and Data Relay Satellite System (TDRSS) is a constellation of communications satellites in geostationary orbit and a communication network "referred to as the NASA Space Network, consists of the on-orbit telecommunications TDRS satellites stationed at geosynchronous stationary positions and the associated TDRS ground stations located at White Sands, New Mexico and Guam. The TDRSS is capable of providing near continuous high bandwidth (S, Ku, and Ka band) telecommunications services for low Earth orbiting user spacecraft and expendable launch vehicles,

[19] USASMDC/ARSTRAT, "SMDC-ONE Nanosatellite Techical Demonstration," Accessed at: <http://www.smdc.army.mil/FactSheets/SMDC-One.pdf>.
[20] Air University, "Force Support – Air Force Satellite Control Network," Maxwell AFB, 2012. Accessed at: <http://www.au.af.mil/au/awc/awcgate/au-18/au18004a.htm>.

including the Hubble Space Telescope, the space shuttle and the space station. As such, the TDRS System is a basic agency capability and a critical national resource."[21]

TDRSS has potential for nanosatellites, but the issues are similar to AFCN, including miniaturization of TDRS compatible radios, resource allocation and competition, and system ability of the TDRSS to accommodate increasing numbers of nanosatellites.

Feasibility Of A MUOS Cross-Link

MUOS is a narrowband Military Satellite Communications (MILSATCOM) system that supports mobile and fixed-site terminal users in the Ultra High Frequency (UHF) band. It adapts a commercial third generation Wideband Code Division Multiple Access (WCDMA) cellular phone network architecture and combines it with geosynchronous satellites in place of cell towers.[22]

MUOS was designed to support ground, maritime and airborne terminals. MUOS provides uninterrupted coverage up to approximately 65 degrees latitude. The curvature of the Earth limits terrestrial coverage above the 65 degrees latitude. However, the MUOS radiation pattern extends well into the Low Earth Orbit. A satellite in most LEO orbits would be able to establish a communication link even while transiting over the poles. The MUOS WCDMA waveform was designed to accommodate handheld terminals similar in size to an AN/PRC-148 or AN/PRC-152 with less than 7 watts transmitted power. A radio of this size, weight and power could be integrated into a nanosatellite.

An existing MUOS link model was modified to examine the feasibility of a cross-link. A notional nanosatellite was modeled using a 3-U CubeSat bus and simple antenna,[23] plus a software defined radio capable of communicating with MUOS. Next, a circular, 700 km sun synchronous orbit was modeled in Satellite Tool Kit to determine the average and maximum range to the MUOS satellites. The results were combined with the radio parameters in the MUOS link model to show that the 9.6 kbps data rate could be achieved at all points in the nanosatellite orbit, and 32 kbps were possible most of the time. Finally, the new calculations were verified by the MUOS program office.

MUOS Cross-Link Advantages

A MUOS cross-link provides many advantages for nanosatellites. Satellite operators could communicate with their LEO satellite(s) at any time and at any point in orbit, including the poles. The ability to communicate on demand will enable nanosatellites to perform many missions previously thought to require larger satellites or large numbers of ground stations.

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[21] NASA Goddard Space Flight Center, "Tracking and data Relay Satellite K/L," 2012. Accessed at: <http://tdrs.gsfc.nasa.gov/tdrs/136.html>.

[22] U.S. Navy, "Mobile User Objective System," Accessed at: <https://acquisition.navy.mil/rda/media/files/programs/muos>.

[23] USASMDC/ARSTRAT, "SMDC-ONE Nanosatellite Techical Demonstration," Accessed at: <http://www.smdc.army.mil/FactSheets/SMDC-One.pdf>.

MUOS is integrated with the DoD Teleport program, providing terminals using the Point to Net service direct Internet Protocol (IP) access to SIPRnet and NIPRnet. A nanosatellite could use the service to upload payload data directly to a server on the appropriate network. Satellite operators could securely send commands to nanosatellites on demand.

A MUOS cross-link will have significantly improved security over commercial SATCOM options. A High Assurance Internet Protocol Encryptor (HAIPE) is required to protect data traveling over the MUOS link. This allows IP data to flow from the terminal to the intended networks while staying encrypted. The end to end link would stay on DoD networks at all times.

The multi-billion dollar MUOS program is a sunk cost. There are no system fees, no “per-bit” costs, and no long term contract commitments for DoD users. Nanosatellite programs would not need dedicated ground stations. MUOS would provide the IP routing network, and no additional ground infrastructure would be required. The burden of frequency approval would be significantly reduced by utilizing MUOS approved communication standards.

MUOS Cross-Link Considerations

First the nanosatellite must be able to live with the limited data throughput. While 32 kbps will usually be available, at times the link will only support 9.6 kbps. This will force the use of low data, or force a need for increased onboard processing capability to minimize data transfer requirements.

The link will be subject to the MUOS priority and pre-emption scheme. Depending on the satellite’s priority level and congestion within the current MUOS spot beam, pre-emption is possible. However, this is only likely in areas heavily populated with terrestrial units using WCDMA capable radios. The flight software must be capable of handling this situation, and some missions may require additional memory for a store and forward capability for critical data once the link can be established.

MUOS cross link capability will require increased complexity in the nanosatellite. The WCDMA waveform is over a million lines of code, significantly more than most of today’s dedicated channel radios. The satellite will need a HAIPE, and therefore will need to securely manage encryption keys. The flight software will need to manage the more complex radio and encryptor.

The cross-link capability will use more power than current space-to-ground systems as the free space loss for the link to GEO requires more power. The radio will always need to be powered up in order to receive calls on demand. The HAIPE will increase the consumed power as well. This may drive the need for larger and more efficient solar panels, or improve the duty cycle.

A satellite will traverse MUOS spot beams in a matter of minutes. When a terminal crosses from one beam to another, there is a beam handover event, which will temporarily halt communications. Possible workarounds are being evaluated.

Challenges

While a MUOS cross-link is possible in a nanosatellite, many technical challenges must be solved to provide an operational capability.
A MUOS capable terminal has yet to be operationally tested, even for terrestrial uses. To date the smallest radio in development is a man-pack version that is about three times larger than a CubeSat. The system will also require a certified High Assurance Internet Protocol Encryptor (HAIPE). A WCDMA radio and HAIPE must be developed at about one-tenth the size of the man-pack radio, and able to operate in space.

MUOS was designed with a maximum terminal speed of several hundred miles per hour. A satellite in LEO would be traveling nearly ten times this fast. Since the MUOS satellite design is locked, the nanosatellite would need to adjust for the Doppler effect. The offset calculation will not be simple because the nanosatellite must determine which MUOS satellite it is currently communicating with and if it is traveling toward or away from MUOS. This may require the addition of a GPS receiver to the nanosatellite.

MUOS Cross-Link Applications

A MUOS cross-link capability could potentially support many missions for small satellites, and open up new opportunities. The proposed cross-link could be used for TT&C, as a polar communication relay, and as a method to immediately download time sensitive payload data.

Telemetry, Tracking and Command (TT&C) are essential tasks for any space vehicle. From big to small, there is no space mission possible without a reliable TT&C link. These tasks include monitoring and maintaining space vehicle and payload state of health, reconfiguration, and command of the space vehicle. For many DoD space missions, this task has been accomplished by AFSCN. For nanosatellites, telemetry and tracking is generally accomplished with a radio beacon and stand alone ground stations. Command functions are accomplished through various radios with varying success.

Currently most CubeSats have no propulsion capability, no active station keeping and a limited attitude control. There are still many tasks for the satellite operator. Space vehicle welfare depends on the timely intervention from the operator when trouble arises. Thermal condition monitoring and payload duty cycles must be carefully controlled and monitored. These tasks, and many others, require a reliable and available data connection.

Furthermore payloads often have time sensitive information that needs to be transmitted to the ground operator. A MUOS cross-link allows for immediate download of this information even over oceans, and inaccessible territories.

Upcoming Missions

There are many current and upcoming missions that could make use of a MUOS cross-link. Ice-Cap and VECTOR are examples. ICE-Cap is a mission being planned to test the MUOS cross-link capability. ICE-Cap is a communication mission to provide Legacy UHF communications for SATCOM disadvantaged areas in higher latitudes. The ICE-Cap satellite will act as a primary relay station to transfer the legacy UHF signal to MUOS that would then relay the signal back to the ground. This double hop relay capability will provide a short communication window to a polar unmanned monitoring station or a disadvantaged user. Another mission that ICE-Cap is aiming to accomplish is to measure worldwide MUOS signal strength and to create a worldwide quality of service map.

Another example of a system that could use a cross-link capability is the Joint Capability Technical Demonstration (JCTD) project VECTOR. Currently, VECTOR demonstration relies upon a dedicated ground control stations, dedicated user terminals, and dedicated teleports to get the information into the network. Even with these capabilities, access is limited. This means that the satellite is only able to downlink its data a few times per day. The access windows are very brief, only three to five minutes at a time, providing limited access to evaluate the system, and increases data latency. A MUOS cross-link would provide a significantly improved evaluation opportunity.

Demonstration Mission

Hardware Overview

Size, weight and power are ever-present engineering challenges, even more when working within the CubeSat standard. The MUOS crosslink is being designed as an end cap module for a 3U form factor. The enclosure is expected to be 1/2U which is approximately 10cm x 10 cm x 5 cm). The entire enclosure is expected to weigh no more than 1 kg. The module will have a standard physical and data interface.

Within this communication module will be the software defined radio card, a High Assurance Internet Protocol Encryption card, a power card, and a deployable omnidirectional antenna. The enclosure will also aid in heat dissipation and be used to provide RF isolation from the rest of the CubeSat bus.

Power is currently the limiting factor for the project. The transmit power required to be able to close the link to a geostationary satellite is significant. According to link margin calculations using an omnidirectional antenna, the communication link could be established with 3 Watts of radiated power. Based on early design estimations, the total power consumed will be on the order of 26 Watts to maintain a secure half duplex link.

Challenges

The power requirements for the communication link are substantial. Depending on the available power, the communication duty cycle would be rather short on each orbit. Even though the link would always be possible, the availability of power serves as a limiting factor.

The CubeSat attitude and the orientation of the antenna also play a role. While using an antenna that approximates an isotropic radiator, there are still fractions of the view angle that are blocked by the body of the CubeSat.

The mission

ICE-Cap will test feasibility of a MUOS cross-link concept. The ICE-Cap mission intends to accomplish several objectives: to test feasibility of MUOS range extension to UHF SATCOM users in polar latitudes, test the feasibility of TT&C and payload data connection through MUOS IP network, and provide the first MUOS quality of service map. Virtual mission operations over the SIPRNet will enable users to issue TT&C commands and transfer data to/from the satellite using simply a SIPRNet terminal. If successful, ICE-Cap will pave the way for persistent communication to LEO satellites using MUOS.

Conclusion

While there are many challenges to overcome, MUOS cross-links may be feasible for LEO satellites, even at higher latitudes and over the poles. Spacecraft as small as a CubeSat may be able to act as an orbiting WCDMA terminal, taking advantage of the resources provided by MUOS. The link will provide throughput as high as 32 kbps with direct access to secure networks.

CubeSat-compatible components, including a MUOS terminal and HAIPE, are already in development. The initial design will require approximately ½ “U” of space. A demonstration CubeSat mission is planned with a potential launch in late 2014. Once proven in space, the design could become a standard communications package, and enable faster integration for future missions.

Cross-links through MUOS will enable additional nanosatellite missions and decrease costs. There is no recurring cost for government terminals to transmit data through the MUOS network. In many cases, mission specific ground stations can be eliminated, further reducing hardware, integration and manpower costs.