Saved by Iridium? An Alternative to GPS

A Monograph

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14. ABSTRACT
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Abstract

Saved by Iridium? An Alternative to GPS by Major Leticia M. Walpole, U.S. Army, 50 pages.

The Department of Defense (DoD) has depended on different space-based assets as critical components to battlefield operations. As technology has evolved, space-based assets have become the eyes and ears of the military. Unfortunately, these assets have become one of the most vulnerable U.S. infrastructures. In 1995, the U.S. Global Positioning System (GPS), a complex and sophisticated space-based asset, became fully operational, providing accurate, reliable, and secure information on position, navigation, and timing to the joint force. The joint force uses GPS navigation to locate objectives and coordinate movement of ground forces and supplies. In addition, cruise missiles, smart bombs, and artillery projectiles currently use GPS to guide them to enemy target coordinates. GPS also provides a timing element that has become critical for the military in communications, computer networks, combat planes, and Unmanned Aerial Vehicles. Space-based technologies reach down into everyday military activity, so interrupting service immediately degrades operations. GPS capabilities are great and adversaries may be quick to deny or degrade them. Currently, there is not an alternative to GPS for ground, air, sea, or space operations. The methods of operating with a degradation or loss of GPS are contingent on the type of operation, whether it is land, sea, air, or space; as the current backup alternatives to GPS can only support one operation at the time. For this reason, it is critical for the joint force to have at least one backup alternative. At this time, the only alternative appears to be space-based, as a space-based alternative can provide simultaneous global coverage more affordably and accurately on PNT to the entire joint force. The most feasible potential space-based alternative to GPS is the existing commercial Iridium system, a sixty-six satellite communication constellation in low-earth orbit, under a program known as the high integrity GPS or iGPS. This constellation would be outfitted to transmit GPS signals to achieve benefits similar to GPS. The Congressional Budget Office recommends that all GPS receivers operate with an additional signal from the U.S. Iridium constellation frequencies and vice versa. If a full space outage happens, a Rapidly Deployable satellite system must be ready to use immediately.

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Acronyms

DoD	Department of Defense
GPS	Global Positioning System
PNT	Position, Navigation, and Timing

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Introduction

Navigation via GPS is ubiquitous. GPS conducts navigation for vehicles, soldiers, and artillery rounds only as long as service is accessible, not blocked, degraded, or destroyed.

> For centuries, explorers have navigated by fixed stars. Today our increasingly expeditionary military navigates by orbiting emitters. Satellites enable flexible communication and precise navigation that were unimaginable a generation ago. Space-based technologies reach down into everyday military business so much that interrupted service immediately and fundamentally degrades operations.[1]

"Adams describes various threats to US satellites, systems that use their signals and a military that depends on falling stars."[2]

At the present time, there is not one single ground, sea, aerial, or space system that can fully backup the utility of GPS to the military's operational capability without making adjustments to an existing system. Depending on the circumstances, if the joint force does not prepare an alternative to GPS, the force personnel and equipment could lose the advantage over the adversary. As the numbers of GPS vulnerabilities are many, at least one single dependable alternative must be in place. Considering the importance of GPS capabilities to battlefield operations, this monograph posits the following research question: How should the joint force continue battlefield operations in the event of degradation or loss of GPS?

In 1995, GPS became fully operational and since then the military has benefited from this extraordinary technology.[3] GPS is a space-based system that provides position,[4] navigation,[5] and

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[1]Thomas K. Adams, "10 GPS Vulnerabilities," http://www.c4i.org/gps-adams.html (accessed 17 April 2012).

[2]Ibid.

[3]Congressional Budget Office, *The Global Positioning System for Military Users: Current Modernization Plans and Alternatives* (Washington, DC: Government Printing Office, 2011), 23.

[4]Department of Commerce, *National Space Based PNT Policy* (Washington, DC: Government Printing Office, December 2004), http://www.pnt.gov/101/ (accessed 1 July 2011). "Positioning, the ability to accurately and precisely determine one's location and orientation two dimensionally (or three dimensionally when required) referenced to a standard geodetic system (such as World Geodetic System 1984, or WGS84)."

timing,[6] known as PNT or PVT (where the "V" is for velocity).[7] As stated in Joint Publication 3-14, *Space Operations*, "GPS PPS [position precise system] and inertial navigation systems are the only authorized PNT sources for all military operations,"[8] but it is important to understand that the function of the inertial navigation systems acts as the glue to make the GPS systems work properly.[9] Table 1 is a representation of the synchronization of GPS functional alignment in space. The author will use these variables to set the first evaluation and elimination criteria to identify the alternative to GPS. These variables are the most important ones, and they show how GPS conducts all simultaneous operations in four operational domains for the warfighter on the battlefield.

Table 1. GPS Functional Alignment in Space

POSITIONING	Latitude	Longitude	Height	**PVT or PNT**
NAVIGATION	Velocity East	Velocity North	Velocity Up	
TIMING	Time			

These variables would be the first evaluation criteria in relation to land, sea, air, and space as the most significant applications indicated in table 2.

Significance

Field Manual 5-0, *The Operations Process* states, "Initiative gives all operations the spirit, if not the form, of the offense. Operationally, seizing the initiative requires leaders to

[5]Department of Commerce, *National Space Based PNT Policy*. "Navigation, the ability to determine current and desired position (relative or absolute) and apply corrections to course, orientation, and speed to attain a desired position anywhere around the world, from sub-surface to surface and from surface to space."

[6]Department of Commerce, *National Space Based PNT Policy*. "Timing, the ability to acquire and maintain accurate and precise time from a standard (Coordinated Universal Time, or UTC), anywhere in the world and within user-defined timeliness parameters. Timing includes time transfer."

[7]Department of Commerce, *National Space Based PNT Policy*.

[8]Joint Chiefs of Staff, Joint Publication (JP) 3-14, *Space Operations* (Washington, DC: Government Printing Office, 2009), E-1.

[9]Ibid.

anticipate events so their joint forces can see and exploit opportunities faster than the enemy can or a situation deteriorates."[10] Space is a domain that no nation owns, but that all rely on and that is becoming increasingly congested, contested, and competitive.[11] In the author's view, the U.S. currently leads the world in space advantage and supremacy, and such a benefit implies great risk. If something were to happen to deny access to space, the U.S. would be the most affected, and other countries know this. The enemy presents itself at any time, at any place, in many shapes and forms, often for no apparent reason. As Ecclesiastes 9:18 states, "Wisdom is better than weapons of war, but one sinner destroys much good."[12] For this reason, "our military and intelligence capabilities must be prepared to 'fight through' a degraded environment and defeat attacks targeted at our space systems and supporting infrastructure. We must deny and defeat an adversary's ability to achieve its objectives."[13] JP 3-14, *Space Operations* states, "GPS plays a key role in military operations in all four domains (land, sea, air, and space) and is likely to do so well into the future. Capabilities are increasing across the space, control, and user segments."[14] Represented in table 2 are the indications of these exceptional benefits. A few examples of the land operations GPS applications are: "The inherent precision of GPS allows precise site surveys, emplacement of artillery, target acquisition, and location. GPS establishes a 'common reference grid' within the operational area, enables a 'common time,' helps establish 'common direction,' and facilitates synchronized operations."[15] Table 2 provides the reader with an accurate

[10]Department of the Army, Field Manual (FM) 5-0, *Operations* (Washington, DC: Government Printing Office, 2010), 5-1.

[11]Department of Defense and the Office of the Director of National Intelligence, *National Security Space Strategy* Unclassified Summary (Washington, DC: Government Printing Office, 2011), i.

[12]*The Holy Bible New International Version: Containing the Old Testament and the New Testament*, trans. The Committee on Bible Translation, ed. New York International Bible Society (Grand Rapids, Michigan: Zondervan Bible Publishers, 1978), 723.

[13]Department of Defense and the Office of the Director of National Intelligence, *National Security Space Strategy*, 11.

[14]Joint Chiefs of Staff, Joint Publication (JP) 3-14, *Space Operations*, E-2.

[15]Ibid.

description of some of the significant applications of GPS among the joint force in all four domains. A GPS alternative must be able to perform at the same standards as GPS or better.

Monograph Limitations

This study is unclassified and uses no "For Official Use Only" information. This limits the parameters and depth of the topic and constrains some details of discussion. Technical and scientific calculations are in existence by experts in the fields, including the Johns Hopkins University Applied Physics Laboratory and Iridium Satellite LLC studies. Finally, it did not discuss the implications to civilian Global Positioning System (GPS) uses.

Methodology

Because the focus of this study is not to analyze the technical merits of the alternate systems, it uses existing research from the John Hopkins Applied Physics Laboratory, Iridium Corporation, and other sources and weighs them against joint force variables: Position, Navigation, and Timing (PNT) global coverage, simultaneity, U.S. owned, accuracy, and cost.

Table 2. GPS Significant Applications

Operations on Land
Minefields and obstacles can be accurately surveyed, emplaced, and recorded.
The improved accuracy of artillery fire through precise gun emplacement, precision gun laying, precision observer location, a reduction in adversary target location error, and precision guided artillery and mortar rounds.
Armored units can travel “buttoned-up” and still maintain highly accurate position awareness.
Exact location and navigation information helps logistic support by expediting resupply efforts. The precise information also supports the timely and efficient evacuation of wounded personnel to aid stations.
Enables unit training.
Enables all weather air support.
Operations at Sea
Ships and submarines can precisely plot their position, thereby allowing safe port operations and navigation through restricted waters.
Survey coastlines accurately by using a combination of laser range-finding and highly accurate position information.
Mines can be laid and precisely plotted for friendly force avoidance and safe, efficient retrieval.
Rendezvous at sea, sea rescue, and other operations that require precise tracking can be facilitated using space-based PNT support.
Operations in the Air
Information on PNT enhances airdrop, air refueling, search and rescue, reconnaissance, terminal approach and recovery, low-level navigation, targeting, and precision weapons delivery.
Air corridors for friendly return-to-force procedures can be set with greater accuracy, and aircraft have a greater capability to follow these corridors safely.
Nontraditional ISR and dynamic targeting enables near-real-time reallocation of airborne firepower.
Operations in Space
The GPS navigation service provides exact positioning to other satellites to enable their “position autonomy.” The same service enables “orbital rendezvous” between space systems (e.g., space docking for the space shuttle). It also provides precise time to communications satellites and to systems in geosynchronous orbits. New launch vehicles rely upon GPS position and derived velocity information to aid in determining attitude orientation.

Source: Joint Chiefs of Staff, Joint Publication (JP) 3-14, *Space Operations* (Washington, DC: Government Printing Office, 2009), E-2–E-4.

The military has become so reliant on space-based technologies that any interruption in their services would seriously degrade operations. Space-based technologies reach down into everyday military business so much that interrupted service immediately degrades operations. At this time, no single ground-based or air-based system alternative can completely replace the global availability and accuracy of GPS. The methods of dealing with loss of GPS depend on the situation. What this means is that in the absence of GPS, for example, a convoy that is navigating with the use of a receiver must use the traditional first generation assets (i.e., map and compass) if the GPS signal is lost. At high sea, if a ship loses its GPS signal close to the magnetic poles while navigating through high winds, the use of a map and compass would be less useful than celestial navigation, unless there is severe fog. For this reason, if a reliable, all-scenario, simultaneous alternative is not in place, the possibility of losing the position, navigation, and timing advantage over the adversary exists. In order to maintain an advantage over adversaries, the Department of Defense (DoD) adapted and depended on different assets as critical components to battlefield operations. As technology has evolved, space-based assets have become the eyes and ears of the military.

GPS Advantages

Due to the position of the GPS constellation's infrastructure, control, management, and enhancing capability, an adversary could deploy space assets to attempt to destroy it. In today's world, very few adversaries have the capability to reach semi-synchronous orbits. However, all countries have the right to use space. Space is an extraordinarily complex and violent environment with different implications than terrestrial or airborne environments. It gives great advantages over other nations; the author believes that now and for many years to come, the U.S. has and will continue to have space dominance. *The National Military Strategy* states, "The U.S. is to maintain preeminence in space."[16] Since space has no boundaries or limitations, it is possible to achieve global land-coverage with GPS, which is an advantage the U.S. Army has over most nations at this time. For this reason, "There is a clear linkage between the exploitation of space and the warfighters' ability to achieve success on the battlefield."[17] The Air Force Public Affairs

[16]Joint Chiefs of Staff, *The National Military Strategy of the United States of America Redefining America's Military Leadership* (Washington, DC: Government Printing Office, 2011), 8.

[17]Department of the Army, *United States Army Space Master Plan* (Washington, DC: Government Printing Office, 2000), ES-3.

Agency, 2d Space Operations Squadron Command states, "Since its origin more than 30 years ago, GPS has evolved into an indispensable resource that enables more dependable success in the battlefield."[18]

Understanding these GPS advantages and the principal foundation of the "Future Force" concept to "see first, understand first, act first, and finish decisively,"[19] at the strategic, operational, and tactical levels of operations, we must ensure a secondary system is in place and ready to use. Using space-based assets, the U.S. can obtain the Future Force concept and continue to have advantages over the adversary. Advantages over the adversary significantly improved over the years with the help of GPS.

The author will describe three different scenarios: (1) Before GPS, (2) with limited GPS operational capabilities, and (3) with full operational GPS capabilities. An example of all three scenarios is written in Marcus Baram's article from *ABC News*, which states, "During World War II, tens of thousands were killed by their fellow soldiers."[20] After having limited operational capabilities of GPS, the ratio was less than previous wars "when 17 percent of American casualties were killed or injured due to friendly fire."[21] These two cases had full operational GPS capabilities. Baram further states, "the number of overall friendly fire incidents in Afghanistan and Iraq is quite low."[22] However, studies also show that GPS space-based technologies may not always be available due to their different vulnerabilities. "Space systems are vulnerable to a range of attacks that could disrupt or destroy the ground stations, launch systems or satellites on

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[18]Richard A. Williams, "AF GPS Program Earns International Award," Air Force Space Command, http://www.schriever.af.mil/news/story.asp?id=123275044 (accessed 6 November 2011).

[19]Training and Doctrine Command, TRADOC Pamphlet 525-7-4, *The United States Army's Concept Capability Plan (CCP); Space Operations 2015-2024* (Fort Monroe, VA: Government Printing Office, 2006), 79.

[20]Marcus Baram, "Friendly Fire Deaths Haunt," *ABC News*, 27 March 2007, http://abcnews.go.com/US/story?id=2985261&page=1 (accessed 31 March 2012).

[21]Ibid.

[22]Ibid.

orbit."[23] For this reason, Public Law 106-65 states, "U.S. is an attractive candidate for a 'Space Pearl Harbor.'"[24]

The joint force has an interest in identifying a reliable and accurate alternative to GPS table 3 shows the complex advantages. This alternative must be ready to use to avoid fratricide and to collaborate simultaneously on position, navigation, and timing in all types of scenarios and locations without degradation by a continuous use.[25]

> The threat to the U.S. and its allies in and from space does not command the attention it merits from the departments and agencies of the U.S. Government charged with national security responsibilities. Consequently, evaluation of the threat to U.S. space capabilities currently lacks priority in the competition for collection and analytic resources. Failure to develop credible threat analyses could have serious consequences for the United States. It could leave the U.S. vulnerable to surprises in space and could result in deferred decisions on developing space-based capabilities due to the lack of a validated, well-understood threat.[26]

[23]Commission to Assess United States National Security Space Management and Organization, Report of the Commission to Assess United States National Security Space Management and Organization: Pursuant to Public Law 106-65 (Washington, DC: Government Printing Office, 11 January 2001), http://www.dod.mil/pubs/spaceintro.pdf (accessed 21 August 2011), xii.

[24]Ibid., xiii.

[25]Bengt Boberg, "Robust Navigation: Allowing Other Systems to Support GPS," *Swedish Journal of Military Technology* 3-4 (2005): 27, http://www.foi.se/upload/english/activities/robust-navigation.pdf (accessed 13 January 2012).

[26]Commission to Assess United States National Security Space Management and Organization, Report of the Commission to Assess United States National Security Space Management and Organization: Pursuant to Public Law 106-65, xiii.

Table 3. GPS Advantages

Accuracy
The GPS constellation provides continuous global service. Accuracy of the service is provided by the type of receiver used, the number of satellites in view, and the geometric configuration of those satellites.
Accessibility
Because GPS equipment is passive, it is capable of providing continuous real-time information. Any authorized user with a keyed PPS receiver has access to the most precise position, navigation, and timing information. However, commercial user equipment cannot receive and process the precise positioning service information and is limited to the SPS signal.
Graceful Degradation
Each GPS satellite can store information on board for up to 60 days. In the event that the GPS constellation cannot be updated, accuracy will gradually degrade. The rate of degradation is very slow in the first few days but increases with time. This allows GPS to be used for several days even if the update capabilities are interrupted.
Common Grid
The default navigation grid used by the GPS is the World Geodetic System 1984 (WGS-84). WGS-84 can be easily converted to any grid reference using the terminal device.
Jamming
Space-based navigation systems (e.g., GPS) are resistant to some types of jamming. The use of GPS encryption (like a more robust military code [M- Code]) and nulling antennas/filters, as well as the correct placement of GPS receivers on various platforms, improves jamming resistance. Tactical measures employed by the joint force decrease vulnerability from ground-based jamming (such as placing a hand-held receiver at the bottom of a foxhole).
Anti-Spoofing (A/S)
With the precise capability provided by the GPS, a logical concern is that an adversary could generate false signals to mislead an authorized user with respect to position or timing information. A/S technology is designed to Space-Based Positioning, Navigation, and Timing.
Mitigate receiver confusion that could be caused by intentionally misleading transmissions.
U.S. Owned and Operated
The U.S. has the ability to modernize, replace, enhance, abandon, and encrypt the signal, etc., at any time, by order of the DoD.

Source: Joint Chiefs of Staff, Joint Publication (JP) 3-14, *Space Operations* (Washington, DC: Government Printing Office, 2009), E-2–E-4.

Operational Art

GPS space-based assets are critical because joint force planners and commanders use the operational art elements in relation to space, time, and purpose to achieve full spectrum dominance. The understanding of space assets and capabilities began in the 1960s at the strategic level of war with space-force enhancement. In the 1990s, the distribution of space assets shifted from the strategic level of war to the operational and tactical levels of war.[27] Table 4 shows that not all the elements of operational art apply to space, but planners must consider them when conducting mission planning. Joint Publication (JP) 3-14, *Space Operations* states:

> Since operational art integrates ends, ways, and means across the levels of war, operational art and design should be considered when planning space operations at all levels. Space forces and capabilities can support or enable operational art and design. They are a means to achieve the required end, or a way to support or enable other means to achieve the required end. As such, space forces and capabilities must be considered equally with forces and capabilities in other domains.[28]

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[27]Kendall K. Brown, ed., *Space Power Integration, Perspectives from Space Weapons Officers* (Maxwell Air Force Base, AL: Air University Press, 2006), 120.

[28]Joint Chiefs of Staff, Joint Publication (JP) 3-14, *Space Operations*, V-2–V-3.

Table 4. Characteristics of Operational Design

End State and Objectives
Since space operations are usually in support of other operations, the end state is not usually space specific.
Centers of Gravity (GOGs)
Given our dependency on space capabilities, space should be considered a COG for the joint force commander (JFC). Space assets are also important in helping to identify enemy COGs.
Decisive Points
By correctly identifying and controlling decisive points, a commander can gain a marked advantage over the enemy and greatly influence the outcome of an action. For example, decisive points for the assured access to space are launch complexes and ground stations.
Direct vs. Indirect
In theory, direct attacks against enemy COGs is the most direct path to victory. However, where direct attack means attacking into an opponent's strength, JFCs should seek an indirect approach. If public support for military operations is an adversary's COG, then the use of SATCOM to deliver IO messages is an example of an indirect approach against an adversary's COG.
Lines of Operations
As JFCs visualize the design of the operation, they may use multiple lines of operations. Generally, lines of operations describe the linkage of various actions on nodes and/or decisive points with an operational or strategic objective. In as much as space operations support most operations, lines of operations may be a factor during space planning.
Operational Reach
Operational reach is the duration and distance across which a unit can successfully employ military capabilities. Since national boundaries do not extend into space, satellites may provide the most timely access to denied areas.
Simultaneity and Depth
The intent of simultaneity and depth is to bring both military and nonmilitary power to bear concurrently across the tactical, operational, and strategic levels of war, to overwhelm the adversary across multiple domains, thus disrupting the opponent's decision cycle causing failure of their moral and physical cohesion. PNT and SATCOM enable precision operations on a global scale and can be optimized to provide capabilities anywhere within a theater, or within multiple theaters. Additionally, space force enhancement contributes to the establishment and maintenance of a space common operating picture, which is critical to carrying out simultaneity and depth in joint operations.
Timing and Tempo
The joint force should conduct operations at a tempo and time that best exploits friendly capabilities and inhibits the enemy. With proper timing, JFCs can dominate the action, remain unpredictable, and operate beyond the enemy's ability to react. For instance, the employment of offensive space control (OSC) capabilities against adversary communications can inhibit the enemy's timing and tempo.

Source: Joint Chiefs of Staff, Joint Publication (JP) 3-14, *Space Operations* (Washington, DC: Government Printing Office, 2009), V-3–V-5.

GPS Vulnerabilities

There are many vulnerabilities that can prevent the Navigation System for Timing and Ranging, also referred to as GPS, from functioning correctly (see tables 5 and 6). For example, "disruptions in service could require military forces to either use larger munitions or to use more munitions on the same target to achieve the same level of success."[29] The methods of dealing with the loss of precision and accuracy of GPS during operations depend on the situation. The Commission to Assess states:

> Providing active and passive protection to assets that could be at risk during peacetime, crisis or conflict is increasingly urgent. New technologies for microsatellites, hardenes electronics, autonomous operations and reusable launch vehicles are needed to improve the survivability of satellites on orbit as well as the ability to rapidly replace systems that have malfunctioned been disable or been destroyed.[30]

An example of a current system that copes with local jamming of munition delivery is the Joint Direct Attack Munition, a tail kit attached to a dumb bomb.[31] The Joint Direct Attack Munition uses GPS in addition to an inertial measurement unit to give the best solution for precision. While GPS is available (far away from the jammer), a combination of measurements from GPS and the inertial measurement unit to the bomb are working together to acquire the precise target. This combination of measurements continuously corrects the inertial measurement unit precision error. If the jammer burns through and GPS is lost, the inertial measurement unit continues to guide the munition to its target. The inertial measurement unit error grows with time, but the Joint Direct Attack Munition time of flight is short so this is an acceptable solution.

This combination of measurement solutions does not apply to a Soldier's handheld GPS, because the error would be instantaneous as there is not a mechanism on them to maintain the

[29]Chistina Chaplain, *Global Positioning System: Significant Challenges in Sustaining and Upgrading Widely used Capabilities* (Washington DC: Government Printing Office, 2009), 5.

[30]Commission to Assess United States National Security Space Management and Organization, Report of the Commission to Assess United States National Security Space Management and Organization: Pursuant to Public Law 106-65, 32.

[31]Boeing, "Defense, Space and Security; Joint Direct Attack Munition (JDAM)," http://www.boeing.com/defense-space/missiles/jdam/index.htm (accessed 21 December 2011).

receiver on track. For example, it is hard to jam four satellites at once. If the adversary jammed one satellite, the U.S. has the technology now to locate the target and destroy it. In a jammed environment, lives and operations can become vulnerable and immediately at high risk, if old traditional navigation methods are not available. For this reason, a reliable alternative to GPS must be in place that can duplicate what GPS provides during a jammed environment.

Table 5 shows GPS vulnerabilities in three major groups most likely to occur. These three major groups are: (1) hostile actions, (2) controllable risks, and (3) inaction of DoD representatives. Joint Publication 3-14, *Space Operations* states, "Space capabilities are subject to the effects of space weather, including sun spot activity. Additionally, ground-to-satellite links are susceptible to jamming, and C2 facilities are subject to attack."[32] Table 6 describes some of the GPS vulnerabilities in further detail.

Table 5. Three Major Groups of GPS Vulnerabilities

Hostile Attacks	Controllable Risks	Other Vulnerabilities
Direct or Kinetic	Environmental Effects	Self-Induced
Directed Energy or EPW	Space Debris	Human System Element
Nuclear Detonation	No Space Ownership	Doctrine
Terrorist Organizations	Lack of GPS Design in Operational Art	Leadership
Jamming or Spoofing	Light Square Interference	Training
GPS Timing	Signal	Exercises
Limitations of GPS		Scenarios

[32]Joint Chiefs of Staff, Joint Publication (JP) 3-14, *Space Operations*, E-2.

Table 6. Explanation of GPS Vulnerabilities

Limitations of GPS
Adversary exploitation of the Standard Positioning Service (SPS) can reduce the U.S. military advantage.
Jamming GPS
Can adversely affect civil and first responder operations, as well as joint military operations within a geographic area. The stronger the jammer, the larger the affected area. CCDRs and their subordinate JFCs must factor potential GPS jamming into their electronic warfare (EW) plan. Consideration must also be given to friendly interference, which is mitigated via the joint restricted frequency list.
Signals
From at least four satellites are required to build a three-dimensional position and navigation picture (only one signal is needed for timing). Units relying on hand-held GPS receivers in areas of dense vegetation or steep terrain may have diminished GPS capabilities due to the lack of LOS reception of GPS signals.
GPS navigation signals
Are also affected by ionosphere scintillation, tropospheric errors, and signal multipath issues. Receivers capable of two frequency (i.e., some combination of L1, L2, and/or L5) reception minimize errors.
Denial of the GPS "navigation"
Signal may have a direct negative impact on joint systems that have nothing to do with "navigation," This is particularly true for communications systems that rely on GPS timing.

Source: Joint Chiefs of Staff, Joint Publication (JP) 3-14, *Space Operations* (Washington, DC: Government Printing Office, 2009), E-2–E-4.

GPS Alternatives

Because of the vulnerabilities inherent in the GPS system, several different organizations are seeking viable GPS alternatives. The basic requirement for such an alternative would be one with the ability to provide position, navigation, and timing similar to, or better than, GPS. James Jacoby, Paul W. Schick, Frank Richwalski, and Kevin Zamzow point out that "essential requirements for that alternative would be the ability to provide timing performance similar to that of GPS and to distribute coordinated universal time."[33]

Since the beginning of human kind, navigation has played a significant part in the success of battles. Many inventions have evolved to assist with navigation, positioning, and timing, each

[33]James Jacoby et al., *Advantages of a Combined GPS/Loran-C Precision Timing Receiver* (Madison, WI: Locus, Inc., 1999), http://www.timingtechnologies.com/Locus%20Timing99.PDF (accessed 4 September 2011), 2.

one providing better technology and faster operations than the last. Humans have used the sextant, map, and compass for hundreds of years. The map and compass are useful when there are land features to reference. The sextant helps determine latitude from the stars. John Harrison invented the chronometer for the British admiralty in the 1750s to help determine longitude from celestial observation because timing reference of sufficient quality was unavailable. While these methods are still in use today, Soldiers' and Sailors' skills using these tools have atrophied with the fielding of GPS. In today's military, little time is spent training and exercising the skills required to use a map, compass, and sextant. Joint forces should consider these as alternatives when GPS capability is degraded or lost. For simplicity, the best-known GPS alternatives are placed in four main categories: (1) Other Space Constellations, (2) Ground-Based Radio Navigation, (3) Automatic Navigation, and (4) Traditional Navigation Technologies (see table 7). Each one of these major categories has several sub-components, which will be weighed against different evaluation criteria: (1) PNT (Global Coverage), (2) Simultaneity, (3) U.S. Owned, (4) Accuracy, and (5) Cost.

The scope of this paper is not to focus on the numerous complex civilian implications if GPS is degraded or lost or to address any technical or scientific analysis. The author intended to convey the implications to the military and therefore selected evaluation criteria focused on military applications. Table 7 lists the possible alternatives that the author identified for further analysis.

Table 7. Eighteen GPS Alternatives Classified in Four Major Categories

OTHER SPACE CONSTELLATIONS
Iridium
Responsive Constellation
GONASS
GALILEO
BEIDOU-2
IRNSS
GROUND BASED RADIO NAVIGATION
LORAN
LACATA
VHF
DME
INS
AUTOMATIC NAVIGATION
TERCOM
DESMAC
PTAN
Radio Navigation
TRADITIONAL NAVIGATION TECHNOLOGIES
Map
Compass
Chronometer
Sextant

GPS Alternative Analysis

The author selected the following variables to assist in determining the best alternative to GPS.

1. PNT Coverage: The alternative must be able to perform, positioning, timing, and navigation for all military domains globally (land, sea, air, and space).

2. Simultaneity: The alternative must be able to conduct operations simultaneously across all domains, without degradation of capabilities.

3. U.S. Owned: The Alternative should be a U.S. owned and operated system, so that it is available for military use twenty-four hours per day year round with no restrictions or limitations.

4. Accuracy: The alternative must be able to guide the objective to the exact location within centimeters of the desired destination.

5. Cost: The cost of new system implementation must be reasonably cheap compared with the cost of maintaining a full GPS constellation and upgrading the receivers.

In table 8, the author lists eighteen GPS alternatives divided into four major categories, analyzed against the five variables: (1) PNT, (2) simultaneity, (3) U.S. owned, (4) accuracy, and (5) cost. The weight of these variables represents the complex and accurate capabilities of GPS. If the GPS alternative does not at least meet the exact specifications or requirements of GPS, it gets a value of zero. For an alternative to get a value of one, it must at least meet the exact specifications of requirements of GPS or better. The weight of each variable is a comparison between the categories within the same variable, but each variable is not equally weighed. The alternative with the highest total number of met variables is the selected alternative.

Table 8. Alternatives in Relation to Different Variables

ALTERNATIVES	PNT	SIMULTANETTY	U.S. OWNED	ACCURACY	COST	TOTAL
CURRENT SYSTEM						
GPS	1	1	1	1	1	5
OTHER SPACE CONSTELLATIONS						
Iridium	1	1	1	1	1	5
Responsive Constellation	1	1	1	1	0	4
GONASS	1	1	0	1	0	3
GALILEO	1	1	0	1	0	3
BEIDOU-2	0	0	0	1	0	1
IRNSS	0	0	0	0	0	0
GROUND BASED RADIO NAVIGATION						
LORAN	0	0	0	1	0	1
LACATA	0	0	1	1	0	2
VHF	0	1	1	1	0	3
DME	0	1	1	1	0	3
INS	0	0	1	1	1	3
AUTOMATIC NAVIGATION						
TERCOM	0	0	1	1	1	3
DESMAC	0	0	1	1	1	3
PTAN	0	0	1	1	1	3
Radio Navigation	0	0	1	1	1	3
TRADITIONAL NAVIGATION TECHNOLOGIES						
Map	0	0	1	0	1	2
Compass	0	0	1	0	1	2
Chronometer	0	0	1	0	1	2
Sextant	0	0	1	0	1	2

Utilization of Other Space Constellations

Boeing BTL System–Iridium

In May 1998, President Bill Clinton issued an infrastructure protection directive known as PDD-63.[34] This directive identifies GPS as one of the twelve essential infrastructures to the

[34]The White House, Presidential Decision Directive (PDD) 63, *Protecting America's Critical Infrastructures*, 22 May 1998, http://www.fas.org/irp/offdocs/pdd-63.htm (accessed 3 February 2012).

minimum operations of the economy and government.[35] For this reason, the Congressional Budget Office is considering three different alternatives to overcome the vulnerabilities of GPS. The first alternative is to upgrade the antennas in the current GPS receivers. This upgrade would cost DoD millions of dollars.[36] For this reason, the Government Budget Office is looking at different alternatives.

The next alternative, the most favorable to the Congressional Budget Office, is to have the GPS signals retransmitted to modified receivers via the 66-satellite communications constellation. A demonstration of this approach is under the program dubbed High Integrity GPS, or iGPS. Iridium Communications of McLean, Virginia, owns and operates the Iridium constellation. Signals from the low-orbiting Iridium satellites would be less susceptible to jamming than the transmissions from the GPS satellites because the signals are stronger and have less distance to travel to the receivers.[37]

It is surprising to know that a communications constellation can provide an enhancement to GPS. Lt. Gen. John Campbell, Executive Vice President of Government Programs, Iridium, said, "Because of the unique design of our global satellite network, Iridium is able to help deliver such added precision and robustness to this important [GPS] capability used in the U.S. Department of Defense mission-critical operations."[38] These enhanced signal frequencies from Iridium would permit properly prepared joint force members and their equipment to quickly lock on and maintain a navigation frequency. In a degraded GPS environment, Iridium would provide an enhanced signal even while functioning in obstructive zones such as metropolitan areas,

[35] Ibid.

[36] Ferster Warren, "Study: Alternative Approach to GPS Modernization Could Reap Big Savings for the Pentagon," http://www.spacenews.com/military/111103-alternative-gps-modernization.html (accessed 17 March 2012).

[37] Ibid.

[38] Rob Goldsmith, "Boeing/Iridium Team Completes High Integrity GPS Program Milestones," http://spacefellowship.com/news/art10053/-boeing-iridium-team-completes-high-integrity-gps-program-milestones-.html (accessed 16 March 2012).

woodlands, foothills, valleys, as well as under jamming or spoofing attempts or amid battlefield radio frequency noise, a vulnerability to the current GPS.[39] Iridium announced in 2010, two milestone accomplishments that enhanced iGPS. The first milestone, completion of the Enhanced Narrowband (ENB) software modification to computers on Iridium satellites, enables second-generation GPS-aiding signals to be broadcast through the entire Iridium constellation. These broadcasts will enable rapid, more accurate GPS position fixes anywhere in the world. The GPS-aiding signal will allow appropriately equipped war fighters to quickly lock on and maintain a GPS signal, even while operating in restrictive environments such as urban areas, forests, mountains and canyons, as well as under enemy jamming attempts or amid battlefield radio frequency noise.[40] The second obstacle accomplished by Boeing-Iridium is acquiring a signal while moving. "When a military GPS receiver is jammed, it cannot obtain a position fix, and movement only makes the situation worse,"[41] said Whelan. "Even from a cold start, it took only minutes for the High Integrity GPS-aided receiver, in a moving vehicle, to receive the GPS signal while being jammed. Without assistance from the High Integrity GPS system, a position fix would never have been obtained."[42]

The third alternative from the Congressional Budget Office is a combination of the first and second options.[43] All 66 Iridium satellites project 48 overlapping spot beams each on the Earth's surface. The proximity of the Iridium constellation to the earth's surface coupled with the high power spot beams result in a much higher level of jam resistance than the weak signal from

[39]Ibid.

[40]Ibid.

[41]Ibid.

[42]Ibid.

[43]Congressional Budget Office, *The Global Positioning System for Military Users: Current Modernization Plans and Alternative*, 29–30.

GPS.[44] In his study, Bryan Bell shows that the Iridium satellite enhanced access to the GPS signals despite the degradation of 2–3 GPS planes.[45]

Boeing authors described another use of the Iridium constellation at the 2011 Position, Navigation, and Timing Symposium hosted by the Stanford Center for Position, Navigation, and Time.[46] In their paper, "The Boeing authors described a flexible system that made optimal use of both Iridium and GPS. It was flexible in that it could obtain a Position, Navigation and Timing solution with only one Iridium satellite even if GPS were completely unavailable."[47]

Russian Global Orbiting Navigation Satellite System

The U.S. could request access to the Global Orbiting Navigation Satellite System (GLONASS) if the U.S. GPS is degraded or lost and the joint force needs global coverage. The advantages are that the cost would be minimal and the accuracy would be similar to that of GPS. In 1976, "the former Soviet Union began development of their GLONASS radio-based satellite navigation system operated by the Russian Aerospace Defense Forces."[48] The GLONASS constellation is comprised of twenty-four satellites that transmit two types of frequency signals. It "has been fully operational since 2010 with a new updated version of satellites, the GLONASS-K, which superseded the GLONASS-M."[49] It provides global coverage but is not compatible with the radio-frequency channel of GPS, as the algorithm and frequencies are completely different.[50]

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[44] Iridium Communication, "The Global Network: Satellite Constellation," www.iridium.com/DownloadAttachment.aspx?attachmentID=1197 (accessed 18 April 2012).

[45] Bryan M. Bell, "Assuring GPS Capabilities Under a Contested Space Environment: An Implementation Plan" (Master Thesis, Air Force Institute of Technology, 2010), 3–10.

[46] Steve Steiner, "GPS Program Update" (Stanford's 2011 PNT Challenges and Opportunities Symposium, 18 November 2011), http://scpnt.stanford.edu/pnt/index.html (accessed 20 December 2011).

[47] Ibid.

[48] Myron Kayton and Walter F. Fried, *Avionics Navigation Systems* (New York: John Wiley and Sons, Inc., 1997), 157.

[49] Ibid., 158.

[50] Ibid.

To use this system, the U.S. would have to coordinate with Russia on the possibility of synchronizing signal frequencies. The economic cost to the U.S. would be minimal and the coverage for timing, position, and navigation accuracy to the joint force would be in the U.S. interest if coverage exists in the area of operations. If the U.S. GPS satellites become degraded or lost, then perhaps the option would be to synchronize with Russia to continue GPS coverage. This would be a problem were Russia allied to the enemy, in which case the U.S. could no longer depend on the Russian system.

European Union Galileo

The U.S. could request access to Galileo if the U.S. GPS is degraded or lost. As Europe is now looking at the possibility to incorporate the Galileo satellite with the U.S. GPS frequencies. Europe's Galileo, a satellite navigation system like GPS, is currently under development by the European Union and European Space Agency. It receives its name from the Italian astronomer Galileo Galilei.[51] The €20 billion European Union project launched the first two satellites on 21 October 2011, and the plan is to begin operations in 2014, and then become fully operational in 2019 with a signal that is complementary to GPS.[52] The Galileo constellation focuses on the deployment of "Thirty satellites in medium-Earth orbit on three planes inclined at 56 degrees to the equator at 23,616 km altitude."[53] Galileo will provide better coverage than GPS, thanks to the location, inclination, and better atomic clocks. Galileo's design methodology followed the lessons learned from the U.S. to make Galileo a more efficient GPS. This is particularly important for the economic growth of the European Union,[54] and it shows that in the near future, Europe would be independent from the U.S. space technologies. If the U.S. GPS satellites become degraded or lost,

[51]Carlo Coraza, "Satellite Navigation; Galileo: Satellite Launches; Launch of First 2 Operational Galileo Satellites," (European Commission Press Release, 2011), http://ec.europa.eu/enterprise/policies/satnav/Galileo/satellite-launches/index_en.htm (accessed 28 December 2011).

[52]Ibid.

[53]Ibid.

[54]Ibid.

one option would be to use their system when it is fully operational, so that the joint force could continue to conduct operations.

Chinese: Beidou-2, BD2

The Chinese have three Beidou-2/G3 satellites at Geostationary Orbit, and they are planning to deploy a regional satellite navigation system called the Beidou-2/Compass by 2012. The plan is to have at least fourteen space vehicles. These satellites are a composition of five geostationary orbits, four medium Earth orbits, and five inclined geosynchronous orbit satellites. However, by 2020, the global system scheduled for full deployment will include twenty-seven medium Earth orbits, three geosynchronous orbit satellites, and five geostationary orbits with a full constellation of thirty-five satellites versus the U.S. constellation with twenty-seven. The plan is to transmit on three frequencies that are the same as those in GPS. The Chinese intentions are to have the Compass assets compatible with the GLONASS, Galileo, and GPS.[55] If the U.S. GPS satellites become degraded or lost, perhaps the option is to synchronize with Chinese officials to continue to have GPS coverage through their constellation. One problem would be if they decided to change or jam the frequency during military operations, in which case the U.S. could no longer depend on the Chinese system.[56]

Indian Regional Navigation Satellite System

The U.S. could request access to the Indian Regional Navigation Satellite System if the U.S. GPS is degraded or lost, but only if it provides coverage in areas of interest to the U.S. India plans to have an operational system in orbit around 2014.[57] The plan expects to have the first

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[55]Glenn Gibbson, "China Begins Broadcasts on Latest Compass GNSS GEO Satellite," *Inside GNSS*, 11 June 2010, http://www.insidegnss.com/node/2134 (accessed 28 December 2011).

[56]Ibid.

[57]K. Raghu, "India to Build a Constellation of 7 Navigation Satellites by 2012," *The Wall Street Journal*, 5 September 2007, http://www.livemint.com/2007/09/05002237/India-to-build-a-constellation.html (accessed 29 December 2011).

satellite launch in 2012–2013 with an initial investment of $304 million. The Indian Space Research Organization plans to develop the space-based navigation system that will be under total control of the Indian government. Their constellation will consist of seven satellites 36,000 kilometers above earth, in Higher Geostationary Earth Orbit. They will transmit signals with a bigger signal footprint and with a fewer number of satellites.[58] The constellation would only provide regional coverage in India, which could be a problem for U.S. military operations if needed coverage was in the areas that they did not cover.

Local and Regional Radionavigation Infrastructures

Long Range Navigation

In the 1940s, the Long Range Navigation (LORAN), previously known as Loomis Radio Navigation, mainly consisted of nautical navigation services using low frequency radio transmitters. It is a terrestrial radio navigation system. The Coast Guard developed and maintained the evolution of LORAN to what became Long Range Navigation-C. During the 1950s, Long Range Navigation provided radio navigation and timing for the coastal waters off the continental U.S. and Alaska. Since approved in the 1960s, it has been used as a supplemental air navigation system. It expanded to cover the continent of the United States in the early 1990s.[59]

John Volpe points out that Long Range Navigation-C does not degrade like GPS because of jamming, loss of line of site, or environmental conditions. The system generates a high-power, low frequency signal that is much easier to receive in areas that are problematic for GPS.[60] This system relies upon a plurality of ground-based signal towers, preferably spaced 100–300 kilometers apart, with frequencies of the order of 100 kilohertz and maximum reception distance

[58]Ibid.

[59]John A. Volpe, "Benefit-Cost Assessment of the use of LORAN to Mitigate GPS Vulnerability for Positioning, Navigation, and Timing Services" (Final Report, March 2004), http://www.volpe.dot.gov/cgibin/goodbye.cgi?url=http://ntl.bts.gov/lib/36000/36100/36102/CarrollJ_BenefitCostAssessmentLORAN.pdf (accessed 5 December 2011), 1.

[60]Ibid., 2.

of hundreds of kilometers.[61] The performance of Long Range Navigation-C was comparable, or better, than that of GPS for aviation.[62] Long Range Navigation-C thus provides a viable and robust backup or alternative to GPS for users, including civilian users in the U.S. and Canada. It in fact greatly reduced the threat to Homeland Security posed by intentional jamming conducted by terrorists or thieves wishing to avoid fees,[63] or unintentional jamming from systems such as the proposed Light-Squared deployment.[64] A U.S. company recently acquired permission to operate Light-Squared, but there are multiple concerns with this decision. "Although Light-Squared will operate in its own radio band, that band is so close to the GPS signals that most GPS devices pick up the stronger Light-Squared signal and become overloaded or jammed."[65]

The DoD used the system for 53 years, and ultimately ceased transmission on 8 February 2008.[66] Figure 1 shows the worldwide coverage by Long Range Navigation before it was turned off. Now, the coverage is only in other continents.

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[61]Ibid., 9.

[62]Jacoby et al., *Advantages of a Combined GPS/Loran-C Precision Timing Receiver*, 4.

[63]Economist, "No Jam Tomorrow Navigation: As the uses of Satellite-Positioning Technology Continue to Grow, What can be done to Stop Deliberate and Dangerous Jamming of the Signals?" *Technology Quarterly* (Q1 2011), http://www.economist.com/node/18304246 (accessed 20 December 2011).

[64]Space-Based Positioning Navigation and Timing, National Executive Committee, "LightSquared and GPS," Last updated 7 July 2011, http://www.pnt.gov/interference/lightsquared/ (accessed 20 December 2011).

[65]Ibid.

[66]Volpe, "Benefit-Cost Assessment of the use of LORAN to Mitigate GPS Vulnerability for Positioning, Navigation, and Timing Services," vii, 1.

Figure 1. Worldwide Coverage Areas by the Enhanced Long Range Navigation System

Source: ITT-Advanced Engineering and Sciences Division, TR07001-Rev 2, “Satellite Navigation Backup Study” (Report for NGATS Institute, Washington, DC, 2007), 4-8.

LOCATA Range Instrumentation

In 2003, Locata Corporation started developing a constellation of satellites that could overcome the technical challenges required to create a localized autonomous terrestrial replica of global navigation satellite system/GPS. “LOCATA’s technology enables cm-level positioning in severe multipath environments where conventional high-accuracy radio positioning has previously been impossible; it employs time synchronized terrestrial transceivers, called LocateLites.”[67] Locata is the integration of GPS/INS/Locata systems to form a technology that will work in restricted environments regardless of direct or indirect line-of-site with the GPS satellite. After several tests, the system proved useful for indoor positioning and the development of better technology is ongoing. The adaptation of receiver technology is especially useful for

[67] Chris Rizos et al., “Locata: A New High Accuracy Indoor Positioning System” (2010 International Conference on Indoor Positioning and Indoor Navigation (IPIN), 15–17 September 2010, Zurich, Switzerland), http://www.locatacorp.com/wp-content/uploads/2011/09/UNSW-Locata-IEEE-Indoor-GPS-paper-iPIN-Conf-Zurich-Sept-2010.pdf (accessed 27 December 2011).

troop navigation in jungles or urban environments because of its accuracy and resistance to enemy attack.[68]

Automatic Image, Terrain, and Celestial Aided Navigation

Inertial Navigation System

Since the 1940s, there have been two types of inertial navigation systems and they have become an important component in how the military determines position, velocity, and altitude.[69] The U.S. joint force uses inertial navigation systems and they "are now standard equipment on most planes, ships, and submarines."[70] The system is comprised of at least three gyroscopes (for measuring rotation rate) and three accelerometers (for measuring force to determine the acceleration). These sensors constitute an inertial measurement unit or inertial reference unit. Once initialized and updated by independent navigation sources, such as GPS or celestial navigation, the inertial navigation system can work anywhere on earth.[71] The GPS is the asset that provides the Inertial Navigation System with the on-line calibration of navigation systems at a very realistic cost.[72] Most of today's military equipment is dependent on space-based modern technology and have inertial navigation systems that act as glue for redundancy precision. For example as the smart bomb travels to its destination, the inertial navigation system calibrates itself via the aid of the GPS to maintain a precise path free of error. "A pure INS integrates several differential equations containing inertial measurements to provide a navigation

[68]Ibid.

[69]Jay Farrell and Matthew Barth, *The Global Positioning System and Inertial Navigation* (New York: McGraw-Hill Companies, 1999), 1.

[70]Ibid.

[71]Mohinder S. Grewal, Lawrence R. Weill, and August P. Andrews, *Global Positioning System, Inertial Navigation, and Integration* (New York: A John Wiley and Sons, Inc. Publication, 2001), 11.

[72]Farrell and Barth, *The Global Positioning System and Inertial Navigation*, 2.

solution."[73] GPS must continue to enhance INS and vice versa, since "GPS and INS have complementary characteristics."[74]

Terrain Contour Matching

Precision missiles such as the Tomahawk use Terrain Contour Matching to navigate. Terrain Contour Matching uses an on-board, three-dimensional contour map of the terrain and is highly reliable. During flight, the missile compares the loaded information against what it sees, with measurements made by an on-board radar altimeter. A Terrain Counter Matching system substantially raises the precision of missiles compared to inertial navigation systems. The increased accuracy allows a Terrain Contour Matching-equipped missile to fly closer to obstacles at generally lower altitudes, making it harder to detect by ground radar.[75] One of the reasons for the successful operations during Desert Storm was the precise use of the Terrain Counter Matching system inside the Tomahawk missiles.[76]

> Operation Desert Storm was the first combat test of the cruise missile system. It also marked the first coordinated Tomahawk and manned-aircraft strike in history. Within the first few minutes of Operation Desert Storm, Tomahawk missiles launched from the battleships Missouri and Wisconsin struck with accuracy at Iraqi command centers, and radar installations. In the war, Tomahawks missiles were used to destroy surface-to-air missile sites, command and control centers, and electrical power facilities and were credited with the destruction of Iraq's presidential palace.[77]

Digital Scene-Matching Area Correlation

Digital Scene-Matching Area Correlation compares what a missile sees to data stored in the on-board computer as it approaches a target. "DSMAC [Digital Scene-Matching Area Correlation] is dependent on intelligence to provide it with up-to-date information about target

[73]Ibid., 1.

[74]Ibid., 246.

[75]Frontline, "The Gulf War: Tomahawk Missiles," http://www.pbs.org/wgbh/pages/frontline/gulf/weapons/tomahawk.html (accessed 28 December 2011).

[76]Ibid.

[77]Ibid.

buildings and civilian shelters."[78] To provide a position update during missile flight, the digital scene-matching area correlation system takes pictures of the ground. A comparison and storage of these sensed images are reference images and the best match used to determine the current missile position. They are accurate, but extremely expensive for what they can do. However, DSMAC is resistant to enemy attacks and provides highly reliable precision navigation so missiles can acquire their targets.[79]

Precision Terrain Aided Navigation

In 1950, Johns Hopkins University Applied Physics Laboratory designed Terrain Aided Navigation (TAN) to guide missiles with continuous position updates.[80] At the time, missiles only had inertial navigation sensors. "Advances in the technology of remote earth sensing and the development of advanced radar altimeters enable a more accurate TAN, called Precision Terrain-Aided Navigation (PTAN)."[81] This technology is accurate, relatively inexpensive, resistant to enemy attacks, and provides positioning, navigation, and timing, so missiles can acquire their targets.[82]

Radionavigation Alternatives

In a study, "convened and funded by the U.S. Army,"[83] on a topic of "Radionavigation Alternatives for U.S. Army Ground Forces in GPS Denied Environments,"[84] a group of engineers

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[78]Grewal, Weill, and Andrews, *Global Positioning System, Inertial Navigation, and Integration*, 23.

[79]Ibid.

[80]Frederick W. Riedel et al., "Guidance and Navigation in the Global Engagement Department," *The Johns Hopkins APL Technical Digest* 29, no. 2 (2010), http://www.jhupl.edu/techdigest/TD/td2902/Riedel.pdf (accessed 28 December 2011), 123.

[81]Ibid.

[82]Ibid.

[83]Mark S. Asher et al., "Radio-Navigation Alternatives for US Army Ground Forces in GPS Denied Environments" (International Technical Meeting of the Institute of Navigation, 24–26 January 2011, San Diego, CA), 508.

at Johns Hopkins University Applied Physics Laboratory “analyzed the tradeoff involved in designing a local or theater GPS system.”[85] To do so, they studied “an Unmanned Aircraft Systems and a Rapidly Deployable Satellite Constellation. These physical architectures correspond to ground operations in scenarios ranging from complete air superiority to completely denied airspace.”[86] A One-way User Device receiver and a Two-way User and Reference device ranging system were designed that could assist joint forces on the ground as they conduct their daily battlefield operations.[87] These Unmanned Aircraft Systems are free of jamming, spoofing, and interference and can be easily and rapidly deployable in a GPS degraded environment for personnel conducting military operations. The group of experts used these devices on complex jamming environments and they worked perfectly. These systems are desirable for personnel navigation in urban, jungle, or mountainous areas where the GPS signal is most likely to be degraded or anywhere in the world GPS signal is lost or degraded. The advantage of these systems is that they would not interfere with today’s GPS architectures.[88]

The second developed alternative from Dr. Asher’s group is the Rapidly Deployable Satellite Constellation known as the “Responsive Constellation Reconstitution.”[89]

Responsive Constellation Reconstitution

> The ability to rapidly reconstitute a critically impaired or otherwise lost PNT capability is intimately predicated on the capabilities of both the launch and space segments. The United States is presciently aware of this dependency and has, as a consequence, established the Operationally Responsive Space (ORS) office in 2007 to cultivate the

[84]Ibid.

[85]Ibid., 530.

[86]Ibid., 509.

[87]Ibid., 510.

[88]Ibid., 508–9.

[89]Ibid., 525.

enabling architectures, technologies, procedures, logistics tails, and capabilities to deploy needed warfighter solutions on a timescale of days to a week.[90]

Figure 2 shows the PNT Microsatellite concept showing both stowed and deployed configurations of the Responsive Constellation.

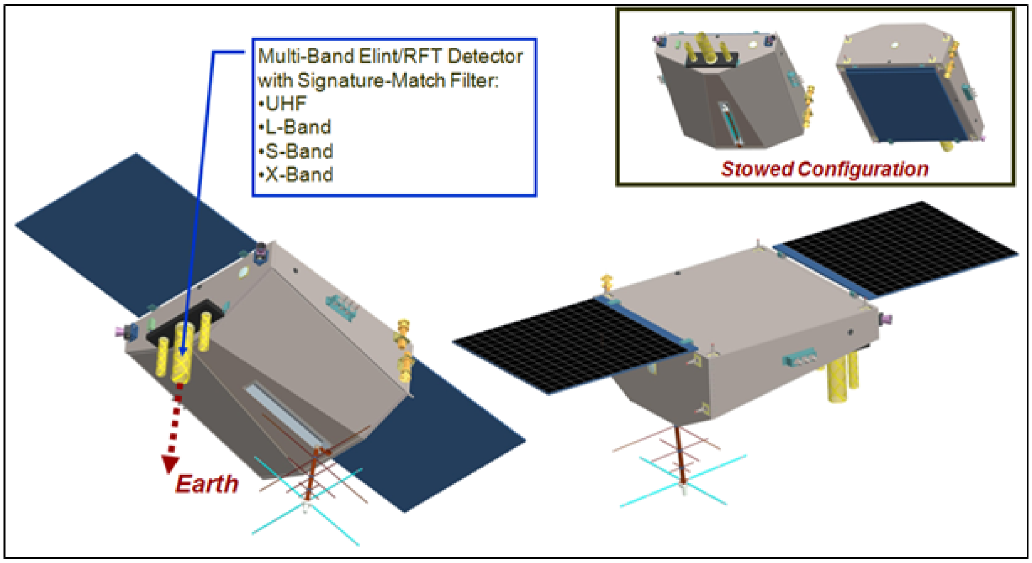

Figure 2. Responsive Constellation

Source: Mark S. Asher, Stephen J. Stafford, Robert J., Bamberger, Aaron Q. Rogers, David Scheldt, and Robert Chalmers, "Radionavigation Alternatives for US Army Ground Forces in GPS Denied Environments" (Proceedings of the 2011 International Technical Meeting of The Institute of Navigation, San Diego, CA, January 2011) (Baltimore, MD: Johns Hopkins Applied Physics Laboratory), 527 http://www.ion.org/search/view_abstract.cfm?jp=p&idno=9494

The Operationally Responsive Space (ORS) office, as part of its efforts, is working to establish a qualified stable launch vehicle to deploy this constellation to Low Earth and Highly Elliptical orbit. ORS is considering the missile tube of the Submarine Launched Ballistic Missiles for the deployable lift. During joint forces battlefield operations from a degraded or denied airspace, ORS considered a two-way link coverage from a constellation of "5–10 satellites,

[90]Ibid.

deployed individually across three−−five critically inclined orbital planes separated by right ascension of ascending node . . . will afford continuous coverage to theaters of interest.”[91]

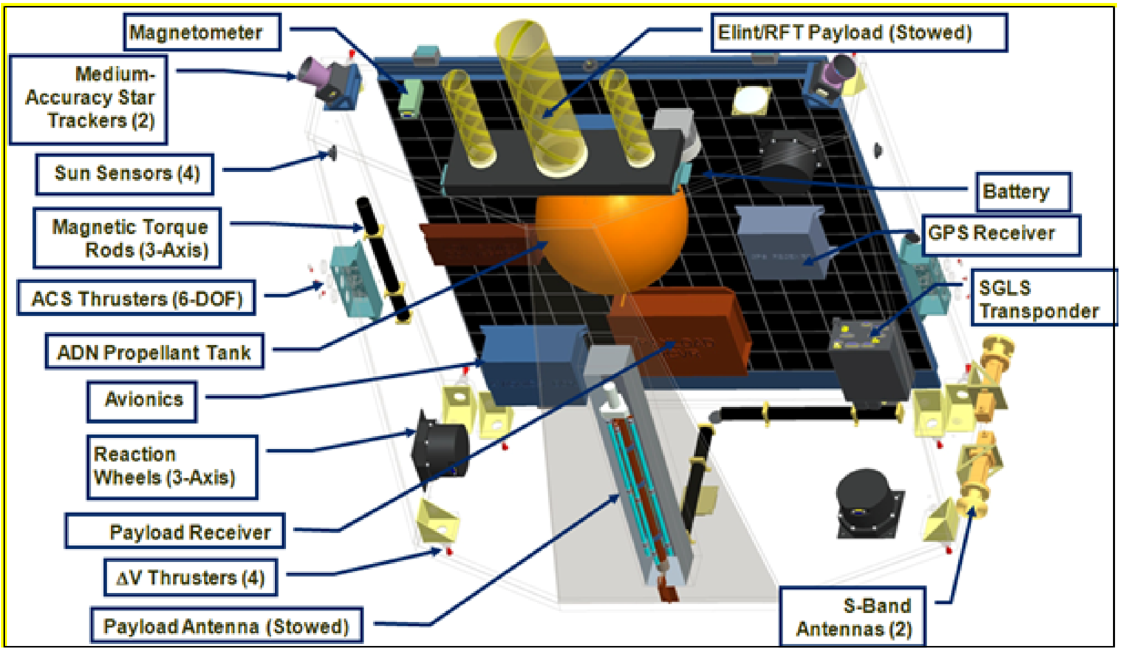

Figure 3. PNT Microsatellite Internal Packaging Design

Source: Mark S. Asher, Stephen J. Stafford, Robert J., Bamberger, Aaron Q. Rogers, David Scheldt, and Robert Chalmers, “Radionavigation Alternatives for US Army Ground Forces in GPS Denied Environments” (Proceedings of the 2011 International Technical Meeting of The Institute of Navigation, San Diego, CA, January 2011) (Baltimore, MD: Johns Hopkins Applied Physics Laboratory), 527 http://www.ion.org/search/view_abstract.cfm?jp=p&idno=9494

This Rapidly Responsive Constellation system can provide simultaneous coverage on battlefield operating areas were GPS signal is lost or degraded to continue to conduct battlefield operations within a matter of hours. As a space-based asset, it is impressive that this deployable system could continue to conduct full spectrum operations across all domains of ground, sea, air and space.

[91]Ibid., 525-526.

First Navigation Technologies

Map

Maps have been in existence for over 3,000 years, and no technology can replace the accuracy of a good map and navigation skills. As U.S. technology improves, however, the joint force tends to learn what is easy, fast, simultaneous, effective, and efficient to be competitive. For this reason, the skill of map navigation has degraded over the years. No matter how sophisticated, colorful, or accurate maps are, they are useless in untrained hands. "Today, the complexities of tactical operations and deployment of troops are such that it is essential for all soldiers to be able to read and interpret their maps in order to move quickly and effectively on the battlefield,"[92] especially on a degraded environment.

Compass

In the absence of GPS, the joint force can still conduct basic navigation maneuvers of personnel and logistics utilizing the compass as an alternative. "The compass allows determination of direction relative to local magnetic north."[93] There is evidence that Chinese sailors were using effective magnetic compasses as early as the 6th century BCE, as they were the first to discover the magical lodestones (a piece of stone that is magnetized). The way that they discovered the compass was that when placed in a wooden box, the handle always pointed south. When acquired from the Chinese concept years later, the Europeans used the compass for navigation.[94] With today's quickly advancing technology, the compass can be extremely valuable if used properly. For example, buildings and dense forestry often degrade GPS signals by interfering with the satellite signal. With a compass, however, a skilled joint force member can

[92]Department of the Army and. Marine Corps, Field Manual (FM) 90-2/FMFM7-27, *Desert Operations* (Washington, DC: Government Printing Office, 1993), 5.

[93]Farrell and Barth, *The Global Positioning System and Inertial Navigation*, 12.

[94]Edwin M. Knights, "Navigation before Netscape," *History Magazine* (October-November 2001): 6.

find his way through terrain recognition, celestial, or solar navigation. Different environments also have different effects on a compass, such as when they are close to the magnetic poles or near an electromagnetic field. For this reason, the operator must be fully competent and understand the effects of the environment on the reliability of the compass. For the operator to rely only on a compass in today's complex and fast environment the mission criticality must "be carefully considered."[95]

Chronometer

For hundreds of years, navigators have used chronometers to aid themselves in navigation to determine the current longitude of a ship while it was sailing. In degraded GPS environments, modern naval captains still rely on chronometers as an alternative for navigation. It is a very precise clock made to balance in all positions. Chronometers have always been set to show time in a particular location whose longitude was taken as reference. Knowing the time/location and knowing the time/location of where they were, sailors were able to determine their current location. Still today, most ships and aircraft have chronometers. However, chronometers require knowledge, expertise, and patience to read correctly, and in the heat of battle operations, could be hard to use.[96]

Sextant

Today, even with the technology of GPS people still use the stars for navigation. "The art of studying the sky to guide ships across the ocean is called celestial navigation."[97] For hundreds of years, people used sextants for ground and sea navigation. A sextant is simply a tool that can assist a captain to measure the angle between a celestial body and the horizon. An individual

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[95]Farrell and Barth, *The Global Positioning System and Inertial Navigation*, 12.

[96]Ibid., 187.

[97]Knights, "Navigation before Netscape," 5–12.

utilizes that data to analyze longitude and latitude to calculate approximately the location and direction. Celestial navigation using a sextant is complex and requires calculating, correcting, referring to tables, and a knowledge of the heavens and the earth.[98] The problem with the sextant is that one cannot use it on a cloudy day, or during dense fog as the individual cannot see the stars due to low visibility. However, they are very useful and every ship and plane must have a sextant at their own reach, to use only in emergencies if GPS and the alternative are degraded or to have as another alternative, but only if the sky is clear.

Conclusion

There are many challenges to identifying a system that will be all things to all people but through history, we find our future. Galileo said, "I have loved the stars too fondly to be fearful of the night."[99] How fitting, his words lost to time, the past with the present and our future. It is known that battles took place on land for centuries and as technology evolved, the wars have been conducted on other domains. The second domain was the seas, and then it moved to the air. The author believes that, it is only a matter of time, when the darkness of space-based assets will be the next war. It is only a matter of time, before the enemy will have the full capability to destroy one or many satellites at once. It would then be the next Space-Pearl-Harbor. As it shows that for many years, the DoD has depended on different assets as critical components to daily battlefield operations. As technology has evolved, space-based assets have become the ears and eyes of the military. GPS capabilities are great, and adversaries will likely take efforts to deny them. What is devastating is that currently, there is not a single solution that can serve as an alternative to GPS for ground, air, sea, or space operations, which can completely replace the global availability and accuracy of GPS for the joint force personnel and equipment. The methods of operating with a

[98]Grewal, Weill, and Andrews, *Global Positioning System, Inertial Navigation, and Integration*, 239.

[99]Goodreads, "Galileo Galilei quotes," http://www.goodreads.com/author/quotes/14190.Galileo_Galilei (accessed 19 April 2012).

degradation or loss of GPS are contingent on the types of battlefield operations. In addition, where the operations are taking place as the current alternatives can only support one operation at the time. For this reason, it is critical for the joint force to have at least one fully operational alternative capable of simultaneously conducting operations like GPS. At this time, the only alternative to GPS has to be another space-based asset, as a space-based alternative can extend coverage to the entire joint force simultaneously. The existing space-based alternative to GPS is the commercial Iridium system, a sixty-six satellite communication constellation in low-earth orbit, under a program known as the high integrity GPS or iGPS. This constellation provides capabilities, applications, and benefits similar to GPS. It is in place and ready to use for PNT. The Congressional Budget Office recommends that all GPS receivers have to operate with an additional signal from the U.S. Iridium constellation frequencies. A third alternative to GPS can be the Rapidly Deployable Responsive Satellite as it can cope with the redundancy of a space-based alternative if the GPS and Iridium constellations were to be destroyed simultaneously. Alternatively, existing GPS frequencies need to operate with the Iridium and the Responsive receivers signals. We owe it to the security of our nation and the freedom of our people, for that we must be ready and prepare now, so that we do not have a space 9/11 or a Pearl Harbor.

Bibliography

Adams, Thomas K. "10 GPS Vulnerabilities." http://www.c4i.org/gps-adams.html (accessed 17 April 2012).

Asher, Mark S., Stephen J. Stafford, Robert J. Bamberger, Aaron Q. Rogers , David Scheldt, and Robert Chalmers. "Radio-navigation Alternatives for US Army Ground Forces in GPS Denied Environments." International Technical Meeting of the Institute of Navigation, 24-26 January 2011, San Diego, CA.

Baram, Marcus. "Friendly Fire Deaths Haunt." *ABC News*. http://abcnews.go.com/US/story?id=2985261&page=1 (accessed 31 March 2012).

Bell, Bryan M. "Assuring GPS Capabilities Under a Contested Space Environment: An Implementation Plan." Master Thesis, Air Force Institute of Technology, 2010.

Boberg, Bengt. "Robust Navigation: Allowing Other Systems to Support GPS." *Swedish Journal of Military Technology* 3-4 (2005): 23-29. http://www.itloptronics.com/landSystems.asp (accessed 13 January 2012).

Boeing. "Defense, Space and Security; Joint Direct Attack Munition (JDAM)." http://www.boeing.com/defense-space/missiles/jdam/index.htm (accessed 21 December 2011).

Brown, Kendall K., ed. *Space Power Integration; Perspectives from Space Weapons Officers*. Maxwell Air Force Base, AL: Air University Press, 2006.

Chaplain, Chistina. *Global Positioning System: Significant Challenges in Sustaining and Upgrading Widely Used Capabilities*. Washington, DC: Government Printing Office, 2009.

Commission to Assess United States National Security Space Management and Organization. Report of the Commission to Assess United States National Security Space Management and Organization: Pursuant to Public Law 106-65. Washington, DC: Government Printing Office, 11 January 2001. http://www.dod.mil/pubs/spaceintro.pdf (accessed 21 August 2011).

Congressional Budget Office. *The Global Positioning System for Military Users: Current Modernization Plans and Alternatives*. Washington, DC: Government Printing Office, 2011.

Coraza, Carlo. "Satellite Navigation: Galileo: Satellite Launches; Launch of First 2 Operational Galileo Satellites." European Commission Press Release, 2011. http://ec.europa.eu/enterprise/policies/satnav/galileo/satellite-launches/index_en.htm (accessed 28 December 2011).

Dennehy, Kevin. "LBS Alternatives to GPS." *GSP World: Geospatial Solutions*, 28 November 2007. http://www.gpsworld.com/lbs/lbs-alternatives-gps-1819 (accessed 19 November 2011).

Department of Commerce. *National Space Based PNT Policy*. Washington, DC: Government Printing Office, December 2004.

Department of Defense and the Office of the Director of National Intelligence. *National Security Space Strategy* Unclassified Summary. Washington, DC: Government Printing Office, 2011.

Department of the Army. Field Manual (FM) 5-0, *Operations*. Washington, DC: Government Printing Office, 2010.

———. *United States Army Space Master Plan*. Washington, DC: Government Printing Office, 2000.

———. *United States Army White Paper: Concepts for the Objective Force.* Washington, DC: Government Printing Office, 2001.

Department of the Army and Marine Corps. Field Manual (FM) 90-2/FMFM7-27, *Desert Operations*. Washington, DC: Government Printing Office, 1993.

Economist. "No Jam Tomorrow Navigation: As the Uses of Satellite-Positioning Technology Continue to Grow, what can be done to Stop Deliberate and Dangerous Jamming of the Signals?" *Technology Quarterly* (Q1 2011). http://www.economist.com/node/18304246 (accessed 20 December 2011).

E. J. Ward, Inc. "Terminology." http://www.ejward.com/Solutions/GPSAVLVehicleTracking/GPSTerminology/tabid/82/Default.aspx (accessed 31 March 2012).

Farrell, Jay, and Matthew Barth. *The Global Positioning System and Inertial Navigation*. New York: McGraw-Hill Co., 1999.

Federal Aviation Administration. "FAQ: GPS Basics." http://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/faq/gps/#1 (accessed 19 November 2011).

———. "GNSS Frequently Asked Questions-GPS." http://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/faq/gps/#1 (accessed 19 November 2011).

Frontline. "The Gulf War: Tomahawk Missiles." http://www.pbs.org/wgbh/pages/frontline/gulf/weapons/tomahawk.html (accessed 28 December 2011).

Gibbson, Glenn. "China Begins Broadcasts on Latest Compass GNSS GEO Satellite." *Inside GNSS*, 11 June 2010. http://www.insidegnss.com/node/2134 (accessed 28 December 2011).

Goldsmith, Rob. "Boeing/Iridium Team Completes High Integrity GPS Program Milestones." Space Fellowship, 11 July 2009. http://spacefellowship.com/news/art10053/-boeing-iridium-team-completes-high-integrity-gps-program-milestones-.html

Goodreads. "Galileo Galilei quotes." http://www.goodreads.com/author/quotes/14190.Galileo_Galilei (accessed 19 April 2012).

Government Accountability Office. *Global Positioning System: Challenges in Sustaining and Upgrading Capabilities Persist*. Washington, DC: Government Printing Office, 2010. http://www.gao.gov/new.items/d10636.pdf (accessed 19 November 2010).

———. *Global Positioning System: Significant Challenges in Sustaining and Upgrading Widely Used Capabilities*. Washington, DC: Government Printing Office, 2009.

Grewal, Mohinder S., Lawrence R. Weill, and August P. Andrews. *Global Positioning System, Inertial Navigation, and Integration*. New York: A John Wiley and Sons, Inc. Publication, 2001.

Hegrenaes, Øyvind, Einar Berglund, and Oddvar Hallingstand, "Model-Aided Inertial Navigation for Underwater Vehicles." www.navlab.net/Publications/Model-Aided_Inertial_Navigation_for (accessed 31 March 2012), 8.

The Holy Bible New International Version: Containing the Old Testament and the New Testament. Translated by The Committee on Bible Translation. Edited by New York International Bible Society. Grand Rapids, Michigan: Zondervan Bible Publishers, 1978.

ITT-Advanced Engineering and Sciences Division. TR07001-Rev 2, "Satellite Navigation Backup Study." Report for NGATS Institute, Washington, DC, 2007.

Jacoby, James, Paul W. Schick, Frank Richwalski, and Kevin Zamzow. *Advantages of a Combined GPS/Loran-C Precision Timing Receiver*. Madison, WI: Lucus, Inc., 1999. http://www.timingtechnologies.com/Locus%20Timing99.PDF (accessed 4 September 2011)

Joint Chiefs of Staff. Joint Publication 3-14, *Space Operations*. Washington, DC: Government Printing Office, 2009.

———. *The National Military Strategy of the United States of America: Redefining America's Military Leadership*. Washington, DC: Government Printing Office, 2011.

Kayton, Myron, and Walter F. Fried. *Avionics Navigation Systems*. New York: John Wiley and Sons, Inc., 1997.

Knights, Edwin M. "Navigation before Netscape." *History Magazine* (October/November 2001): 23.

McClure, William B. *Technology and Command: Implications for Military Operation in the Twenty-First Century*. Maxwell Air Force Base: Air University, Center for Strategy and Technology, July 2000.

Raghu, K. "India to Build a Constellation of Seven Navigation Satellites by 2012." *The Wall Street Journal*, 5 September 2007. http://www.livemint.com/2007/09/05002237/India-to-build-a-constellation.html (accessed 29 December 2011).

Riedel, Frederick W., Shannon M. Hall, Jeffrey D. Barton, James P. Christ, Brian K. Funk, Thomas D. Milnes, Peter E. Neperud, and David R. Stark. "Guidance and Navigation in the Global Engagement Department." *The Johns Hopkins APL Technical Digest* 29, no. 2 (2010). http://www.jhuapl.edu/techdigest/TD/td2902/Riedel.pdf (accessed 28 December 2011).

Rizos, Chris, Gethin Roberts, Joel Barnes, and Nunzio Gambale. "Locata: A New High Accuracy Indoor Positioning System." 2010 International Conference on Indoor Positioning and Indoor Navigation (IPIN), 15-17 September 2010, Zürich, Switzerland. http://www.locatacorp.com/wp-content/uploads/2011/09/UNSW-Locata-IEEE-Indoor-GPS-paper-iPIN-Conf-Zurich-Sept-2010.pdf (accessed 27 December 2011).

Science Channel. "How do Inertial Guidance Systems Get Satellites to the Right Locations?" http://curiosity.discovery.com/question/inertial-guidance-systems-work (accessed 28 December 2011).

Space-Based Positioning Navigation and Timing. National Executive Committee. "LightSquared and GPS." Last updated 7 July 2011. http://www.pnt.gov/interference/lightsquared/ (accessed 20 December 2011).

Steiner, Steve. "GPS Program Update." Stanford's 2011 PNT Challenges and Opportunities Symposium, 18 November 2011. http://scpnt.stanford.edu/pnt/index.html (accessed 20 December 2011).

Training and Doctrine Command. TRADOC Pamphlet 525-7-4, *The United States Army's Concept Capability Plan (CCP); Space Operations 2015 - 2024*. Fort Monroe, VA: Government Printing Office, 2006.

Volpe, John A. "Benefit-Cost Assessment of the use of LORAN to Mitigate GPS Vulnerability for Positioning, Navigation, and Timing Services." Final Report, March 2004. http://ntl.bts.gov/lib/36000/36100/36102/CarrollJ_BenefitCostAssessmentLORAN.pdf (accessed 5 December 2011).

Warren, Ferster. "Study: Alternative Approach to GPS Modernization Could Reap Big Savings for the Pentagon." http://www.spacenews.com/military/111103-alternative-gps-modernization.html (accessed 17 March 2012).

The White House. Presidential Decision Directive (PDD) 63, *Protecting America's Critical Infrastructures*, 22 May 1998. http://www.fas.org/irp/offdocs/pdd-63.htm (accessed 3 February 2012).

Williams, Richard A. "AF GPS Program Earns International Award." Air Force Space Command. http://www.schriever.af.mil/news/story.asp?id=123275044 (accessed 6 November 2011).

Wood, Charles. "Some Basics of Air Navigation." http://www.navfltsm.addr.com/basic-nav-general.htm (accessed 27 December 2011).