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FIGHTING IN A CONTESTED SPACE ENVIRONMENT: TRAINING MARINES FOR OPERATIONS WITH DEGRADED OR DENIED SPACE-ENABLED CAPABILITIES

by

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June 2015

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Space is an increasingly congested, contested and competitive environment. At the same time, the Marine Corps is becoming increasingly reliant on the capabilities space-based assets provide. This includes each of the space force enhancement capabilities, but particularly satellite-based voice and data communication; position, navigation, and timing information; and battlefield intelligence. Space capabilities are vulnerable to both space-based and terrestrial-based countermeasures. This study was conducted to determine the extent to which the Marine Corps educates and trains warfighters to operate in a battlefield where space-centric enabling capabilities are degraded or denied. The study surveyed the systems and capabilities on which the Marine Corps relies in order to enhance its execution of the highly dynamic range of military operations as well as the threats to those systems and capabilities. Furthermore, the study examined to what levels and extent related training and education should take place, and which venues would best host that training. Based on the analysis, this thesis recommends leveraging internal Marine Corps expertise, increasing integration of space-related education and training into schoolhouse curricula and training exercises, and leveraging joint space expertise and resources to enhance Marine Corps readiness to excel in a contested space operational environment.

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FIGHTING IN A CONTESTED SPACE ENVIRONMENT: TRAINING MARINES FOR OPERATIONS WITH DEGRADED OR DENIED SPACE-ENABLED CAPABILITIES

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ABSTRACT

Space is an increasingly congested, contested and competitive environment. At the same time, the Marine Corps is becoming increasingly reliant on the capabilities space-based assets provide. This includes each of the space force enhancement capabilities, but particularly satellite-based voice and data communication; position, navigation, and timing information; and battlefield intelligence. Space capabilities are vulnerable to both space-based and terrestrial-based countermeasures. This study was conducted to determine the extent to which the Marine Corps educates and trains warfighters to operate in a battlefield where space-centric enabling capabilities are degraded or denied. The study surveyed the systems and capabilities on which the Marine Corps relies in order to enhance its execution of the highly dynamic range of military operations as well as the threats to those systems and capabilities. Furthermore, the study examined to what levels and extent related training and education should take place, and which venues would best host that training. Based on the analysis, this thesis recommends leveraging internal Marine Corps expertise, increasing integration of space-related education and training into schoolhouse curricula and training exercises, and leveraging joint space expertise and resources to enhance Marine Corps readiness to excel in a contested space operational environment.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACE	Aviation Combat Element
AEHF	Advanced Extremely High Frequency
ARSST	Army Space Support Team
ASAT	Anti-Satellite
BDA	Battle Damage Assessment
C/A	Coarse/Acquisition
COMSATCOM	Commercial SATCOM
COP	Common Operational Picture
DOD	Department of Defense
DSCS	Defense Satellite Communication System
E_b/N_o	Bit Error Rate to Noise Spectral Density Ratio
EHF	Extremely High Frequency
EMP	Electromagnetic Pulse
FEC	Forward Error Correction
FECC	Fires and Effects Coordination Cell
FFT	Friendly Force Tracking
FLTSATCOM	Fleet Satellite Communication System
FSS	Fixed Satellite Services
GCE	Ground Combat Element
GEO	Geosynchronous Orbit
GIANT	GPS Interference and Navigation Tool
GPS	Global Positioning System
HF	High Frequency
HQMC	Headquarters, Marine Corps
IMINT	Imagery Intelligence
ISR	Intelligence, Surveillance, and Reconnaissance
ITU	International Telecommunication Union
JFCC-Space	Joint Forces Component Command for Space
JNWC	Joint Navigation Warfare Center
LEO	Low Earth Orbit

LPD	Low Probability of Detection
LPI	Low Probability of Intercept
LZ	Landing Zone
MAGTF	Marine Air Ground Task Force
MARFORSRTAT	Marine Forces Strategic Command
MAWTS-1	Marine Aviation Weapons and Tactics Squadron One
MCAGCC	Marine Corps Air Ground Combat Center
MCAS	Marine Corps Air Station
MCTOG	Marine Corps Tactics and Operations Group
MEB	Marine Expeditionary Brigade
MEF	Marine Expeditionary Force
MEU	Marine Expeditionary Unit
MILSTAR	Military Strategic and Tactical Relay
MOS	Military Occupational Specialty
MSC	Major Subordinate Command
MSIC	Missile and Space Intelligence Center
MSS	Mobile Satellite Services
MSTP	MAGTF Staff Training Program
MTT	Mobile Training Team
MUOS	Mobile User Objective System
NASIC	National Air and Space Intelligence Center
NAVOPS	Navigation Operations
NAVWAR	Navigation Warfare
NNWC	Navy Network Warfare Command
NRO	National Reconnaissance Office
NTC	National Training Center
OODA	Observe, Orient, Decide, Act
PDOP	Precision Dilution of Precision
PGM	Precision Guided Munitions
PLI	Information Operations and Space Integration Branch
PMOS	Primary Military Occupational Specialty
PNT	Position, Navigation, and Timing

PP&O	Plans, Policies, and Operations
PPS	Precise Positioning Service
PRN	Pseudo-Random Noise
RF	Radio Frequency
SA	Selective Availability
SAS	Space Aggressor Squadron
SATCOM	Satellite Communications
SFE	Space Force Enhancement
SHF	Super High Frequency
SIGINT	Signals Intelligence
SME	Subject Matter Expert
SNR	Signal-to-Noise Ratio
SOTG	Special Operations Training Group
SPMAGTF	Special Purpose Marine Air Ground Task Force
SPS	Standard Positioning Service
STRATCOM	Strategic Command
TACDEMO	Tactical Demonstration
T&R	Training and Readiness
TRAP	Tactical Recovery of Aircraft and Personnel
TT&C	Telemetry, Tracking, and Control
TTP	Tactic, Technique and Procedure
UAS	Unmanned Aerial System
UFG	Ulchi Freedom Guardian
UFO	UHF Follow-On System
UHF	Ultra-High Frequency
URE	User Range Error
VTC	Video Teleconference
WGS	Wideband Global SATCOM

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I. INTRODUCTION

Space has become a critical component to the military's strategic, operational, and tactical planning and execution. This warfighting domain is an increasingly congested, contested, and competitive environment [1]. Not only are there threats from near-peer adversaries, but critical force enhancement capabilities provided by space-centric capabilities can be interfered with or blocked with relatively inexpensive and easy-to-access technology and equipment. This means that counter space capabilities are becoming more available to a broader group of less developed nations, terrorists, and criminal organizations. This degradation or denial can have significant negative impacts on operational timelines, lines of communication, and intelligence collection.

The Marine Corps relentlessly employs maneuver warfare elements and combined arms in its operational planning and execution. The advantage in these operations is drawn from a Marine Air Ground Task Force's (MAGTF's) superior capabilities in command and control, communications, intelligence, and precision targeting. These capabilities are increasingly enabled and enhanced by space-based assets and capabilities.

Air Force Colonel John Boyd developed a well-regarded theory about decision-making processes that has been applied to how decisions are made for combat operations. It is popularly referred to as the "OODA Loop" [2]. In summary, the concept applied to maneuver warfare asserts that a commander who can observe, orient, decide, and then act (OODA) faster than an adversary will ultimately win in a contest of arms. Space-centric capabilities enable the United States to sustain a faster and more reliable OODA loop than its adversaries. Degradation or denial of those assets and capabilities slows this decision cycle by eliminating critical enhancements to the warfighting functions and introducing increased levels of uncertainty.

It is important to emphasize that the loss or degradation of these capabilities will not necessarily stop the Marine Corps' ability to operate. The Marine Corps has a long and undisputed history of fighting and overcoming adversaries regardless of conditions and availability of resources. However, given the level to which space-enabled capabilities have been integrated into the MAGTF planning and operational construct, significant interference, degradation, or denial of these capabilities will severely impact MAGTF operations across all warfighting functions. This will effectively slow the MAGTFs OODA Loop and shrink the gap between friendly and enemy capabilities as well as timeliness and effectiveness in planning and executing operations.

The keys to maintaining the advantage are to: educate commanders, staffs, and operators on the threats and implications to operations; develop valid tactics, techniques, and procedures (TTPs) to counter those threats; and then to exercise and enhance this knowledge and these skills in unit drills, training evolutions, and exercises.

This study evaluates the extent to which the Marine Corps is reliant on these enabling space-based capabilities, the threats to those capabilities, and the scope and amount of training that is currently available to the operating forces. Based on this analysis, recommendations are made on how education and training can be improved and expanded in order to make commanders, staffs, and the operators at the point of friction capable of effective operations, even in the face of degraded or denied space capabilities.

II. MARINE CORPS RELIANCE ON SPACE

The Marine Corps relies heavily on multiple critical operational and tactical capabilities provided by space-centric assets. These capabilities are doctrinally referred to as space force enhancements and include satellite communications (SATCOM); position, navigation, and timing (PNT); intelligence, surveillance, and reconnaissance (ISR); missile warning and attack assessment; and environmental monitoring [3]. Figures 1–5 are examples of space systems on orbit that are enabling each of the respective space force enhancements.

A. SATELLITE COMMUNICATIONS

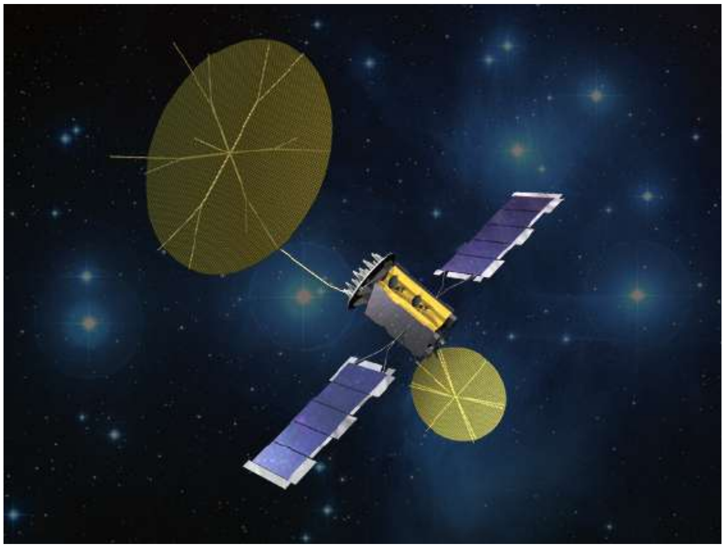

Figure 1. Mobile User Objective System (MUOS) Narrowband Communications Satellite, from [4].

SATCOM links permit the MAGTF to expand its area of influence and scope of operations by facilitating communication with elements operating beyond line-of-sight range. This capability provides access to global information and intelligence networks, ship-to-shore communication, and connectivity between elements in austere areas where there is limited or no other communication infrastructure available. These factors are critical to the expeditionary nature of MAGTF operations and core capabilities. With these lines of communication, MAGTFs can operate in a much more distributed manner and are able to more reliably sustain effective command and control during operations over greater distances with fewer forces.

B. POSITION, NAVIGATION, AND TIMING

Figure 2. Global Positioning System (GPS) Block IIR-M Satellite, from [5].

Space-based position, navigation, and timing (PNT) assets provide highly accurate and reliable position information, navigation solutions, and critical timing synchronization that enable more effective planning, training, and execution of MAGTF operations. The main PNT system used by U.S. military forces is the Global Positioning System (GPS) operated by the U.S. Air Force. Although the service is publically available, it has military-specific capabilities. Position information is critical for friendly force tracking (FFT) and targeting. PNT capabilities also facilitate reliable and efficient navigation of maneuvering units and provide critical guidance to precision munitions. This enables prosecution of targets from greater stand-off distances with greater precision and accuracy, which reduces collateral damage and eases logistical strains, as fewer warheads are required. The precise timing facilitates secure communications via frequency hopping and other cryptologic and communication systems requiring precise synchronization. Data networks rely on precise timing signals provided by PNT systems to synch network traffic, manage data flow, and maintain integrity. This is increasingly vital as military forces are becoming ever more reliant on distributed networks.

C. INTELLIGENCE, SURVEILLANCE, AND RECONNAISSANCE

Figure 3. U.S. Air Force Operationally Responsive Space One (ORS-1) Imaging Satellite, from [6].

Space-based intelligence, surveillance, and reconnaissance (ISR) provides capabilities that uniquely augment air and ground-based ISR assets. The high ground of space affords the ability to overcome line-of-sight (LOS) restrictions experienced by terrestrial collection assets, as well as opening access to virtually the entire globe. With the right sensors, space-based collection assets can provide day or night, all-weather, deep reconnaissance of otherwise denied areas. Territorial airspace claims do not extend into space and therefore spacecraft have unique access to observe and collect intelligence on targets or points of interest otherwise inaccessible to airborne platforms due to overflight restrictions.

Space systems in low-earth orbit (LEO, approximately 100 miles to 1,200 miles in altitude) offer the best resolution for imagery and other collection, but cannot offer persistent coverage over a target due to the physical constraints of the orbits. If positioned in higher orbits, like geosynchronous orbits (GEO, 22,236 miles in altitude), space systems can provide persistent coverage to as much as a third of the surface of the earth; however, this altitude generally limits resolution compared to the capabilities of lower orbiting satellites.

It would not be uncommon for the best or only early surveillance or reconnaissance available to be from a space-based asset, specifically in the event of an amphibious forced entry operation or deep strike. With a thorough understanding of the available capabilities, MAGTF intelligence officers can integrate the products these assets provide into their collection plans and leverage these capabilities to better inform the commander and staff.

D. MISSILE WARNING AND ATTACK ASSESSMENT

Figure 4. Space-Based Infrared System (SBIRS) Geosynchronous (GEO) Satellite, from [7].

Short-, medium-, and long-range ballistic and cruise missile technology is becoming more prevalent and there is a consequent significant increase in the likelihood that MAGTF will be exposed to these threats. Early detection, characterization, and threat warning, if these weapons are employed, are key aspects to ensuring the MAGTF will be able to mitigate the threat and defend itself in a timely manner. Robust space-based missile warning capabilities, working in conjunction with terrestrially-based systems, enable critical and timely detection and subsequent notification. Although the organizations that operate the systems and disseminate the notifications are generally joint in nature and not directly controlled by the Marine Corps, their capabilities can be leveraged by MAGTF commands as long as the lines of communication and coordination have been established. These lines of communication can be established and preserved even in an expeditionary environment, but the notification channels must be consistently monitored to ensure connectivity is maintained.

E. ENVIRONMENTAL MONITORING

Figure 5. Defense Meteorological Satellite Program (DMSP) Block 5D2 Satellite, from [8].

Terrestrial weather conditions such as severe storms or unfavorable surface conditions on land or at sea can have significant impacts on military operations. Space-based environmental monitoring systems sensors can identify and characterize environmental phenomena on land, in the air, at sea and in space that can impact military planning and operations. In addition to terrestrial weather, environmental monitoring systems can aid in landing zone (LZ) or beach evaluation and vegetation characterization, and can be used to monitor forest fires, volcano activity, and even air quality. Another aspect of environmental monitoring is forecasting and detecting solar activity. This activity can have significant negative effects to ultra-high frequency (UHF) communication. Extremely high frequency (EHF) communications are sensitive to moisture in the air and can also be affected by dense jungle canopy. Understanding the terrestrial and space weather conditions, forecasts, and possible implications to operations can help MAGTF commanders and staffs avoid adverse conditions, synch operational plans and considerations with real world conditions, and allow for the exploitation of these conditions to enhance operations.

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III. SPACE FORCE ENHANCEMENT AND THE SIX WARFIGHTING FUNCTIONS

Space force enhancements play critical enabling roles in each of the warfighting functions. The modern MAGTF is structured and trained to operate across the spectrum of conflict with these space-enabled capabilities. Understanding how space force enhancements are implemented in support of the warfighting functions is critical to understanding how loss or degradation of the applicable capabilities will affect warfighting function capabilities. Table 1 shows how each of the elements of space force enhancement individually relate to the six warfighting functions.

	Command and Control	**Intelligence**	**Maneuver**	**Fires**	**Logistics**	**Force Protection**
Satellite Communication (SATCOM)	-C2 of Forces -FFT -UAS C2	-Intelligence Product Dissemination	-Communications for distributed operations	-C2 for Fires	-Logistics Support Requests	-Missile Warning dissemination
Position, Navigation, and Timing (PNT)	-Comm System Timing -Encryption -FFT	-Targeting -TRAP -Personnel Recovery	-Navigation -FFT	-Precision Guided Munitions (PGMs) -Synchronization of fires	-Logistics tracking	-Fratricide Avoidance
Intelligence, Surveillence, and Reconnaissance (ISR)		-IMINT -SIGINT	-Route planning -Route reconnaissance	-Targeting -Battle Damage Assessment (BDA)		-Perimeter/local area security monitoring
Missile Warning						-Tactical warning of missile attacks
Environmental Monitoring	-Terrestrial Wx Effects -Space Wx Effects -Terrain Evaluation	-Terrestrial Wx effects to munitions and guidance	-Wx effects to terrain and mobility	-Terrestrial Wx effects to munitions and guidance	-Logistics planning	

Table 1. Space Support to the Warfighting Functions, after [9], [10].

(1) Command and Control

Space Force Enhancements provide a commander with expanded communication and situational awareness capabilities beyond those provided by terrestrial systems. Space-based ISR can provide invaluable insight and access to denied areas. SATCOM facilitates communication with widely distributed and mobile forces. Space-based PNT and SATCOM capabilities also permit near-real-time and accurate tracking of friendly forces in order to prevent fratricide. PNT provides for accurate synchronization of encrypted communication systems allowing options for secure communication channels. Space-based environmental monitoring systems inform the commander on not only terrestrial weather considerations, but also space weather that may affect terrestrial and space-based communication signals.

(2) Maneuver

As previously mentioned, SATCOM provides the critical communication links that provide the commander greater options in maneuvering widely distributed forces. PNT enables those forces to rapidly, accurately, and reliably navigate in unfamiliar terrain and in areas where navigation is particularly challenging such as featureless desert, dense jungle, or open water. Environmental monitoring provides maneuvering forces an idea of surface conditions they can expect that will affect route selection and maneuverability. Also, weather forecasting affects movements on the sea from ship-to-shore as well as ability to maneuver on land.

(3) Fires

SATCOM expands options for command and control of fires with distributed forces, both from higher echelons as well as from troops on the ground. PNT capabilities expand the options in the use of GPS-guided precision guided munitions (PGMs) for increased accuracy, operability in adverse weather that degrades other forms of precision guidance (laser, infrared seekers, etc.), and collateral damage reduction, as well as reducing the number of munitions required to achieve the desired effects on a target. More precise synchronization of fires is also enabled by PNT. Space-based ISR systems can provide accurate battle damage assessment (BDA) in areas denied to other platforms.

Environmental monitoring systems aid in planning weapon target pairing by enabling consideration of the effects of weather and surface conditions at a target.

(4) Intelligence

There are numerous space-based imagery intelligence (IMINT) and signals intelligence (SIGINT) capabilities that can provide critical information that could not be gathered in any other manner. Updated intelligence products can be requested, received, and disseminated via SATCOM voice and data links to isolated and austere operating environments. Reliable positioning enables development of target lists and determination of friendly and enemy positions, as well as preparing for and executing contingencies like tactical recovery of aircraft and personnel (TRAP). The commander can also exploit ISR and communication capabilities provided by SATCOM enabled unmanned aerial systems (UASs). These systems are terrestrially based, but SATCOM links enable a farther reach.

(5) Logistics

Even logistic lines are aided by space-based capabilities. PNT permits near real-time tracking of supply locations and shipments and SATCOM provides for more responsive supply movements. SATCOM allows otherwise isolated units to reach back with logistical requests or concerns and also allows for shipments to possibly be redirected in-transit if needs or requests change.

(6) Force Protection

Satellite missile warning systems provide early warning of missile attacks and SATCOM facilitates dissemination of those warning messages all the way down to the tactical level of command, as long as those lines of communication have been established. Also PNT systems and associated FFT systems provide the ability to more vigilantly avoid incidences of fratricide in the execution of kinetic operations.

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IV. THREATS TO SPACE-BASED CAPABILITIES

Areas of space force enhancement are contested and the capabilities are threatened. There are threats to both the space systems and the capabilities they deliver. The enabling capabilities provided to the warfighter by space assets actually come from an integrated network of systems. This network can be broken down into three segments: the ground segment, the space segment, and the communication link segment. Each segment has unique threats to its ability to execute its particular mission set.

A. GROUND SEGMENT

The ground segment of the space systems network includes terrestrially based terminals, both mobile and fixed, antennas, processing facilities, and terrestrial communication links, whether it is cable, fiber optic, or another method connecting these facilities.

There are two main threats to the ground segment of the space network: kinetic attacks and cyberattacks. Kinetic threats include easily imaginable acts as sabotage or an air or ground attack that targets buildings, hardware, antennas, or fiber optic lines of communication. Figure 6 shows how catastrophic an attack on a ground station in wartime can be. Cyber threats can affect both hardware and software and can be used to disrupt operations or damage equipment.

Figure 6. Kuwaiti Satellite Antenna Site Destroyed during 1990 Iraqi Invasion, from [11].

B. SPACE SEGMENT

The space segment consists of on-orbit assets. These are the spacecraft busses and payloads that are generally built to last long periods of time in an inhospitable environment and are often the most expensive component of the network. These systems must by nature be highly reliable and resilient because at the current state of technology, there are few if any practical options or means to repair, refuel, or refit a satellite on orbit if the system or a component thereof fails or is damaged.

There are multiple threats to the space segment of the network. These include kinetic energy weapons, directed energy weapons, and nuclear effects. In addition to these threats originating from adversarial entities, there are threats to the spacecraft that do not come from enemy action. Space debris and the natural space environment present hazards that must be planned for and mitigated. Figure 7 shows examples of both kinetic and directed energy capabilities that have been observed.

One of the reasons space systems can be so susceptible to offensive attack is due to the nature of the predetermined orbits which makes their paths predictable which, in turn, makes them relatively easy to characterize and track.

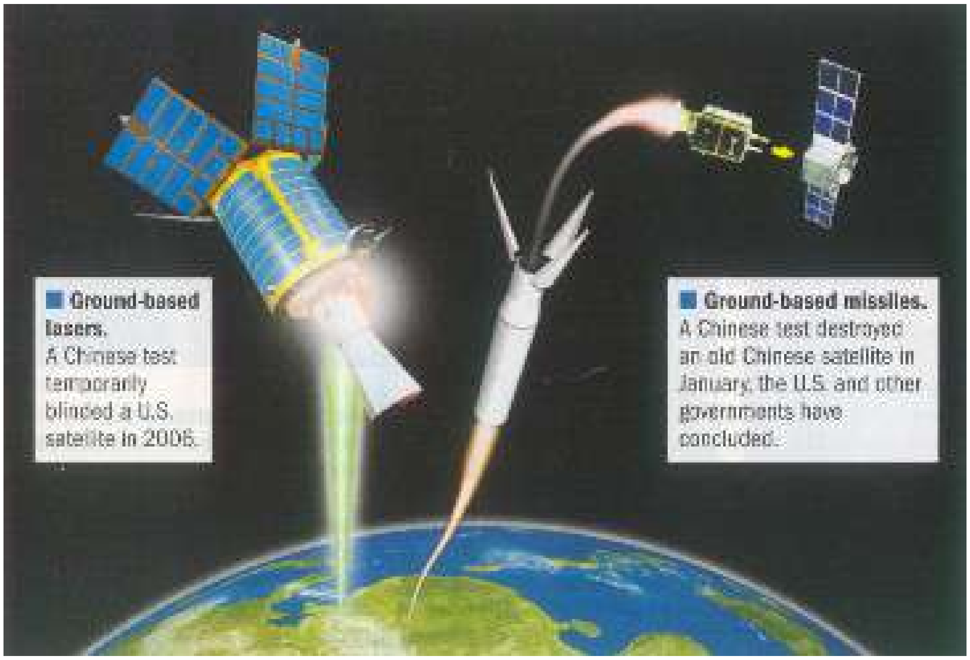

Figure 7. Depiction of Chinese ASAT Capabilities, from [12].

(1) Kinetic Energy Weapons

These hard kill weapons are intended to destroy or render a target satellite inoperable. They are broken down into low-altitude, direct-ascent interceptors; low- and high-altitude, short-duration orbital interceptors; and Long-Duration Orbital Interceptors [13]. The target altitudes and time-of-flight characteristics of these anti-satellite (ASAT) weapons are relatively self-explanatory. The long-duration orbital interceptors are generally intended to be launched and positioned well before a target is even identified and then are activated in the event a target has been selected and becomes targetable.

On 11 January 2007, China launched its first successful direct-ascent ASAT weapon. They launched a land-based, medium-range ballistic missile targeted at a defunct Chinese weather satellite. Although both the United States and Russia had conducted similar successful tests in the past, this was the first test for a non-Cold War contender and was widely seen as highly provocative [14]. On 14 February 2008, the United States launched an SM-3 at a defunct U.S. reconnaissance satellite [15]. Although the stated purpose was to destroy the highly toxic hydrazine fuel on board to mitigate health risks if any of the material survived re-entry, it demonstrated that the United States maintains the same ASAT capability.

(2) Directed Energy Weapons

Directed Energy Weapons are generally intended to overwhelm and incapacitate or destroy sensors and subsystems, but can cause greater irreversible damage given enough power. Laser and radio frequency (RF) weapons can target SATCOM, IMINT, SIGINT, or other ISR assets. Particle beam weapons all fall into this category, as well.

The effects of directed energy weapons against imagery systems can be divided in to the categories of "dazzling" and "blinding." Dazzling implies temporary interference with a system's ability to image, whereas blinding generally refers to permanent damage to a sensor; permanent damage is usually the result of a much higher power energy beam than a beam intended to dazzle [13]. Even if only temporary, this capability negates the ability to image for at least a period of time and that might be just enough for an enemy to conceal a critical activity. It was reported that China has demonstrated the ability to at least dazzle an on-orbit system and has done so against U.S. ISR assets in the past [16].

(3) Nuclear Effects

All segments of a space system are vulnerable to a high altitude or space-based nuclear detonation and its effects. These effects include damage due to blast and shock, thermal radiation, transient nuclear radiation, and electromagnetic pulse (EMP) [17]. Historical tests of nuclear detonation effects in space proved that high energy radiation from a nuclear blast can have disastrous effects on spacecraft and communication links. On July 9, 1962, The United States tested a nuclear weapon at high altitude over the Pacific Ocean. The test was called *Starfish Prime* and detonated a warhead on a Thor missile 400 km (240 miles) above the surface. The blast could be seen from Hawaii over 800 miles away and the resulting EMP knocked out streetlights, power grids, and telephone networks across the Hawaiian Islands [18]. The highly energized electrons from such a blast stay in orbit for extended periods of time and can cause severe damage if they come into contact with spacecraft electronics. *Starfish Prime* was confirmed to have damaged at least six satellites, all of which eventually failed as a result of blast effects, and there were other satellite failures that could possibly have been linked to the blast as well [19].

(4) Space Debris

There are over 20,000 pieces of debris the size of a softball or greater that are currently able to be tracked in orbit and there are an estimated 500,000 pieces the size of a marble or larger [20]. The “big sky, little plane” concept is becoming a thing of the past. Debris from the 2007 Chinese ASAT missile test on the defunct satellite added thousands of pieces to the collection [21]; and in 2009 an Iridium communication satellite and a Russian Cosmos satellite collided and spread into over 1,000 pieces of debris 10 cm or larger and thousands more smaller fragments [22]. Figure 8. shows the tracked debris pattern distribution expansion from that collision over time.

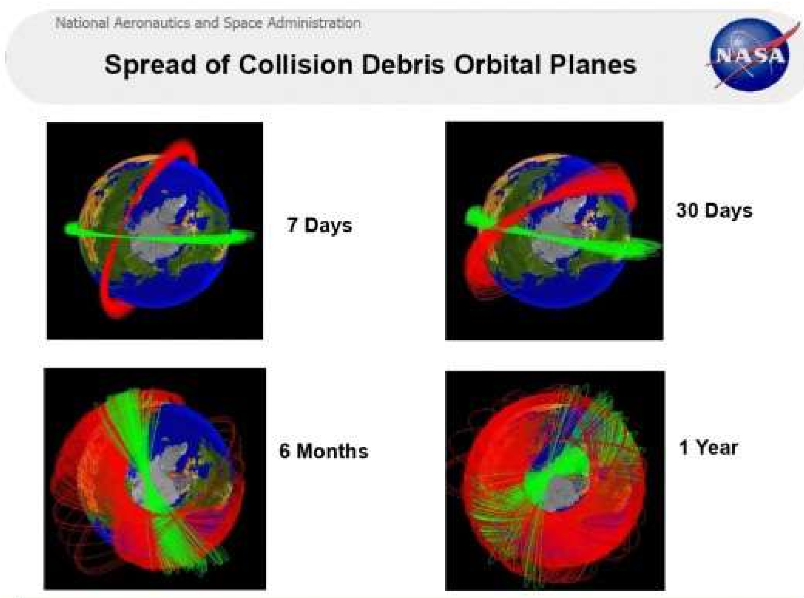

Figure 8. Debris Spread from the Iridium-Cosmos Collision over Time, from [23].

There is everything from spent upper stages of rockets and dead satellites to gloves, tools, and even dust and paint flecks that can still cause serious damage at orbital velocities. Figure 9. shows the results of a half-inch wide impactor after it struck a 7-inch-thick block of aluminum at 15,200 mph (6.8 m/s).

Figure 9. Results of a Half-Inch-Wide Impactor Striking a 7-inch-thick Aluminum Block at 15,200 mph (6.8 km/s), from [23].

(5) Space Environment

The space environment is a naturally hostile and unforgiving setting. There are a number of phenomena that threaten the ability of a space system to operate that must be taken into consideration primarily in the design process. These phenomena are often referred to as space weather and include such factors as atmospheric drag, solar radiation, cosmic radiation, and the highly dynamic thermal environment to name a few. These threats are generally planned for during the design phase of a space system. A spacecraft is generally hardened to endure the expected radiation environment for the duration of its life expectancy. It is important to note that some spacecraft hardening against space environment threats can also benefit the system in the event of a hostile attack.

C. COMMUNICATION LINK SEGMENT

A space system is not useful if it cannot communicate data collected, relay information, whether voice or data, or if the signal is interfered with or manipulated to cause false or corrupted data to be transmitted or received. This threat is not restricted to SATCOM; communication signals can conceivably be affected between ISR assets and the ground stations receiving collected data, and adversaries can interfere with SIGINT and radar collection, as well as any telemetry, tracking, and control (TT&C) link between a satellite and its controlling ground station.

1. Jamming

The target of jamming is to interfere with the reception of a communication signal. It is important to note that any transmitter can generally be employed as a jammer which offers insight as to why jamming technology and techniques have proliferated so much around the world.

There are hundreds of communications satellites and each satellite can host dozens to hundreds of signals. Signal transmissions are assigned to different satellites, center frequencies, polarizations, and bandwidths in order to avoid interference [24]. When signals overlap or conflict in any of these areas, it creates interference—jamming is intentional interference.

A jammer needs three things to be effective. First, the jammer must have sufficient power to disrupt reception. Second, the jammer must match the frequency of the targeted signal. Third, the jammer must have access to the receiver. A jammer does not affect the transmission of a signal; it must have access to the signal path and will affect reception [24].

In order to close a communications link, the transmitted signal must achieve a sufficient signal-to-noise ratio (SNR), or bit error rate to noise spectral density (E_b/N_o) for digital communications. The SNR and E_b/N_o is measured at the receiver and is a function of the power, modulation scheme, data rate, and error correction methods like forward error correction (FEC). Generally, the received signal must be stronger than the background noise, or the noise floor, in order for the signal to be received and effectively interpreted. Figures 10 and 11 depict examples of a signal strong enough to close a link and an underpowered signal that will not be able to close a link, respectively.

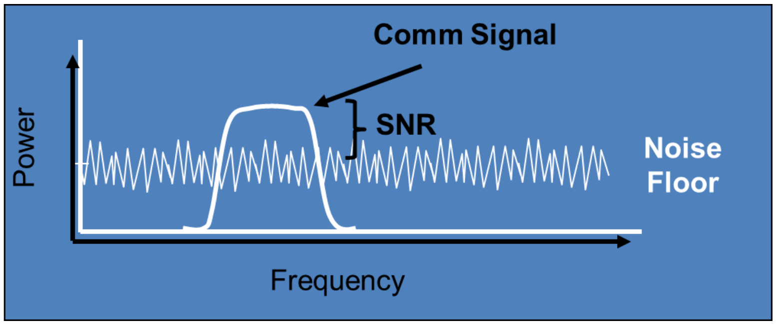

Figure 10. Signal with Enough Power to be Detected above the Noise Floor, from [24].

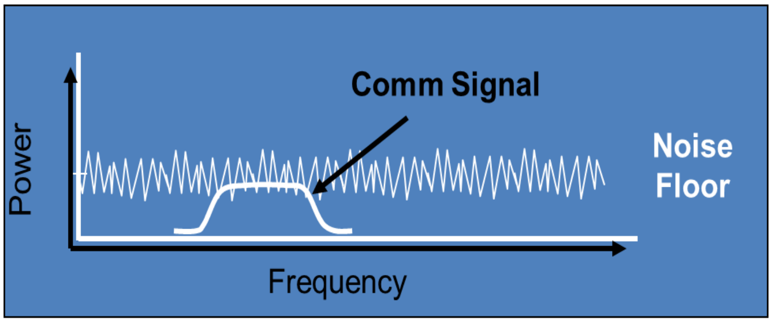

Figure 11. An Underpowered Signal Hidden below the Noise Floor, from [24].

A jamming signal essentially increases the noise floor over the targeted frequency. The jamming signal decreases the SNR to the point that the signal is lost or suffers from significant errors (see Figure 12).

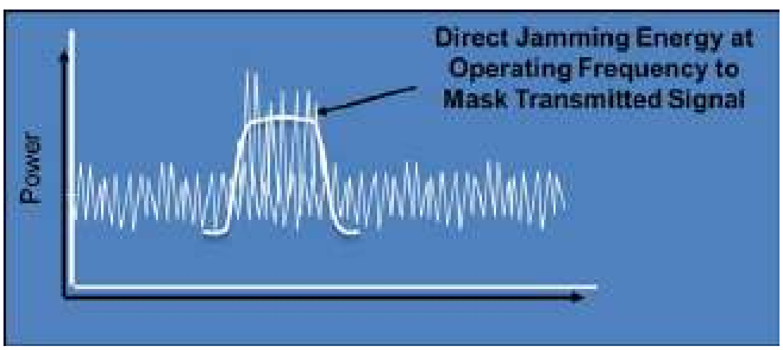

Figure 12. An Example of a Jammed Signal, from [24].

There are three main types of jamming: barrage jamming, spot jamming, and hopping or swept jamming. Jamming can also be targeted at either a terrestrial receiver, called downlink jamming, or at an on-orbit receiver, called uplink jamming.

Barrage jamming, also known as "wideband jamming," is characterized by a signal that is transmitted across a broad range of the electromagnetic spectrum (see Figure 13). The intention is to jam multiple signals using a wideband waveform. This method is simple and effective, but because the power is spread across a range of frequencies, more power is required to be able to affect the full spectrum. This can be wasteful of jammer power if there are only a few actual target signals within that spectrum.

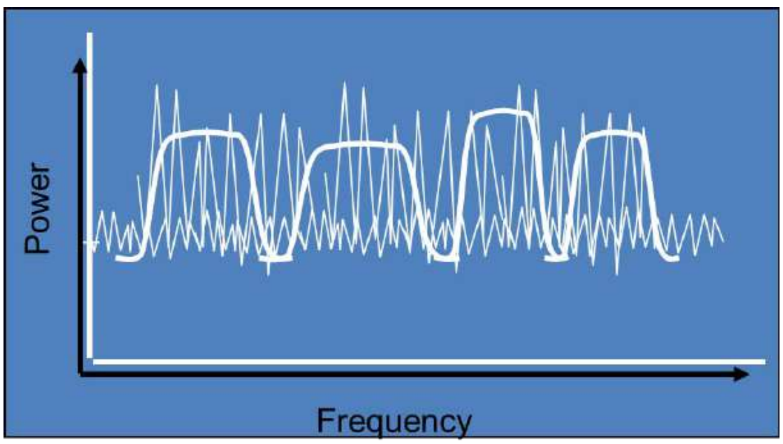

Figure 13. Barrage Jamming, from [24].

Spot jamming, or "narrowband jamming," targets a specific portion or frequency of the spectrum (see Figure 14). The advantage to spot jamming is the power can be focused on a specific band allowing a stronger influence over that targeted frequency. A spot jammer can conduct multiple spot jamming attacks as long as there are the requisite additional signal generators and power available.

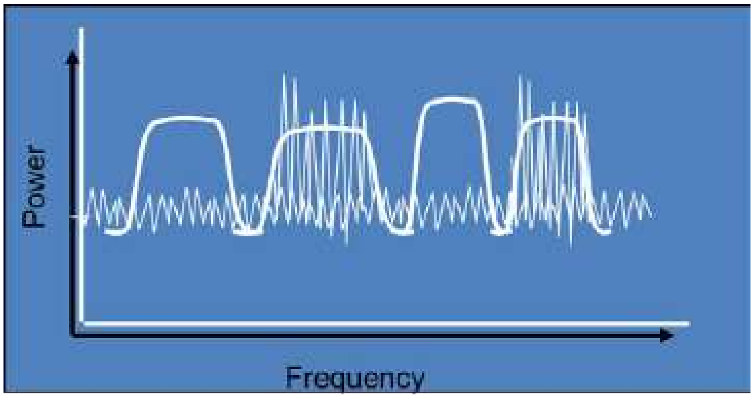

Figure 14. Spot Jamming, from [24].

Hopped/Swept Jamming uses a narrowband waveform to hop or sweep across multiple target signals. This is a simpler form of jamming that allows a jammer to concentrate power and affect more target frequencies (see Figure 15). However, the duration of impact on each of the target signals will be diminished and therefore will be less effective than a continuous jammer.

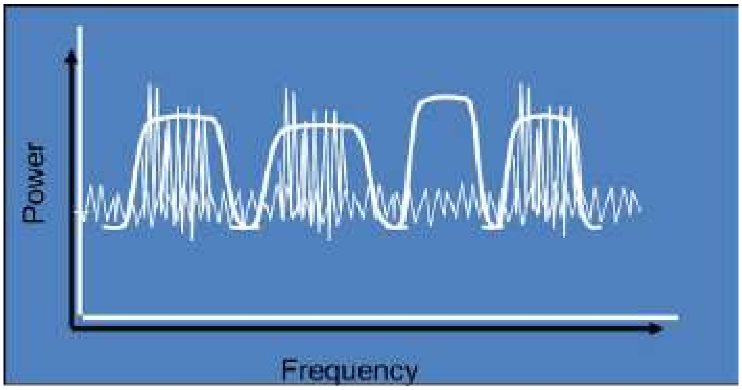

Figure 15. Hopped or Swept Jamming, from [24].

Uplink Jamming is when the interfering signal is targeted at the satellite receivers (see Figure 16). It is the easiest and most common type of jamming because the satellite is generally exposed and the antennas are easily accessed because they are pointed at the surface of the earth. The jammer needs only to be in the uplink footprint regardless of where the targeted ground receivers are. This form of jamming will generally be targeted at SATCOM and TT&C signals.

Figure 16. Examples of Uplink and Downlink Jamming, from [25].

Downlink Jamming targets the terrestrial receivers (see Figure 16). This is generally more difficult because the location of the receiver must be known and jammer must be within line of sight of the receiving antennas signal reception pattern in order to affect the incoming signal. This method of jamming lends itself to airborne jammers. However, all antennas have side lobes in addition to the main signal lobe; the size and extent of the lobes are a function of the antenna design and frequency. Although it will require more power from a jammer, if a jammer can get access to one of the side-lobes, the jammer can have the same effect on the receiver as if it had access to the main lobe. This opens the door for ground-based jammers that would otherwise not have access to a signal if an antenna was pointed to an overhead space asset. This form of jamming will generally be targeted at PNT and SATCOM signals.

2. Spoofing

Spoofing is the most insidious threat and also the most difficult to accomplish. The intent is not to block an incoming signal, but to fool a receiving antenna into believing an erroneous signal is legitimate (see Figure 17). In the realm of PNT, this could include retransmission of a legitimate signal from another location to confuse a receiver or steadily feeding a signal that causes the receiver to lead the system to a specific alternate route. In all forms, this is a relatively more difficult effect because the exact nature of the transmitted signal must be known and replicated by the spoofing system. Spoofing signals will most likely be targeted at PNT, but SATCOM and TT&C links can also conceivably be spoofed as well.

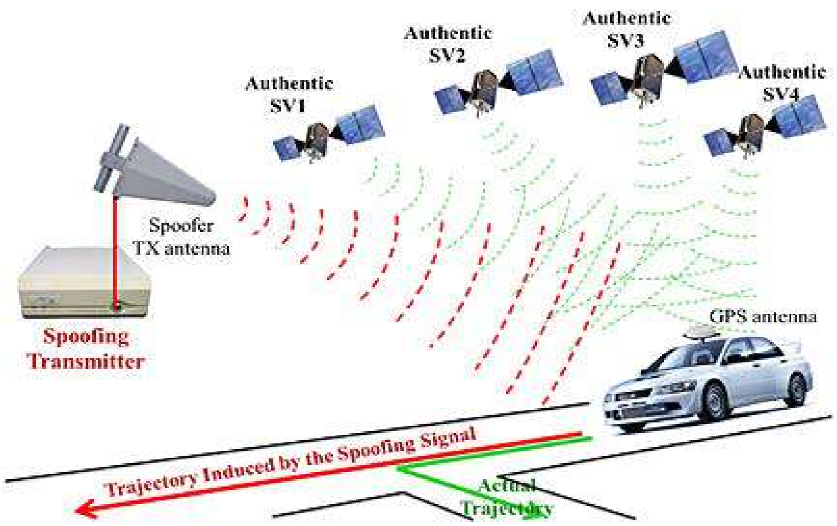

Figure 17. Effects of Spoofing on Navigation Systems, from [26].

3. Direct versus Indirect Effects

Threats can have both direct effects and indirect effects. Jamming or spoofing of PNT receivers directly affects the ability to navigate. However, GPS signals are also heavily used in communications for synchronization of transmission and reception equipment as well as in signal encryption.

V. MARINE CORPS TACTICAL MITIGATION CAPABILITES

The Air Force, Army, and to the extent of UHF SATCOM, the Navy have direct impact on the full spectrum of SFE capabilities as they are the operators of the majority of spacecraft. While the Marine Corps does not own, operate, or manage any space systems, and therefore cannot directly influence their operation, Marines do have the ability to directly apply mitigation tactics, techniques, and procedures (TTPs) to overcome the effects of degradation or denial, specifically in the arenas of SATCOM and PNT. Marines can still integrate considerations for degradation of other SFE areas, but this will generally be a product of the planning process and will take place at higher levels of command.

A. SATCOM

1. Fundamentals of SATCOM

In order to better understand the threats to both civilian and military satellite communication systems, it is important to understand some of the fundamental details about the SATCOM systems and infrastructure in use. These include the frequency bands utilized, the advantages and disadvantages to each of these bands, and an operational design technique known as spot beams.

a. Frequency Bands

There are three main bands in the electromagnetic spectrum that are designated by the United Nations' International Telecommunication Union (ITU) that are used for satellite communications systems, namely ultra-high frequency (UHF, 300MHz to 3 GHz), super high frequency (SHF, 3 GHz to 30 GHz), and extremely high frequency (EHF, 30 GHz to 300 GHz). Each of these bands has applications and advantages and disadvantages in their use (see Figure 18 and Table 2).

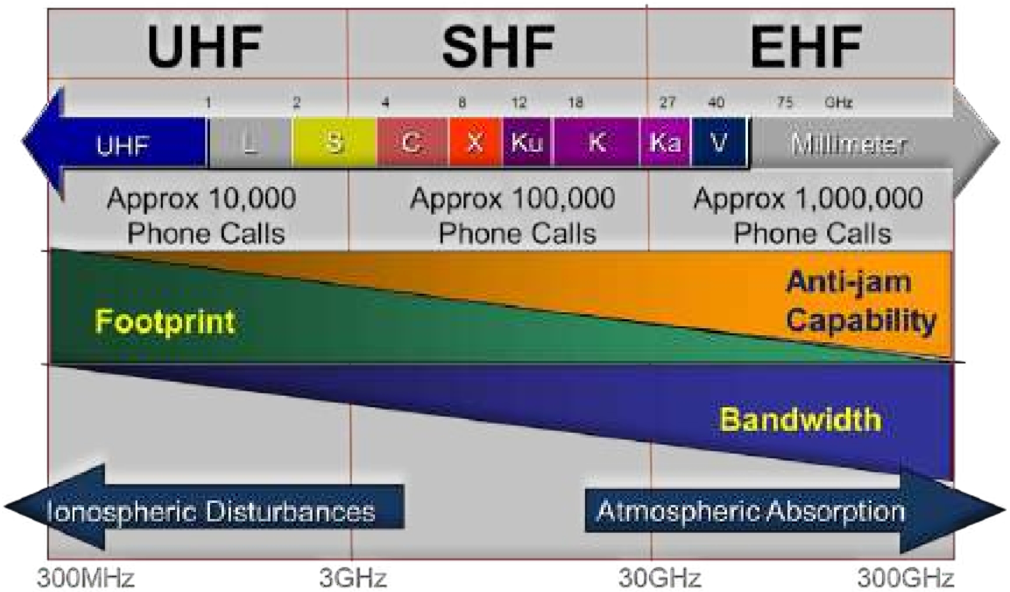

Figure 18. Satellite Communication Frequency Bands, from [26].

(1) UHF

UHF Frequencies offer a number of advantages to the user. First, the UHF frequencies are minimally affected by terrestrial weather and are able to penetrate dense foliage allowing for communication even in triple canopy jungle. UHF terminals allow for a highly mobile user community due to terminals being relatively small and inexpensive as well as the ability to use omnidirectional antennas. The UHF spectrum is also widely used around the world allowing for easier interoperability in joint and combined operations.

Disadvantages to the UHF spectrum include a relatively limited number of channels with limited throughput as compared to other bands. With many of the legacy communication systems, there is limited anti-jam capability due to the systems being transponder-based (also known as “bent pipe”). This means there is no processing done and the signal is retransmitted exactly as it was received, therefor any signal interference between the terrestrial transmitter and the satellite receiver will be retransmitted to the terrestrial receiver. UHF signals in space are susceptible to scintillation which is a function of increased solar activity, other space weather, or a nuclear detonation. Finally, UHF bands are also susceptible to unintentional interference due to the ubiquity of its use around the world.

(2) SHF

These higher frequency bands offer the advantages of greater bandwidth and throughput capacity than UHF signals. This allows for greater use of video teleconferencing (VTC) for planning and briefing, for sensor-to-shooter capabilities and imagery dissemination, as well as near-real-time common operational picture (COP) updates permitting greater situational awareness. These systems also allow for greater protection than UHF systems by incorporating increased anti-jam capabilities as well as low probability of detection (LPD) and low probability of interception (LPI) techniques. These signals are also less susceptible to scintillation than UHF frequencies.

However, SHF signals are more susceptible to atmospheric attenuation, terrestrial weather, and foliage blockage. Also, SHF frequency bands are becoming more crowed as commercial SATCOM systems proliferate.

(3) EHF

EHF frequencies have the greatest bandwidth of the three, allowing for the greatest throughput and/or greatest level of protection. The small beams and the increased capability for spread spectrum modulation schemes enhance the LPI and LPD characteristics. There are also currently fewer users of the EHF spectrum allowing for more freedom in spectrum use. Another significant benefit is EHF frequencies experience little to no effects due to scintillation.

On the down side, EHF signals suffer significantly from atmospheric attenuation and weather in the form of clouds and rain severely degrade the ability to communicate. These systems also have higher power requirements and are more complex and expensive than UHF and SHF systems. The small beams result in less coverage over the ground, limiting the number users that can take advantage of a spot beam.

FREQUENCY SPECTRA	BANDS OF INTEREST	ADVANTAGES	LIMITATIONS
UHF .3-3 GHz	**Military UHF, L, S**	• Small terminals • Economical • Flexible • Highly mobile	• Vulnerable to nuclear event • Susceptible to jamming • Crowded spectrum • Access is difficult
SHF 3-30 GHz	**S, C, X, Ku, K, Ka**	• More bandwidth and channels available • Flexibility in routing • Global connectivity • Less vulnerability to nuclear blackout/scintillation	• Limited frequency allocation • Susceptible to jamming • Ground terminals are large and expensive
EHF 30-300 GHz	**Ka, V, W**	• Extensive bandwidth • Uncrowded spectrum • Jam resistant / LPI • Small equipment • Least vulnerable to blackout / scintillation	• Technologically immature / risky • Susceptible to rain and atmospheric attenuation • Expensive to outfit

Table 2. SATCOM Frequency Utilization Trade-offs, from [27].

b. Spot Beams

A beam from a SATCOM system is the cone in which a communication signal is focused and terminates in what is called a footprint on the surface of the earth. Early communications satellite antennas were designed with hemispherical, or earth-coverage, beams. As frequencies have increased and modulation schemes and other advanced communication technologies have been developed, satellites have progressively been designed to incorporate spot beams (see Figure 19). Spot beams are more focused and the footprints can be shaped to meet operator and user requirements [27].

Spot beams are very useful to improve LPI/LPD characteristics and enable advanced frequency re-use and digital modulation schemes. By being able to target smaller areas or specific receivers on the ground, the risk of third-party interception or interference is reduced, the same frequencies can be used by different users in closer geographical regions, and the power required to transmit is reduced [27].

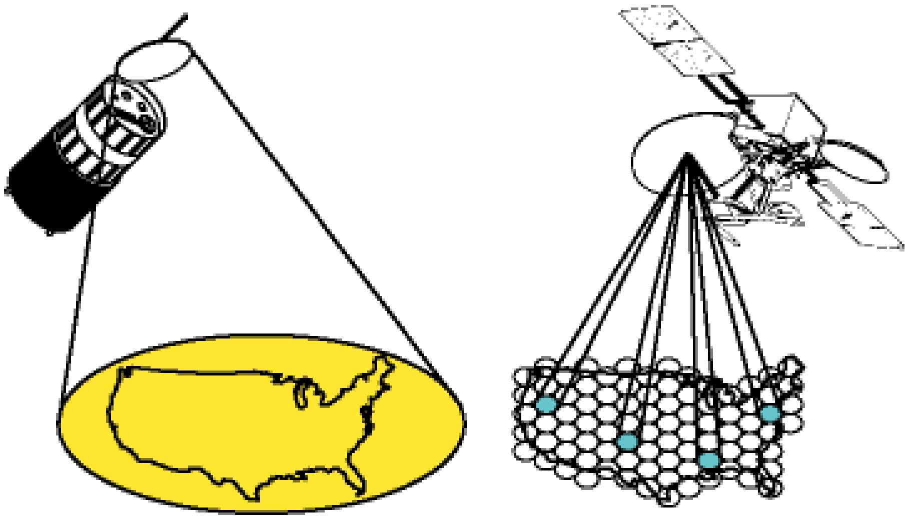

Figure 19. Examples of Hemispherical Beams versus Spot Beams, after [28].

c. *Military SATCOM Systems*

There are dedicated military satellite communication systems providing service in each of the three spectral bands.

There are three systems on orbit providing communication links in the UHF band; two legacy systems, Fleet Satellite Communication System (FLTSATCOM) and UHF Follow-on (UFO), and the new constellation being established, the Mobile User Objective System (MUOS). The U.S. Navy runs the bus and payload operations for each of these systems.

Similarly, there is a legacy system and the current program of record on orbit providing wideband SHF service to the Department of Defense (DOD). The Defense Satellite Communication System (DSCS) is the legacy system and Wideband Global SATCOM (WGS) is the current program of record; the U.S. Army conducts payload operations and control and the U.S. Air Force runs the bus operations.

In the EHF band, Military Strategic and Tactical Relay (MILSTAR) is the legacy system still operating on orbit, and Advanced EHF (AEHF) is the next generation system in operation. Both systems are run by the U.S. Air Force.

d. Civilian SATCOM Systems

Commercial SATCOM is a critical component to the DOD SATCOM infrastructure. Commercial services are often divided into Fixed Satellite Service (FSS), Mobile Satellite Service (MSS), and UHF services [29]. Figure 20. shows the expansion of COMSATCOM usage expressed in the form of expenditures between 2001 and 2010.

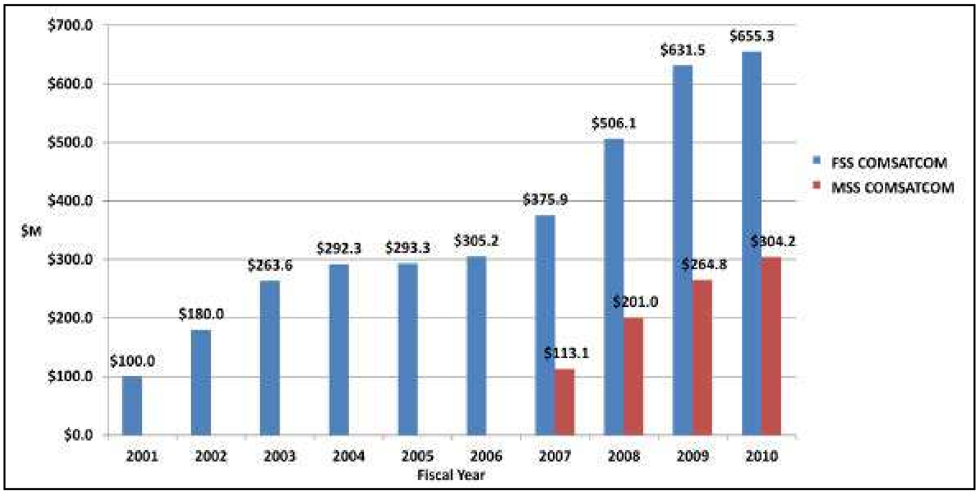

Figure 20. Total DOD FSS and MSS COMSATCOM Annual Expenditures, from [29].

In 2013, commercial SATCOM supported an estimated 40% of DOD SATCOM needs, and was forecasted to grow to 68% over the next decade [30]. The FY15 Presidential Budget contains provisions for $4.5 billion in support of government SATCOM systems. The cost of commercial satellite services is expected to reach $3 to $5 billion in the next 15 years [31]. The GAO reported:

> The Department of Defense (DOD) continues to rely on commercial satellite communications to plan and support operations. DOD use of commercial satellite bandwidth has increased over the past few years, making the department the largest single customer of commercial satellite bandwidth. [32]

Several major satellite communication providers are contracted to provide these services across each of the UHF, SHF, and EHF frequency spectrums. These companies include Inmarsat, ViaSat, Iridium, and Intelsat, among others.

2. DOD SATCOM Use

SATCOM use in the DOD is expanding at an accelerating pace. Figure 21. shows how DOD capacity and usage has expanded from the advent of SATCOM capability.

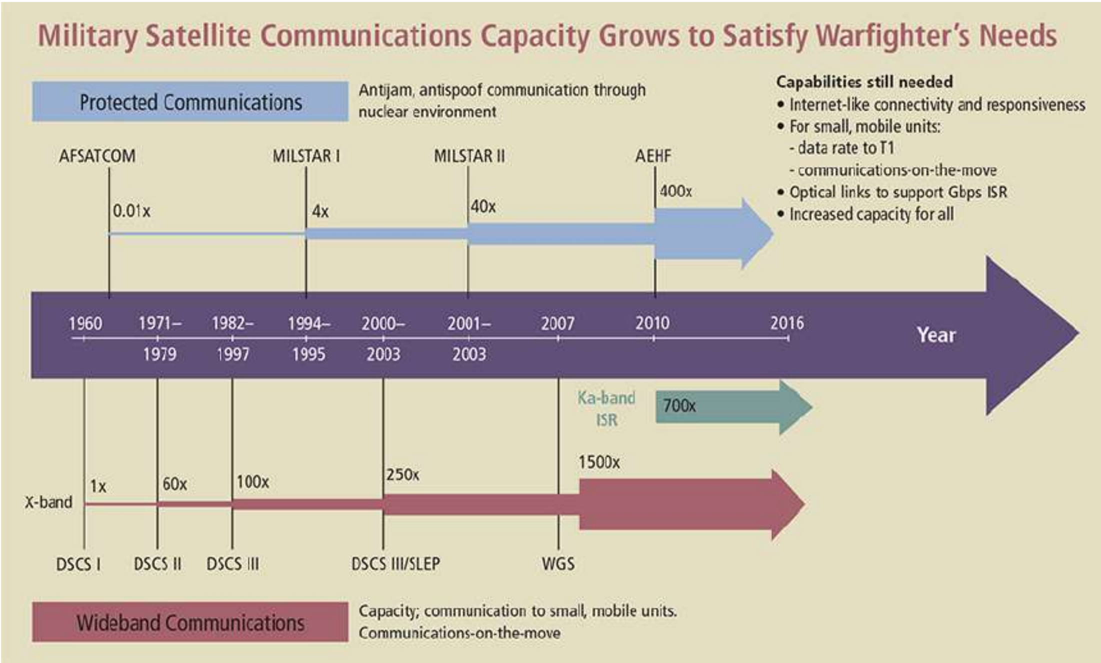

Figure 21. Historical Expansion of DOD SATCOM Use, from [33].

Since Operation DESERT STORM through the initiation of Operation IRAQI FREEDOM in 2003, the military's bandwidth expanded from 100Mbps to approximately 4Gbps. In 2012, one Global Hawk unmanned aerial vehicle (UAV) required approximately 500 Mbps to conduct its mission; that is five times the bandwidth requirement for the entire U.S. military in DESERT STORM [34].

Bandwidth demand has continued to increase as time has progressed and operational tempo has continued to increase, even as major combat operations in Iraq and Afghanistan have wound down. This demand shows no sign of decreasing (see Figure 22). Whether satisfied by DOD systems or commercial SATCOM systems, SATCOM capabilities remain a critical enabling capability, even in the face of very real threats to the infrastructure.

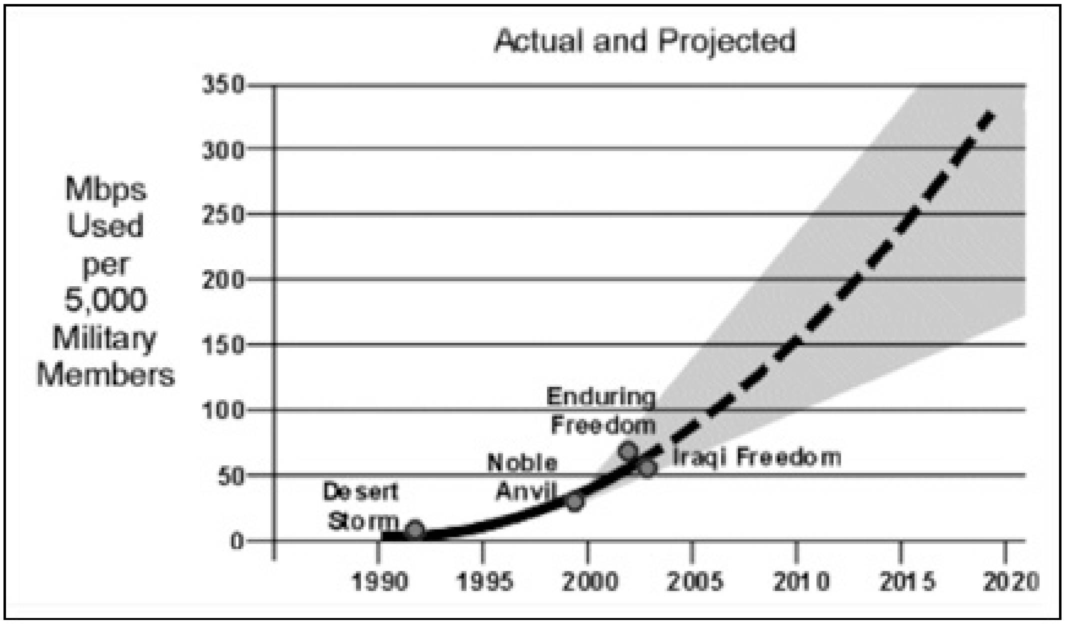

Figure 22. U.S. Military Bandwidth Demands from Desert Storm to Iraqi Freedom, from [33].

3. Mitigating Threats to SATCOM

An in-depth exploration of the full range of mitigation capabilities and TTPs is beyond the scope of this research, but there are a number of basic considerations that should be highlighted and taken into account when dealing with issues related to degraded or denied SATCOM links.

Prior to a mission, planning considerations can be made to reduce vulnerability to threats and to make mitigation implementation smoother. First, make terrestrial lines of communication the primary means of communications to the maximum extent possible. Long distance high frequency (HF) communications are still viable means of communication, even if it has relatively limited bandwidth and quality. Other considerations include having robust secondary and tertiary communication plans and ensuring degradation mitigation steps and alternate communication plans are addressed in rehearsals and exercises.

Once in the execution phase, the first necessary step to effectively overcoming interference is recognizing indications of jamming or other interference and accurately characterizing the nature of the interfering signal. Interference can originate from malfunctioning equipment, overpowered or mistuned friendly communications equipment, interfering effects from space or terrestrial weather or from some other naturally occurring source, or the interference may originate from a malicious source. Something as simple as an oscilloscope can help an operator detect the presence of a jamming signal. For example, knowing the character of the intended signal as represented on an oscilloscope, an interfering signal can be observed and this can offer clues as to the nature of the interfering signal.

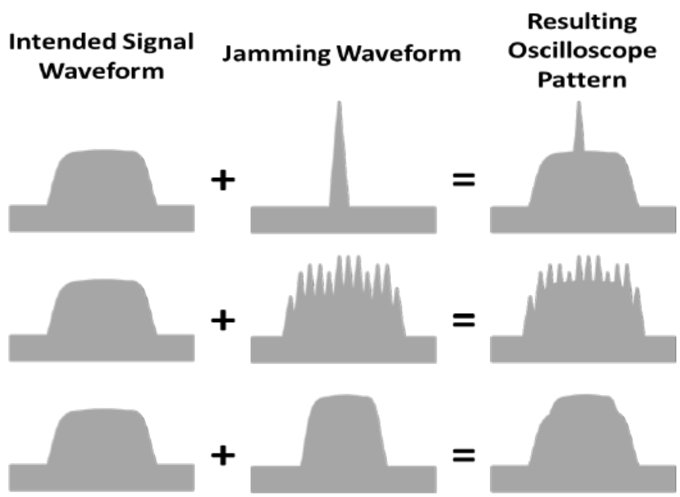

Figure 23. Example of Oscilloscope Readout with Interference, after [24].

Knowing indications of each and methods to rapidly characterize the sources will enable the communicator to resolve the interference or make the necessary adjustments to mitigate the effects on the operations at hand. These mitigation steps can include switching to alternate frequencies or entirely different spectrum bands, depending on the nature of the interference. Transitioning to these alternate communication channels would be a function of the pre-mission planning process.

This interference resolution will often involve interaction and coordination with external agencies. Elevating the reports of interference to higher coordinating levels of command can assist in resolution by identifying if the interference is from an adjacent friendly unit, in which case the command can direct appropriate signal adjustments to resolve the interference. Knowing the proper method and format of reporting can assist higher commands in effectively bringing to bear other capabilities in the areas of characterization, geolocation, and resolution, including joint and national technical means. One of the fundamental means of reporting is the Joint Spectrum Interference Resolution (JSIR) process.[1]

Understanding the threats to communications links is also a vital part of the planning process. Both natural and man-made threats must be taken into account as plans are under development. For example, if adverse space weather is forecast during a planned operation that would degrade critical UHF voice or data communication links, the operational timeline can be adjusted or more robust plans for alternate or secondary communication plans can be put in place. The same considerations can be accounted for in the event of adversarial interference.

The key is building the knowledge and training to the skill sets that will make recognition, characterization, and resolution as fast as possible so interference has as little of a negative impact on operations as possible.

Captain Christopher S. Tsirlis highlighted a few more examples of TTPs that could be implemented to mitigate negative impacts to SATCOM degradation in an article outlining his view that the Marine Corps is over reliant on SATCOM [35]. He endorsed staging data sources as far forward in the battlespace as possible to minimize the need for SATCOM to access the data and leveraging unmanned aircraft or airships with radio relay capabilities to extend the range of terrestrial communications wherever possible. He also proposed increased use of tropospheric communication systems, like the TRC-170.

[1]For more information on the JSIR process, see *Joint Spectrum Interference Resolution Procedures*, CJCSM 3320.02D, Chairman of the Joint Chiefs of Staff, Washington, DC, 2013.

B. PNT

The DOD PNT system, GPS, is based on a constellation of satellites that provide global, continuous, all weather access to signals that provide highly accurate time data which are used for synchronization and to calculate a distance reference to the transmitting satellite. When signals from multiple satellites are combined at a receiver, position and velocity vectors can be calculated to a great degree of accuracy. Because the satellites simply transmit the time-synchronized signal, there can be an unlimited number of users; anyone with an operable receiver has access to the signals.

In order to calculate the basic distance between a receiver and a satellite, the receiver will set an identical pseudo-random noise (PRN) code to that of the satellite upon reception of a signal. The receiver will then compare the continuous reception of this code from the satellite to its own generated code. The difference in timing between these codes will directly correspond to the delay resulting from the time required for the signal to travel from the satellite to the receiver, and thereby the receiver can calculate the range from the satellite to the receiver. The timing must be precise as clock errors result in range and position errors. Signals from multiple satellites can be mensurated to quad-angulate the location and altitude of the receiver.

1. GPS Constellation and Infrastructure

The operational construct provides for 24 satellites in 6 orbital planes, 4 satellites per plane. The orbits are in a 55 degree inclined orbit at approximately 12,550 miles of altitude. This orbital altitude results in a 12-hour, or semi-synchronous, orbital period. This system of satellites provides continuous access to at least 4 satellites anywhere on Earth. There are five monitoring stations dispersed around the world that collect measurements from satellites in view which are sent to the master control station in Colorado Springs, CO, in order to monitor the system accuracy. There are also five separate ground antennas around the world that provide the link for telemetry reception and satellite command. These antennas are remotely controlled by the master control station.

2. GPS Signals

Two available signals are transmitted from the GPS satellites. There is a Precise Positioning Service (PPS) that authorized users have access to that requires the ability to receive a precision code (P-code) signal. Users must have the associated cryptologic hardware and software to decode an encrypted P-code, which also known as a Y-code or P(Y)-code. Users not authorized to use the PPS have access to the Standard Positioning Service (SPS) which is available to all coarse/acquisition (C/A) receivers and is intended for peaceful, civil, commercial, and scientific use [36].

	Precise Positioning Service (PPS)	Standard Positioning Service (SPS)
Position	22 M (Horiz, 95%) 27.7 M (Vert, 95%)	100 M (Horiz, 95%) 156 M (Vert, 95%)
Velocity	0.2 M/S	*0.3 M/S
Time	200 NS	340 NS

Table 3. Accuracy of GPS Services, from [37].

Of note, acquisition of the C/A-code requires relatively high SNR as compared to that required to track a P(Y)-code. This is significant particularly in a jamming environment. If the C/A-code has been acquired, permitting acquisition of the P(Y)-code, then a receiver will be able to maintain lock and access to the GPS signals in the presence of GPS jamming that would block acquisition of the signals.

At one point there was a process available to intentionally degrade the civil GPS clock and ephemeris signal. This degradation capability was called selective availability (SA). Originally it was intended to deny full GPS accuracy for public use; however, President Bill Clinton ordered the discontinuation of SA on 1 May 2000, opening the ten times more accurate signal available for public use [38]. While the United States retains the capability to activate SA on legacy satellites, the Block III GPS satellites do not have the ability to implement SA [39].

Another feature that has been added to the GPS satellites is the Military code or M-Code. This is a signal designed to improve the anti-jam capability and secure access by authorized military users. Whereas previously military receiver had to acquire and lock onto the C/A-code in order to be able to lock on to the P(Y)-code, the M-code is designed for autonomous acquisition, meaning a receiver does not have to have access to the C/A or P(Y) codes in order to acquire a navigation signal [40].

3. NAVWAR and PNT Planning Considerations

Navigation warfare (NAVWAR) involves protecting friendly use of PNT capabilities, primarily GPS, and preventing hostile use of GPS or other PNT systems, all the while trying to minimally impact civil use outside the area of conflict. The lead organization in the U.S. military involved in NAVWAR is the Joint Navigation Warfare Center (JNWC). The JNWC is under Strategic Command's Joint Functional Component Command for Space and is dedicated to enabling PNT superiority to the DOD, combatant commanders, and joint force commanders. The JNWC offers subject matter expertise in planning and conducting NAVWAR operations across the spectrum of conflict and in operational applications and implications. This expertise comes in the form of around the clock availability as well as in deployable teams that can be formed to meet specific operational needs of a requesting command.

There are a number of products that can be of particular use in planning for operational NAVWAR considerations. Some of these products can be JNWC-produced or staffs and operators can be trained to develop them independently given access to the proper resources. One of these products involves determining user range error (URE), aggregate errors associated with the satellite clocks, receiver clocks, atmospheric interference, orbital geometry, and environmental conditions that lead to multipath signal errors. URE graphs, in addition to graphs of local position dilution of precision (PDOP), which is a function of the URE and satellite geometry with respect to a receiver, can provide an idea of the accuracy and precision of GPS signals that can be expected in a geographic location during a specified period of time. These forecasts provide the ability for the appropriate commander, staff, or operator to determine if the expected level of

GPS accuracy and precision meet the minimum criteria that will be required to successfully execute an operation, or if modifications or alternate plans need to be developed to mitigate less than optimal GPS performance. These estimates and forecasts can be developed for standard conditions or they can be modeled to include hostile jamming or other interference.

Another product or tool available that incorporates URE and PDOP predictions, among many others, is the GPS Interference and Navigation Tool (GIANT). GIANT plots are mission-level performance and effectiveness simulations that model GPS signal accuracy and effectiveness. In addition to URE and PDOP, GIANT can model a jamming environment by graphically depicting the effects of a jammer of a specified power in a specified location. This allows for comparing jamming effectiveness against various weapon systems and platforms, where a C/A signal can be acquired and handed off to a P(Y) signal to track before being adversely affected, as well as route planning to mitigate jamming effectiveness [41].

Another capability that can be exploited involves SIGINT detection of GPS jamming signals. Staffs can request data on historical trends of the activity, character, and type of potential jamming signals that have been detected in a particular area and how that activity may or may not have changed recently. Consideration can also be given to requesting additional or more focused and robust collection of GPS jamming signals in a particular area of operation or in the vicinity of priority targets. The next critical step to this would be to ensure that lines of communication are established to be able to funnel SIGINT collects to the operators who will be able to use that information and implement it to adjust plans as necessary.

4. DOD PNT Use

During Operation Desert Storm, less than 8 percent of air-delivered munitions were precision guided, none of which were GPS-guided. Fast forward to Operations Iraqi Freedom and Enduring freedom where the majority of the 70 percent of air-delivered munitions that were precision guided were GPS-guided [42].

In addition to precision munitions, the Marine Corps uses PNT systems for navigation, ranging and targeting systems for fire support, as well as synchronization of cryptographic systems and communications networks. GPS is also used on board satellites to obtain accurate orbital data and to control spacecraft orientation. There are few systems in the DOD inventory that are not either primarily or secondarily enabled by GPS.

5. Mitigating Threats to PNT

As with SATCOM interference, a thorough examination of the range of degradation and denial mitigation capabilities and considerations is beyond the scope of this study. However, there are a number of general considerations that can form a basis upon which training programs and evolutions can be developed to build the necessary skill sets to most effectively mitigate interference with PNT capabilities on the battlefield.

From GPS navigation and tracking to communication synchronization, PNT signals are used at every level of command right down to the rifleman on patrol.

Similar to SATCOM interference, the ability to recognize the indications of jamming or spoofing is a critical skill to develop. It may not be as simple as recognizing the loss of the ability to acquire or track the signal. In navigation, understanding the need to seek out key features along a route and proactively tracking your actual position relative to your intended course is a critical practice. Enough cannot be said about the importance of thorough pre-mission route studies and maintaining the perishable skills of working with a map and compass.

In order to compute navigational data from a GPS signal, the receiver must first acquire the signal and then be able to maintain lock and track the signal along the relative motion between the satellite and receiver. In general, it is more difficult to acquire a signal than it is to track the signal. From the perspective of a jammer, it is much easier to prevent a receiver from acquiring a signal than it is to prevent the receiver from tracking the signal. It often takes much more power to jam an acquired signal. With an understanding of these effects and with appropriate technology and planning considerations in place, operators can significantly mitigate negative impacts that jammers can have on an operation.

In addition to navigational considerations, another important consideration that must be planned for prior to mission execution is the implications of degradation to the accuracy of GPS guided munitions. For example, there can often be a required level of accuracy mandated for a desired certainty of effects on a target or there may be direction as to the level of acceptable collateral damage. If a primarily-GPS guided munition’s accuracy is degraded below that level, either more warheads could be used to ensure desired effects, alternate guidance means or alternate weapons systems could be paired with the target, or the strike could be called off altogether. These contingencies and rules of engagement should be established beforehand to the maximum extent possible and clear chains of communication should be established and exercised in the event of unforeseen circumstances. At absolute least, Marines employing GPS-centric munitions should be able to recognize these effects, understand the implications, and train to the requisite TTPs to mitigate the negative impacts.

Implications of PNT signal interference to communications must also be understood and accounted for. The precise timing signal provided by GPS, with accuracy on the order of nanoseconds, is integrated into terrestrial and celestial voice and data networks and is a fundamental component of frequency modulation schemes and numerous encryption regimes. Communicators must be educated on the extent to which their systems integrate and rely on GPS timing. The training should also include how to distinguish between system malfunctions and hostile interference as well as mitigation strategies like alternate means of synchronization and other TTPs to restore communications links.

Another fundamental training point that GPS users must understand is the difference between the civil and military signals from GPS satellites. This would mainly be focused at ground troops who might find a personal GPS receiver more convenient or easier to use than a military issued system. It is important to know that although seemingly convenient, the civil signal is much more vulnerable to interference, especially in the face of offensive interference in a conflict. This may work well in peacetime, but low-power GPS jamming systems are very inexpensive and easy to acquire or build with off the shelf parts. A better understanding of the implications of civil vs military GPS receivers would help operators make better decisions about what systems to train with and use.

There are a number of products and tools that are available to planners that model PNT capabilities and limitations as they apply to specific scenarios. Staffs and commanders should be informed of these tools and learn how the products can benefit the planning process. Some of these products include location- and time period-specific analysis of URE and PDOP for a target or operational area. This information can offer valuable insight as to the strength and accuracy of GPS signals at the place and time of a strike which in turn permits more effective planning for target pairing to produce maximum desired effects or to minimize collateral damage.

Another valuable planning tool is the GPS Interference and Navigation Tool (GIANT). This is a modeling tool that provides visual and statistical representations of jamming environments and navigation system performance, and can be used to analyze mission impacts. It can be used to model virtually any known jammer and jamming environment and provides intelligence analysts and operational planners a method to pair weapon systems to targets, mold routing plans, and shape plans to maximize the benefits afforded by GPS-enabled assets and capabilities [43].

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VI. MITIGATION EDUCATION AND TRAINING

In order to take advantage of technology and TTPs that mitigate the effects of contested space capabilities, planners and operators must be educated on the threats and mitigation capabilities and be trained to practically employ them. This education and training must include the nature and character of the threats, how to recognize offensive interference and distinguish it from other forms of degradation, understanding and employing mitigation steps, as well as reporting chains and restoration processes. The education must be applied to the planning process and integrated into operational plans. Concurrent to this process, the training must be practically applied and exercised to build skill sets and evaluate the effectiveness of the training and the capabilities of the operators.

A. CHALLENGES TO DEGRADED SPACE IN EXERCISES

There can be significant challenges with inserting space-related injects into a training scenario or exercise. Due to the often critically-enabling nature of many space-based capabilities, if not managed correctly, their loss or degradation in an exercise environment can hinder subsequent training objectives. Implications must be considered, planned for, and optimized during planning conferences in order to provide for the best possible space-related training while still maximizing the most effective training to support the overarching exercise objectives. One method to ensure space-related degradation does not hinder a higher-level integrated exercise would be to arrange space-specific lower-level events to exercise mitigation TTPs prior to the larger exercise.

B. LEVELS WHERE TRAINING IS NEEDED

As previously stated, education and training are fundamental to developing the TTPs and skills that are necessary to operate in a contested space environment. This training and education must take place at all levels, from the MOS trained space professionals all the way to the junior riflemen navigating with a GPS, but the training must, of course, be applicable to the level of involvement with space-related capabilities. Each level has mission specific considerations that can be highlighted and mitigation

TTPs that can be trained to and implemented. The general levels at which this training and education should be addressed and implemented can be divided into three categories: first, the MOS-trained space cadre in the Marine Corps; second, MAGTF commanders, staffs, and planners; and third, the tactical operators.

In order to be effective, the training scenario has to lead the operator, staff, or commander to make a decision. These decision points are what forces the trainees to practically exercise and apply knowledge and develop the necessary and relevant skills so they can be applied operationally when the need arises. Whether the training is space specific or an inject into a larger more complex evolution, decisions need to be made so that consequences can be realized. The consequences and implications of the decisions are where the trainees are able to gain the experience and learn the effectiveness of certain courses of action.

1. Space Professionals

These Space Professionals are the military occupational specialty (MOS)-trained 8866s, Space Operations Officers, and 0540s, Space Operations Staff Officers. 8866 Space Operations Officers represent the Marine Corps' interests in all space related matters where the Marine Corps has a stake including, but not limited to, plans policies, doctrine, and requirements [44]. 0540 Space Operations Staff Officers are also tasked with making recommendations and participating in planning for space considerations [45]; however this MOS is assigned not as a primary MOS (PMOS), but, when earned, is meant to supplement a billet holder's knowledge and expertise in matters where their PMOS and space-related operations overlap. These 8866 and 0540 Marines are primary stakeholders in integration of space into Marine Corps plans and operations. As primary stakeholders, they must know and understand threats to space capabilities and understand operational implications and be versed in mitigation strategies and capabilities in order to be able to ensure the most up-to-date information, technology, and techniques are made available to every level from MAGTF commanders and staffs to the tactical warfighter.

2. MAGTF Commanders and Staff

The next critical level where training and education on the implications of degraded or denied space capabilities must be implemented is at the MAGTF staff level. This includes staffs from the Marine Expeditionary Force (MEF) down to the Marine Expeditionary Brigade (MEB) and Marine Expeditionary Unit (MEU), as well as to Special Purpose MAGTFs (SPMAGTFs) where these considerations are applicable. Implications of degradation or denial of space capabilities primarily impact the staff billets relating to Intelligence (J/G/S-2), Operations (J/G/S-3), Plans (J/G-5), and Communications (J/G/S-6).

a. Intelligence

Commanders and staffs must be able to understand the enemy counter-space capabilities and the implications to operations. Much of this knowledge and analysis should come from the intelligence section. They are the seekers and purveyors of background information and should have the most up-to-date material available on threats and capabilities that the rest of the staff can draw from.

Intelligence staff members must understand the impact degradation of SATCOM links will have on the ability to receive and disseminate intelligence products. This includes imagery, briefs, manuals, intel updates, and every assortment of voice and data transmissions both from higher commands or aboard a ship as well as the ability to push information to operators in need in a timely manner. If a link is degraded, considerations must be made for how much data can flow and the level of fidelity and resolution of intelligence products that can be transmitted in a given period of time if bandwidth is reduced.

Although the Marine Corps intelligence community will not directly take actions to mitigate threats to national and strategic collection assets, they must understand the impact of possibly not having access to products of these systems in the event they are denied by an adversary. This may even include leveraging commercial capabilities.

b. Operations

The Operations Department runs the day-to-day fight and trains and prepares for tomorrow's fight. With the assistance of the intelligence section, they should not only be aware of threats and capabilities, but also have prepared and be trained and ready to execute applicable TTPs to operate through, mitigate, and overcome to the extent possible effects of enemy counter-space operations. They must also ensure the training and TTPs are promulgated and coordinated throughout the lower echelons of command.

Operations staff members should understand the implications of degradation or loss of PNT signals to PGMs and have plans and accommodations in place for additional warheads, alternate means of guidance, or cancelation of strikes for collateral damage considerations. Plans for alternate means of navigation and direction of forces as well as tracking of friendly units should also be accounted for.

They must also have alternate or secondary communication plans in place in the event primary channels are rendered incapable of transmitting required level of voice and data traffic. This will include ensuring lines of communication linking tactical theater ballistic missile warning assets to operational headquarters are in place and continuously operable.

c. Plans

In order to set the Operations Department up for success, the maximum amount of effort should go into the long term planning efforts of the plans divisions of MAGTF staffs with regard to understanding the nature of, planning for, and being postured to mitigate the effects of enemy counter-space capabilities. Understanding and accounting for both enemy and friendly capabilities and limitations will pay immense dividends when the time comes to execute an operation in the face of a counter-space equipped adversary. These planning considerations should go into every level of conflict, from low-intensity conflict with terrorists to full-scale war with a near-peer adversary as the technology and capabilities have proliferated to the extent that they are available to some extent to virtually anyone.

d. Communications

The communications staff is uniquely capable of being poised to have the greatest effect on mitigating the effects of degradation or denial with regard to communications systems. These will be the subject matter experts (SMEs) in recognition, mitigation, and resolution of SATCOM interference. In the event of interference, communicators must be ready to rapidly execute the alternate communication plans as they concurrently attempt to characterize and resolve the interference. They must also activate the requisite reporting chains (utilizing the JSIR, for example) which will aid in further characterization, possible geolocation and resolution of the interference using assets not organic to the MAGTF.

3. Tactical Operators

The effects of adversarial counter-space operations will likely be first encountered by Marines operating at the point of friction in the tactical environment. These operators must be trained to recognize indications of interference and be ready to execute alternate courses of action or mitigation TTPs. This includes the units and individually or group-assigned SMEs operating subordinately to the above mentioned staff positions all the way down to the rifleman. In order to accomplish the required proficiency, applicable space-related education and training must be integrated into MOS schools, unit training, Training and Readiness (T&R) manuals, and exercises. “Applicable” should be emphasized, as not all levels of operators will require the same depth of training or education, but all levels will require training and education to some extent.

One important point that all Marines dealing with space-related capabilities need to be made aware of is the difference between military and civil GPS receivers. All Marines at the tactical level will at one point or another use GPS. Military receivers are designed to receive and decrypt the P(Y)-code making them more robust and accurate once acquired than the C/A-code-only civil receivers. The difference will be even more significant as the M-code capability becomes more proliferated. Civilian receivers have often been independently procured by individuals or units to augment issued military gear in the face of hard to use or unavailable military-issue equipment. While they can be a valuable tool, Marines have to understand the limitations and constraints of civil receivers and the vulnerabilities in the face of interference. The Marines need to have access to and be proficient at using military receivers requisite with their missions, even if harder to use or interface with than a similar civilian receiver. If Marines do not train with military receivers, they will not become proficient. The optimal solution would be to ensure military receivers are as user-friendly as possible and are available to every operator who could use one if it would enhance their ability to execute an assigned mission set, thus eliminating the temptation to use or seek out civilian receivers.

The next area that effective training would be advantageous is that of SATCOM considerations to every level of communications Marines as well as users who may not be MOS-trained communicators. Even a moderate level of background and education on jamming and interference threats and some basic mitigation principles would pay significant dividends in the event that they face adversarial interference.

With respect to intelligence Marines assigned to ground combat element (GCE) and aviation combat element (ACE) components of a MAGTF, similar considerations should be taken into account regarding understanding adversarial space and counter-space capabilities that could have relevant impacts on their unit’s mission. Furthermore, intelligence Marines should have a clear understanding of how the intelligence products they pull from higher echelons and the products they generate are disseminated and how degraded or denied space-based lines of communication will affect that flow.

VII. MARINE CORPS TRAINING VENUES

A. NAVAL POSTGRADUATE SCHOOL

The majority of Marine Corps MOS 8866 Space Operations Officers are educated at the Naval Postgraduate School in Monterey, California. The two-year Space Systems Operations curriculum includes courses in military applications of space, military satellite communications, space control, space systems and operations, and numerous other in-depth space-related courses of study.

This education provides the foundation for the most robust understanding of the implications of space capabilities to Marine Corps operations at the strategic, operational, and tactical levels. This provides the opportunity for 8866s to become the most broadly educated and well versed Marines in matters of threats to space systems and capabilities, implications to combat operations, and mitigation considerations and strategies.

B. NATIONAL SECURITY SPACE INSTITUTE

The National Security Space Institute (NSSI) is an Air Force Space Command school which provides Department of Defense space professionals with continuing education in pursuit of the Space Professional Development Program and offers two main courses: Space 200 and Space 300 [46].

Space 200 is advertised as a mid-career course for space professional education. The course focuses on Space Systems Development and Space Power. The most pertinent objectives that graduates will be able to bring to the fight are an increased understanding of the impact of space mission areas across the range of military operations and the ability to analyze the impact of competitive space and counter-space capabilities involving joint and coalition forces [46]. This course is a qualifying course for MOS 0540, Space Operations Staff Officers, and would be of value to intelligence and communications staff officers, for example, to better understand the space considerations to their domains.

Space 300 is considered a capstone course for space professional education. This course addresses more strategic and operational considerations involving space capabilities. This course covers such topics as space policy and strategy implications to national security, ways to effectively advocate for space capabilities, and effective employment of space capabilities in support of operational and strategic objectives, among others [46]. This course would be of benefit to staff-level space operations officers and provides a broader understanding of space implications and counter-space mitigation considerations, capabilities, and strategies that they could bring back to their fellow staff members and commanders.

C. ADVANCED SPACE OPERATIONS SCHOOL

As a part of Headquarters Air Force Space Command, Air, Space, and Cyberspace Operations (A3), Advanced Space Operations School (ASOpS) provides in-depth courses on space systems, capabilities, requirements, acquisition, strategies and policies in support of joint military operations and national security. ASOpS offers a wide range of education and training courses scoped for all levels from tactical operations to executive space leadership. Of particular note in matters relating to the considerations of degraded or denied space-enabled capabilities, two particular courses are particularly applicable: the Navigation Operations (NAVOPS) Advanced Course and the SATCOM Advanced Course [47].

The NAVOPS Advanced Course is a three-week, application-level course designed to provide an in-depth understanding of the GPS construct and it provides education and training in matters related to NAVOPS and NAVWAR applications, capabilities, threats and countermeasures [47]. This would be a beneficial course for various MAGTF staff members as well as individuals that might be tasked with instructing NAVWAR-related subjects in education portions of training commands and operational exercises. Although more in-depth than most tactical operators will need, staff members will be able to integrate the knowledge in to operational plans and execution and instructors will be able to craft the learning points to be most applicable to an audience.

The 3-week SATCOM Advanced Course provides space and communications professionals with in-depth understanding of SATCOM systems, covering development, acquisition, employment, and sustainment. The course also covers application and employment of SATCOM systems as well as capabilities, limitations, vulnerabilities and effects [47]. This course of study is most applicable to experienced communication officers and MAGTF communications staff members, in general.

D. COMMUNICATIONS SCHOOLS

Marine Corps Communication-Electronics Schools are the foundational schools for training and educating all communications, maintenance, and aviation command and control and defense Marines with the expressed goal of ensuring commanders and operators have access to critical information when and where they want it [48]. Considering the level to which the Marine Corps relies on SATCOM, communication Marines need robust training in threats to SATCOM capabilities as well as interference recognition, characterization, and resident mitigation strategies and capabilities. Furthermore, training involving reporting chains and procedures are important for communicators to understand strategic characterization, mitigation, and resolution capabilities that can be made available to a MAGTF operation.

E. INTELLIGENCE SCHOOLS

Marine Corps intelligence schools ensure Marines are educated and trained to be effective intelligence operators in the various MAGTF intelligence fields [49]. In addition to training on space-related intelligence capabilities and considerations, it is important to provide instruction on the threats and potential impacts to intelligence-gathering capabilities. This includes determining the communication links that are SATCOM dependent and the implications to the reception and dissemination of intelligence products, as well as implications of the threats to space-based ISR assets, and terrestrially-based, SATCOM-dependent ISR assets. It is also important to emphasize the implications of other adversarial counter-space capabilities in order for intelligence Marines to be aware of the need to include those considerations in collection plans and then provide the relevant information to the staffs and commanders they inform.

F. MARINE AVIATION WEAPONS AND TRAINING SQUADRON ONE

Marine Aviation Weapons and Training Squadron One (MAWTS-1), based at Marine Corps Air Station (MCAS) Yuma, Airzona, is the premier training unit for advanced tactical aviation training. MAWTS-1 provides "standardized advanced tactical training and certification of unit instructor qualifications that support Marine Aviation training and readiness and provides assistance in the development and employment of aviation weapons and tactics" [50]. In pursuit of this mission, the squadron hosts the Weapons and Tactics Instructor (WTI) Course. Held twice a year, this course trains the full spectrum of ACE officers from pilots to aviation intelligence and communication Marines in the broad field of Marine Corps aviation as well as MOS specific in-depth advanced training with their respective weapon systems and capabilities. After graduation, the newly minted WTIs return to their respective units to pass along the tactical knowledge and experience.

The WTI course is somewhat of a mix of academic training and tactical exercises. The first three weeks of the WTI course involves intensive classroom instruction and examinations on the overall perspective of Marine Corps aviation capabilities. This would provide a perfect environment to introduce applicable space-related tactical considerations. This could include an introduction to threats to PNT and SATCOM and mitigation strategies they can incorporate at their level. In the subsequent in-flight segment of the course, integrating requisite injects which cause the student to face decision points which force them to draw on the mitigation knowledge and back-up plans would help the students understand the relevance of the threats and afford them the opportunity to internalize the training.

G. MARINE CORPS TACTICS AND OPERATIONS GROUP

Based at Marine Corps Air Ground Combat Center (MCAGCC), Twentynine Palms, California, Marine Corps Tactics and Operations Group (MCTOG) provides advanced and standardized training in MAGTF operations, combined arms training, and battalion and regimental level unit readiness planning [51]. In addition, MCTOG helps standardize doctrine and training standards in order to enhance pre-deployment training and general proficiency of MAGTF GCE units. While MATWS-1 generally focuses on the ACE and on training individuals in a group atmosphere, MCTOG facilitates GCE training of whole units and senior command elements to specifically operate together [51].

While there are standardized large exercises, MCTOG can craft each exercise to fit the specific needs of the unit in training. The MCTOG is postured to provide everything from classroom instruction on planning and operations to large formation combined arms live-fire exercises. There are numerous venues in which appropriately scoped and valuable space degradation and mitigation training could be easily integrated into training evolutions at almost every level of command.

The U.S. Army has a similar training venue in the National Training Center (NTC) at Fort Irwin, California. In order to facilitate and integrate space related considerations and injects into training exercises across the spectrum of operations, the Army has assigned an FA40, the MOS-designation for a Space Professional, to the Operations Group at the NTC [52]. The FA40 will bring in-depth space-related knowledge and experience to curriculum and exercise planning to add fidelity and relevance to the soldiers' training at the NTC.

H. MAGTF STAFF TRAINING PROGRAM

The MAGTF Staff Training Program (MSTP) in Quantico, Virginia focuses on training senior commanders and their staffs by developing a common understanding of MAGTF doctrine and operations across the range of military operations in order to enhance the capabilities to employ a MEB or MEF in Joint and Combined Task Force environments [53]. This provides an ideal forum to inform, educate, and train senior leaders on the implications of degradation or denial of critical space-enabled capabilities and introduce mitigation strategies and capabilities in order for them to be able to apply that knowledge in planning and command.

I. MEF EXERCISES

The Marine Corps continuously conducts MEF-level exercises around the world to develop and exercise operational plans and increase warfighter proficiency. This is another critical venue in which space capabilities and implications of degradation can be observed, experienced, and evaluated. Simulations must be injected into the scenarios that allow operational commanders and their staffs to develop and exercise TTPs that will allow them to fully exploit space capabilities, observe effects of degraded space capabilities, and then mitigate the effects to the point that the operation can continue and the mission can be accomplished. The optimal goal would be to integrate live, realistic scenarios into the conduct of these exercises without sacrificing other training objectives that are otherwise heavily reliant on space-enabled capabilities.

These are the perfect events to showcase the capabilities of the 8866 Space Operations Officer on the MEF staff. This officer can leverage other services, external agencies, and other resources to build scenarios that will exercise the spectrum of capabilities and offer the ability for Marines at every applicable level to experience effects and implement mitigation strategies.

J. OTHER SOURCES OF INSTRUCTION AND TRAINING

Whether in support of the units and venues addressed above or in support of another unit seeking any level of relevant education or training on how degraded or denied space will operationally impact their mission, there are a number of other offices, units, agencies, and other resources that can be leveraged to provide a full spectrum of support to exercises and operations. These organizations and individuals can provide highly valuable and relevant education and training across the spectrum of threats and operations and can be leveraged to support exercises and training programs and may even be individually requested by operational units if there is availability.

1. Marine Corps Subject Matter Experts

8866 Space Operations Officers and 0540 Space Operations Staff Officer are spread throughout the Marine Corps in various staff and operational billets. With in-depth training and experience from above mentioned educational and training programs, they will often be the conduit through which that training is promulgated or facilitated to operators across the Marine Corps.

Information Operations and Space Integration Branch (PLI), a branch of Plans, Policies, and Operations (PP&O), Headquarters Marine Corps (HQMC), is the lead office for all space-related matters for the Marine Corps and coordinates internal and external plans and support that affect MAGTF space operations. This office is also where the 8866 and 0540 Occupational Sponsor resides. These Marines are uniquely well-positioned to advocate for and facilitate increased opportunities for education, training, and support to MAGTF staffs and warfighters involving degradation or denial of space capabilities.

Other entities that are poised to provide support and facilitate more robust training opportunities are 8866s billeted at Marine Forces Strategic Command (MARFORSTRAT) and Joint Forces Component Command for Space (JFCC-Space). These Marines have developed relationships with and have access to points of contact in the Joint space arena which they can leverage to not only advocate for Marine Corps interests in those areas, but also enhance the Marine Corps' ability to learn about and exploit those capabilities.

There should be a simultaneous "push-pull" relationship between Space Operations Marines and units, staffs, and operators that will ensure access to up-to-date, relevant, and applicable space related considerations that can be used to enhance operational capability. Space Operations professionals should push information and inspire an understanding of the critical need to train to operate in the face of degraded or denied critical space capabilities. As this knowledge and understanding becomes further proliferated, units and training venues should be seeking appropriate and relevant training opportunities, especially when preparing for deployments or exercises.

2. U.S. Air Force 527th Space Aggressor Squadron

Aggressor squadrons in the U.S. Air Force are established to provide realistic and highly capable opposition to operational forces in training. The 527th Space Aggressor Squadron (SAS), and its reserve component sister unit, the 26th SAS, are dedicated to providing that capability as it relates to space, cyberspace, intelligence, and RF transmission professionals. Their mission is to prepare operators to fight in and through contested space environments by knowing, teaching, and replicating realistic and relevant space threats [54].

In partnership with numerous intelligence organizations, they focus on learning about up-to-date adversary systems and tactics and industry capabilities and anticipate future threats. They gather information on all threats to space, but they mainly specialize in electronic warfare capabilities. They take this knowledge and provide it to warfighters spanning a wide range of training audiences from aircrew and infantry to communication specialists, satellite operators, and even senior leadership. They can aid in exercise development and execution and play an active part in debriefing processes during and after events or exercises. In addition to academic and planning assistance, the 527th can replicate various threat systems and capabilities in live-training scenarios to varying degrees. This includes GPS jamming and commercial and military SATCOM link jamming, as well as the ability to replicate adversary SATCOM links and nodes [54].

Although highly proficient, the 527th and 26th are relatively small units and are in high demand. They are significantly constrained by manpower and resource availability despite the high demand for support to everything from tactical, operational, and strategic exercises to operational tests and evaluations as well providing academic support to a number of joint education commands. This unit and its capabilities would be very valuable to leverage in many levels of MAGTF training as long as coordination could be made and resources made available to exploit those capabilities.

3. Army Space Support Team

The Army Space Support Team (ARSST) construct is designed to provide a team of trained space professionals that can facilitate access to Army, joint, and national space capabilities for an operational headquarters. The teams are detached from the Army's 1st Space Brigade and attached to supported units; more than 70 teams have deployed to Afghanistan and Iraq since 2001. Teams have also deployed to numerous other sites around the world as well as within the United States where they provided satellite imagery and satellite communications support to civil authorities in support of disaster relief and consequence management operations [55].

The ARSST is designed to support operational commands and in order for them to be most proficient in doing so and for supported commands to be able to best integrate their robust capabilities into their battle rhythm, ARSSTs also deploy in support of operational exercises. The capability integration and command relationship development are a function of exercising this asset which can be made available to an appropriately scoped MAGTF. However, this capability must be planned for and support requests should be submitted as early as possible in the exercise planning process to ensure the assets and services they provide can be most effectively exploited.

4. Other Valuable Resources

There a significant number of other SMEs, agencies and other entities with valuable insight into threats to space capabilities and mitigation strategies and capabilities. Some examples include the JNWC, the National Reconnaissance Office (NRO), Navy Network Warfare Command (NNWC), National Air and Space Intelligence Center (NASIC), and the Missile and Space Intelligence Center (MSIC), to name a few. These agencies can provide MTTs or can be reached by VTC or other means to provide in-depth and mission-specific training and education.

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VIII. THE STATE OF TRAINING AND EDUCATION

A. MEF EXERCISES

As previously mentioned, MEF exercises are critical venues in which space related interference can be integrated which will enable commanders, staffs, and watch officers to exercise tactical and operational mitigation principles and strategies. A recent series of exercises which III MEF has participated in is an excellent example where this type integration has begun. III MEF, headquartered in Okinawa, Japan, participates in two major annual exercises, in coordination with Joint forces and the South Korean military, to exercise plans involving operations on the Korean peninsula, Exercise Key Resolve and Exercise Ulchi Freedom Guardian (UFG). A crawl-walk-run progression was adopted for implementing space-related injects into the III MEF play in the exercises and was primarily driven by the III MEF Space Operations Officer [56].

In Key Resolve 2014 [56], the MEF staff officer coordinated with the white cell to inject a limited number of SATCOM and GPS jamming reports as the scenario progressed. These notional interference reports were intended to exercise reporting chains within the MEF and triggered simulated reports that were then submitted to the white cell. A member of the white cell, with whom the coordination had primarily been made, had previous space experience and could verify the actions were in line with what was expected [54].

Prior to UFG in August of 2014, III MEF reached out to the Director of Space Forces (DS4), the organization responsible for space operations for the Joint Forces, to coordinate a more robust space involvement in III MEF operations as the scenario played out. In addition to the DS4 cell providing more robust space-related products for the MEF staff's planning, the DS4 provided interference injects, as the MEF white cell had done in Key Resolve 2014. This provided for more involved and higher fidelity injects as well as the exercising of external reporting chains. This also helped build a better understanding of capabilities and limitations among the units and established a stronger relationship between MEF and Joint space entities [56].

In Key Resolve 2015 [56], even more fidelity was added to the play of space in the MEF's conduct of the exercise. Instead of the Space Operations officer being the sole main player in dealing with space interference and other space effects, a space operations Marine was posted at the DS4 to help coordinate between the MEF and the DS4 and the interference injects were actually elevated to the Fires and Effects Coordination Cell (FECC). The FECC was then able to make decisions and take actions to mitigate interference based on the information. For example, there was forecasted space weather that was projected to degrade communication capabilities; the decision was made to employ an additional C-130 to serve as a radio relay back-up to a primary communication plan. Additionally, when notional GPS jamming was reported, actions were taken to mitigate the jammer [56].

As this progression shows, there has been significant progress at III MEF in the arena of accounting for degradation or denial of space capabilities. Overall fidelity and effectiveness could be improved by integrating space considerations more fully in planning conferences as well as in debriefs. This is scheduled to occur for UFG 2015 [56] and will prove invaluable for all parties involved.

B. COMMUNICATIONS SCHOOL

There have been a number of significant advances in educating Marines with respect to SATCOM degradation and denial. The communications schools, directed by the Communications Training Battalion, is currently re-working the full curriculum for the Warrant Officer Communications Course to include a robust curriculum including threats and response planning and coordination, with a plan to implement the curriculum in July of 2015 [57]. The Appendix shows the class titles and durations of the pending curriculum. As these subjects are integrated into the Warrant Officer Communications Course, applicable threat and mitigation education and training will be incrementally integrated into other curricula at the communications schoolhouse [57].

Other initiatives at the Marine Corps Communication Training Battalion involve seeking out other valuable sources of education and training regarding SATCOM degradation and denial. The battalion Operations Officer was able to attend the NSSI

Advanced SATCOM course and suggested there are a number of key billet-holders that would benefit from taking the course [58]. This is an example of further outreach by the schoolhouse to expand the quality and quantity of applicable contested space training.

C. MAWTS-1

A majority of the scenarios in the WTI course have a GPS jammer briefed to the pilots by Intelligence Marines in pre-flight briefs and instructors will often secure a student's GPS in flight to simulate a GPS outage. Students are also forced to account for GPS denial in weaponeering their flights and in ground exercises [59]. While this is relatively low fidelity, considerations are being made to integrate more live, realistic effects into more domains of the course and increase their fidelity. MAWTS-1 has been engaging the NRO for classes to intelligence WTI students and other external agencies for academic training points [60], [61]; this and additional steps such as engaging in space related tactical demonstrations (TACDEMOs) [62], requesting support from the 527th SAS [54], [63], and other cooperative activities with external entities, demonstrate they are actively seeking an expanded integration of relevant training points involving operation in and through degraded or denied space.

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IX. RECOMMENDATIONS FOR EXPANDING IMPLEMENTATION

While there are positive indications that education and training to operate in a degraded or denied space environment are expanding to fill the gap, there is significant room and a critical need for further expansion in the breadth and depth of training integrated across the spectrum of academic and practical application scenarios. The Marine Corps must leverage internal assets, develop and expand schoolhouse education and training, integrate contested space more fully in tactical and operational exercises, and leverage external assets to enhance each of these initiatives.

(1) Leverage Internal Assets

In order to facilitate integration of space degradation and denial into the full range of applicable venues, space professionals from PLI, MARFORSTRAT, JFCC-Space, and MEF staff Space Operations Officers can provide the initiative to promote and facilitate this integration into the day-to-day view of operational units. 0540s and space professionals not currently serving in space-specific billets can also provide valuable insight and initiative to promote and facilitate more robust training points and considerations to their respective commands and operational responsibilities.

(2) Expand Schoolhouse and Staff Education and Training

With the assistance and support of the cadre of space professionals, schoolhouse education and training should be expanded to include relevant, MOS-specific considerations for, implications of, and mitigation strategies for contested space. This includes communication and intelligence schools, from initial MOS schools, to advanced MOS and professional development schools. These considerations should also be included in the MSTP curriculum for commanders and staffs with respect to applying these principles in mission planning and execution.

(3) Integrate Training in Tactical and Operational Exercises

In addition to education and initial training venues, these principles should also be integrated into tactical and operational exercises across the spectrum of MAGTF operations. This includes unit-level training, pre-deployment training, MAWTS-1 WTI classes, large unit exercises overseen by the MCTOG, MEF-level exercises, command post exercises, and even MEU certification exercises overseen by a Special Operations Training Group (SOTG). There is a place in each of these venues for relevant and valuable training points to be introduced and/or exercised to every Marine and level of command.

(4) Leverage External Assets

There are numerous entities external to the Marine Corps that have extraordinary capability to enhance the Marine Corps' training, education, and operational capabilities. To varying extents, the Air Force's 527th SAS, the 1st Space Brigade's ARSSTs, and a vast number of other agency SMEs and MTTs can all provide knowledge, expertise, and capabilities otherwise unavailable to the Marine Corps. Although these capabilities may be limited at times to varying degrees in funding or availability, rare would be the case that every effort would not be made to do everything in their power to support a requesting organization to the maximum extent they are able. These organizations understand the critical nature of training and education in overcoming obstacles that arise due to degraded or denied space-enabled capabilities and are generally highly motivated to assist and promulgate information and valuable training points relevant to their specialties.

APPENDIX. PENDING CURRICULUM FOR THE WARRANT OFFICER COMMUNICATION COURSE

Day	# Hours
Day 1	
Intro to SATCOM History and Organizations	1
SATCOM Systems Overview	1
SATCOM System Environment, Systems, Engineering, and Fundamentals Overview	2
VSAT Training Orientation	0.45
Day 2	
Introduction to SATCOM and Space Block	0.3
Space Organizations and C2 Structures	0.45
Space Environment	1
Atmospheric Effects on Received Signals	0.45
Modulation, FEC and Multiplexing Review	1
SATCOM Engineering I: Payloads, Buses and Architectures	1
SATCOM Engineering II: UHF, SHF and EHF Payloads and Constellations	2
SATCOM Engineering III: Commercial, Coalition and Joint Payloads and Constellations	1
Day 3	
SATCOM Planning I: Intro to SATCOM Planning	1
SATCOM Planning II: Gateway Ops	1
SATCOM Planning III: MILSATCOM	1
SATCOM Planning IV: Joint and NATO Planning	1
SATCOM Planning V: Link Engineering	1
SATCOM Planning VI: Link Engineering TDG	1

SATCOM Planning VII: SATCOM Product Development	1
SATCOM Planning VIII: Resource Planning TDG	0.3
Day 4	
Space and MAGTF Ops Integration	1.5
Amphibious Networks	1
NCTAMS Brief or VTC	1
Joint and Coalition Networks	1
Joint and Coalition Networks VTC	1
Introduction to Degraded and Contested Environments: Threats	1
Transmission Officer Degraded and Contested Ops Considerations	1
Countermeasures, Anti-jamming, Reporting and Response Coordination	1
Day 5	
SATCOM Threat Brief	1
Spectrum-Cyber Threat Brief	1
Introduction to Response Coordination	1
Spectrum Reporting and Response Planning	1
Degraded and Contested Environments Mitigation Management and Planning	1
Introduction to Space Control	1.5
Planning in Degraded Environments TDG	2
Day 6	
Planning in Degraded Environments TDG	2
Policy Brief	1
Foreign SATCOM and Space Tools	1
Future DOD SATCOM	1
Alternate Space Applications	1
EOCC	1

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