AIR COMMAND AND STAFF COLLEGE

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THE POST GPS-ONLY ERA:

POSITIONING, NAVIGATION, AND TIMING (PNT) IN 21ST CENTURY WARFARE

By

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ABSTRACT

This research focuses on the need for the United States Government to expand the Positioning, Navigation, and Timing (PNT) portfolio beyond the use of the Global Positioning System (GPS) and Inertial Navigation Systems (INS) solutions. The central argument of this discussion is focused on the integration of a multiple Global Navigation Satellite System (GNSS) solution in all of our weapon systems to overcome the primary military challenge of the critical PNT challenges of critical timing, navigation, and positioning in a contested, degraded, and operational limited operating environment. The alternative navigation and timing portfolio expands beyond GNSS through adding robust timing architectures and operational depth through the incorporation of upgraded INS systems, critical network timing, and the use of both large and small atomic clock systems on the highest priority mission systems. This research also endeavors to make the connections between GPS and our 21st Century way of life and the other instruments of national power. GPS and the PNT mission set is the cornerstone of our information age technology. The diversification beyond GPS-only PNT solutions is necessary to ensure our national infrastructure, economy, and military dominance for the next century. It concludes with recommendations for how the Department of Defense and the entire United States Government (USG) should act now to implement changes for the United States PNT architecture to overcome the challenges of today and positioned to maintain PNT and NAVWAR dominance in the 21st Century.

INTRODUCTION

The supremacy of the American military is well-documented in the modern era. The twentieth century is often known as "The American Century" and was shaped by the United States evolving from a post-industrial age country with little worldwide presence during the age of European imperialism, to the world's sole remaining superpower at the end of the century. The US military has been the buffer to the world's aggressors and powers enabling an unprecedented era of peace and stability. The supremacy of America has been measured by daring and innovative offset strategies that enable dominance and supremacy on any battlefield around the globe.

The Global Positioning System (GPS) was invented during the American innovation period known as the Second Offset, (1970s and 1980s). The invention of precise positioning, navigation, and timing (PNT) was not only disruptive to the military, its applications have become the cornerstone technology of the 21st century, often hailed as "the most significant invention in all of mankind"[1]. The reliance on GPS as an independent and enabling technology powers our modern world.

The United States, as the world leader in PNT technologies through its PNT system GPS, has enabled the world to rapidly advance in the information age. This reliance on GPS for PNT information across all elements of power and our national economy requires a new analysis for 21st century use and potential augmentation with other source PNT. The United States competitive advantage and use of GPS as a sole-source for PNT information is rapidly coming to an end in the 21st century's Information Age.

The realized revolutionary advantages of the First and Second Offsets enabled the United States to bring precision warfighting to the world. When GPS was initially fielded during Operation Desert Storm its operational use was limited as precision weapons during the first Gulf war were predominantly unguided and precision applications used laser-guided weaponry[2]. Through Operation Allied Force (Bosnia), Enduring Freedom (Afghanistan), and Iraqi Freedom (Iraq), the world saw a more mature application of airpower through integrated GPS giving the U.S. all weather capability, previously limited in laser precision bombing[3]. Instead of leveling cities with carpet bombing as had occurred a generation before in Vietnam, the United States made every bomb lethally efficient with its one bomb one target application of complimenting PNT and laser guided weapons. As our application and use of this critical system evolves, so must the infrastructures and policies supporting its continued development, implementation, and future use.

The evolution and growth of GPS and PNT worldwide necessitate changes within the Department of Defense and the U.S. Air Force. Strategic decisions made in the coming years by the Air Force as the principle acquirer will shape the future of GPS's use, perhaps not only within the Department of Defense (DOD) but the rest of the United States via civilian and commercial applications. The management of PNT as an enterprise within the DOD and U.S. Government (USG) is necessary to facilitate 21st century information dominance. While specific solutions will be reserved for the conclusion, this is a significant area of improvement for this critical national asset.

A new term that will become synonymous with the information age is Navigation Warfare (NAVWAR). The information age of our current century was realized and built on the keystone technology of GPS. That advantage is threatened in a hostile world of peers, near-peers, and hostile states that would revert the United States advantage of GPS through denial, degradation, and other hostile means. NAVWAR is the US DOD's approach to ensuring that there will be PNT access at, to, and through all levels of conflict, contested/congested, and degraded/denied operating environments.

Augmentation of GPS initially occurred within the scientific community in the 1990s. GPS has two services associated with its use; the standard positioning service (SPS) for civil/commercial use and the precise positioning service (PPS) for military use. During initial fielding of the GPS constellation, the SPS service was degraded intentionally through a system design known as selective availability (SA). In order to overcome SA, the scientific community created GPS augmentation through the utilization of known points and correcting for the error (natural and injected). This field eventually became known as Differential GPS and became the foundation for enhancing the natural abilities of the GPS constellation.

The native capabilities of GPS are so well known that other nations are deciding to build their own constellations of satellites to have native PNT capability, have additional PNT solutions if or when there was service interruption of GPS. The advancement of PNT as a science through Differential GPS in the 1990s and 2000s enabled the possibility of multi-PNT systems. With more countries and regional blocs of governments investing in PNT architectures, the operating frequency that GPS operates in will become more crowded. National investments in weapon systems that are able to detect, utilize, and maximize known PNT systems/solutions, multi-GNSS solutions, creating increasingly accurate navigational solutions will become necessary in the contested/denied battlefield of the near future. Without investment in multi-GNSS, GPS operations alone will struggle to maintain the U. S.'s accustomed accuracy and lethality.

Changes to GPS will require full government acceptance and coordination across multiple departments and the involvement of Congress. GPS is codified in public law and has embedded protections. This research is not about the governing laws of the PNT system but rather the application of how to evolve our current advancements and like the Second Offset strategy that enabled GPS's creation, to reemerge in 10-to-15 years from now, exceeding our next closest peer/adversary in PNT utilization, and technology.

Research Question/Methodology

How can the U.S. Air Force grow the PNT mission into a warfighting enterprise/domain while maintaining the Global Positioning System (GPS) as the world standard for space-based PNT services?

This research uses the problem/solution framework. The problem solution framework focuses on the policy-analysis presentation and recommends future opportunities for the U.S. Air Force, as the lead service for PNT and timing technologies in this century. This study has a wide-to-small presentation format to familiarize the audience with the scope of the PNT problem set. Alternative presentations to current operations within the DoD will enlighten the reader and underline the importance of a new opportunity for the Department.

If any solution is to be successful for the Air Force, it should be part of a comprehensive plan that articulates relationships to Joint partnerships, DoD mandates, and National Executive Committee on PNT (Cross-Executive Branch department) integration.

BACKGROUND

DEFINING POSITIONING, NAVIGATION & TIMING

The current state of PNT is a synonymous relationship with GPS, its space-based component. The space component is not the sole component of PNT but is a piece of multiple positioning, navigation, and timing resources available to integrate military civilian, and commercial equipment. While this topic is necessary and vitally important, there is a clear misperception of the capabilities of GPS, and the necessity of continued investment in GPS as the world moves on to a Post-GPS-only PNT environment. While advocating for complimenting GPS with other PNT systems, the U.S. needs to continue to modernize our current infrastructure: space, GPS III satellites; ground, upgrade the ability to command and control our satellite systems; and user segment, fielding next generation receivers and components that optimize the upgraded capabilities of the GPS constellation. Without maintaining the baseline, complimenting capabilities will not advance the PNT mission or give us the competitive advantage in all aspects of PNT.

The tools of warfare and commerce and the digital age that have incorporated GPS will not suddenly be replaced by a panacea GPS follow-on program introduced by the DoD. GPS is going to remain the cornerstone and world standard, but it is necessary to grow its capability, compliment current technology with new generation systems such as e-Loran, additional space-based signals offered through other nation GNSS (Galileo, Glonass, BeiDou, IRNSS, Quasi-Zenith), and other timing sources such as next generation Inertial Navigation Systems (INS), or on-board atomic clocks.

The research presented through this study identifies how to integrate new technology and replace antiquated 20th century technology that can be exploited in an anti-access area denial (A2AD) scenario. This topic is especially interesting for all warfighting elements of the Air Force and other military branches, as it will clearly delineates between GPS and PNT and how to readily identify equipment modifications as well as tactics, techniques, and procedures (TTPs) to overcome threat scenarios. While unclassified in nature, this analysis also identifies the necessary architectures, technologies, and opportunities to fight across all domains.

The question of PNT and the future for NAVWAR are critically important for the coming century. The nation is challenged from anti-insurgency conflicts to full-spectrum warfare; no other century has offered more diverse national security challenges. This question will secure the underlying technologies necessary to win the next conflicts and secure American interests.

Why is PNT provided by GPS so important? GPS is the world standard for accurate PNT services. Just as silicon powered the microchip, PNT enables the critical technology the world depends on every day. PNT services at their core, are atomic clocks in the sky, the constellation of satellites enables products to create the optimal configuration three satellites for x/y/z reference creating a three-dimensional position plus an additional satellite for time. Positioning is just one of the missions of the GPS satellite constellation.

Once a point is known, anywhere on Earth, the GPS receiver references the World Geodetic System data standard of 1984 (WGS-84) and through the process of tri-lateration a position is determined. Navigation occurs when the receiver maintains lock with at least four satellites and utilizing the fourth satellite correcting for time, velocity can be determined, enabling the navigation mission of PNT.

Timing is perhaps the most critical element to our modern way of life, is core to the GPS with the core functionality being atomic clocks. Precise time determination anywhere on the surface of the planet is provided through GPS' atomic clocks and transferred through computer networks, cellphone towers, and other critical infrastructure. Precise timing enables exquisite mapping, autonomous operations of robots, and microsecond penny stock purchasing algorithms for the stock market.

MORE THAN GPS

PNT is more than the GPS system that the world has come to rely on as the enabling technology for our everyday activities. As our world becomes increasingly interconnected wirelessly, the electromagnetic spectrum that supports our technology will become increasingly congested and may even be denied if the world's governments are unable to effectively manage the ever-growing demand.

There is a clear difference between congested and denied. GPS operates within the Ultra High Frequency (UHF) portion of the electromagnetic (EM) spectrum. The UHF portion of the spectrum is in high demand, creating great competition between governments, civilian, and commercial satellite operators. With more nations and regional blocs producing native PNT and GNSS systems, the portion of the UHF frequency spectrum reserved for PNT is becoming increasingly congested. The most effective way for GNSS systems to avoid interfering with one another is to deconflict frequency utilization through the United Nations International Telecommunications Union (ITU) and open dialogue with one another to create interoperable/shared standards.

Denial of GPS frequencies can be unintentional via frequency crowding and two systems broadcasting and nulling each other out, or it could be intentional, commonly known as jamming. In 2013, an individual in New Jersey wanted to prevent his employer from tracking his movements and employed a GPS jammer during part of his work route. Unfortunately, his GPS jammer affected the air traffic control systems at Newark Airport, leading to an ultimate fine of $31,000 and his employment termination.[4] This everyday example illustrates that as lives get more interconnected with precision navigation systems increasingly available in devices, the ability to jam and deny these systems is becoming more prevalent at lower prices. According to the CNET article, the jammer in this situation was bought on the internet for less than $100[5].

An additional threat to the UHF spectrum is the evolution of wireless networks. An example of poor frequency management in the United States, the Federal Communications Commission (FCC) gave permission to an American business, Ligado/Light Squared, to develop a fifth-generation wireless network in the frequency band adjacent to GPS[6]. The problem with developing fifth-generation wireless technology adjacent to GPS is the strength of ground-based networks will overpower the relatively weak signal produced from space for the primary GPS operating frequency[7]. While fifth-generation network connectivity is necessary to evolve our wireless world, the cost to PNT and the UHF spectrum where it operates demonstrates that it is vitally necessary to keep the spectrum free from any interference not only in America but work within the confines of the ITU and diplomacy to ensure the operating frequencies of GPS and other GNSS systems are available to broadcast and enable our other 21st century technologies.

What other systems are available to use with GPS? While GPS was the first system available to the world, during the Cold War Russia produced their GLObal Navigation Satellite System (GLONASS)[8]. With a different architecture and frequency use scheme, the Russian

Federation's GLONASS was the first system to enable dual use in civilian applications[9]. The primary difference between Russia's system and GPS is that GLONASS uses frequency division multiple access (FDMA). versus GPS's code division multiple access (CDMA). The next generation of GLONASS will evolve with more interoperability with GPS and the European Union's GALILEO by moving to the CDMA standard, moving the world to a single standard. A single standard enables increased interoperability between GNSS systems, reducing the burden to program user equipment with different frequency standards, and potentially reducing the need for additional antennas[10]. The difference between CDMA and FDMA is a potential detractor for integration in a future multi-GNSS solution.

Of the foreign GNSS satellite systems, the Russian government has made it a top priority to replenish the GLONASS constellation after it began to fail following the Cold War collapse of the Soviet Union[11]. With the multi-GNSS market maturing, Russia wants to take advantage of its capital investment in its own GNSS solution. Civilian integration of multi-GNSS solution with GPS/GLONASS combination is available in every smartphone (iPhone and Android) since the iPhone4 in 2011, when the Russian government mandated it for access to the Russian marketplace[12]. Additionally, applications such as Garmin[13], precise land observation equipment like Trimble electronics[14], and network devices[15] used for mobile computing/communications have moved to the multi-GNSS solution in order to take advantage of the increased precision of a dual GNSS solution, and increase their market share worldwide through access to multiple markets.

Relative to the earlier discussion of the Selective Availability (SA) function[16] of the earlier GPS constellations during initial fielding, in 2000 then-President Clinton ordered that all SA operations cease, giving the world access to a non-degraded 'clean' GPS signal[17]. This decision enabled GPS to remain the world standard, delayed additional fielding of other GNSS constellations, and finally ushered in the incorporation of the GPS PNT technology into our daily lives. The United States is so resolute in its promise to never enable SA operations that the next generation of GPS satellites (GPS III) will not have the SA capability[18]. Within the PNT community there are theories that the threat of European Union's GNSS solution Galileo was the impetus for President Clinton's Presidential Directive. The threat of Galileo was neutralized and GPS has remained the world leader in PNT since 2000 and Galileo is still years away from a fully fielded GNSS capability. This historical vignette is important to understand the political, economic, and global initiatives impacting GPS.

Not applying the SA technology limited the development and implementation of GALILEO and all other GNSS systems for 20 years. Fielding of GALILEO will now occur over the next 5-10 years after the successful fielding of initial pathfinder constellation since 2008 with full operational capability expected by 2020[19]. The threat of SA and the potential disappearance of GPS's PNT capabilities have encouraged the world's governments to invest in their own GNSS solutions. GALILEO is important to American interests to implement a multi-GNSS solution, GALILEO would be one of two allied partners, the other being Japan's Quasi-Zenith System (QZSS), we would collaborate with to incorporate a more accurate navigational solution. Additionally, the interoperability of GPS and GALILEO is already planned with close European Union cooperation[20]. GALILEO is structured like GPS with a free service and higher accuracy pay service for precision applications and military use.

Strategic partnerships are the key to alternative PNT solutions. A close relationship also exists between the United States and Japan[21]. The Japanese are a key strategic partner in the PACOM theater of operations. Their landscape presents a unique problem for GNSS systems.

The Japanese urban landscape presents a unique challenge in cities such as Tokyo, which is known for its urban canyons[22]. The problem with high-rise buildings is that antennas have problems tracking and acquiring the optimal geometry for a GPS solution. The optimal configuration is three satellites 'just over the horizon' and one satellite directly overhead. With the Japanese urban landscape, the navigational solution is reversed with the GPS antenna forced to acquire four satellites directly overhead. An augmentation solution was created in the Quasi-Zenith Satellite System (QZSS) using regionally optimized geostationary and highly inclined geosynchronous, working in concert with GPS at medium earth orbit to correct the misapplied navigation solution, increasing accuracy and enabling tracking defeating the urban canyon effect.

Like GALILEO, QZSS is designed to work with the GPS constellation to create the best and most accurate navigational solution. The strategic decisions of our closest partners force an intense introspection of U.S. policy and adaptation of a multi-GNSS solution throughout the DOD and the U.S. government. The opportunity for the U.S. adapting multi-GNSS to field appropriate technology when it's most needed may be limited. The analysis to shape future decisions for the next generation GPS systems (GPS III, GPS Next Generation Operational Control System [OCX], Military GPS User. Equipment [MGUE]) decisions should be conducted now. Without immediate action, the next decision opportunity may be 20-25 years in the future with GPS IV.

Additional satellite GNSS solutions include China's BeiDou, and India's Indian Regional Navigation Satellite System (IRNSS). Every major government in the world has access to GPS; however, regional navigation systems such as BeiDou and IRNSS have grown from regional coverage in the early part of this century to fully developed global navigation utilities. GNSS and PNT producing systems are strategically important and worth billions of dollars of investment to assure access to PNT for the major governments of the world. This does not include the GPS-like solution provided by Iridium for commercial use and augmentation to existing systems architectures.

Inertial navigation systems/units (INS or INU) were once primary navigation systems for military aviation. As GPS became fully operationally capable (FOC) after Desert Storm, INU's became better able to complement GPS units. GPS units corrected for the natural drift present in an INS solution, with drift depending on the aircraft, size of INU, and its ability to maintain accuracy. Before GPS, INS's were corrected by navigational fixes to known points, GPS incorporation gave navigational freedom to go anywhere on the planet with corrections available whenever the pilot/user needed their position. As this century evolves, concurrent development is needed to increase the accuracy of the INS units. While a multi-GNSS solution is a possibility, increasing the accuracy of our INS units is a rational development path. Navigational accuracy becomes ever more important as current and next generation upgrades to our military inventory have multiple systems that require navigational solutions for basic operations.

An additional navigation solution for consideration when developing multi-GNSS is the atomic clock. Atomic clocks are what enable the world's GNSS systems. Incorporation in the weapon system itself gives the weapon system a degree of autonomy and the ability to correct both timing and navigational systems in a contested/degraded-operating environment. Atomic clocks come in both large and small forms enabling a variety of weapon systems to utilize the increased benefits in a degraded environment. The addition of atomic clocks in weapon systems allow those weapon systems to maintain a time standard and get the weapon system farther/deeper into the threat environment in order to achieve military objectives.

THE DIGITAL AGE

With advances beyond the industrial age, the Information Age (or Digital Age) is based on precise timing provided by PNT systems, more specifically by GPS. How is it possible that this global utility started by the military in the 1990's is such a cornerstone of our current society?

Communications are essential for today's global economy and worldwide simultaneous communication, and the networks that support the internet requires precise timing. Without precise timing, the networks could not synchronize with other networks (commonly called handshaking). That handshake between networks and the precise time enables all the banking transactions (millions to billions per second), the power/communication distribution that we depend on for the most basic tasks.

Our everyday electronics, such as cellular telephones, have internal gyroscopes, GPS, GLONASS, and time synchronization from the cellular network they are operating on. The mobile devices we use have their own internal clock, and gyroscopes working together to create precise application of PNT. Our common devices have already incorporated multi-GNSS/PNT solutions to replace time intensive manual tasks. Nowhere is this more prevalent than in the Trimble precise land surveying equipment discussed in the previous section.

Another important section of GPS impact on our new economy is big data analytics. From the stock market, where time precision buy and sell orders[23] are carefully timed to make money, to algorithms that account for 70 percent of the volume of trades[24] GPS timing is at the heart of our 21st century economy. The question in analytics is how do you take all the disparate and readily available data and make sense of it? The answer is GPS using geotagging data and as Tech Republic reports: "Thanks to Google Maps, MapQuest, iPhone Siri, and other purveyors of mobile information, we can key in a GPS locator (like a street intersection) and receive contextual data such as what is near by that intersection"[25].

The use of GPS goes further in a company's ability to trace transport/logistical vehicles in remote areas, combining historical trends in accidents to pre-position medical response[26]. The key to GPS and analytical algorithms is their combined ability to create data combinations, correlate disparate facts, and monetize those combinations to disrupt industries changing long-held business paradigms[27]

One of the most interesting applications of GPS and PNT technology is its use in space systems. The principles of GPS apply not only to the ground and air segment, they extend to the space domain as well. The GPS constellations configuration of four satellites in each of six orbital planes allows for continuous coverage of the entire earth and for use by other space vehicles. GPS helping another satellite, you might ask, 'How does a satellite track another satellite?' If the satellite is below the GPS constellation in Low Earth Orbit (LEO) all that satellite has to do is have antennas designed to receive the GPS signal and processors that action the navigational signal[28]. If the satellite is above the GPS constellation in highly elliptical orbit (HEO) or geostationary/geosynchronous orbit (GEO) all it takes is the ability to track GPS satellites in view.[29]

GPS equipment on space systems can provide high-precision orbit determination with minimum ground control, replace high-cost onboard attitude sensors, replace onboard atomic clocks[30], allow formation flying with minimal ground intervention, provide automatic station keeping, and augment radar systems for launch and early orbit determination.[31] With the increased threat of denied/degraded and contested/congested operations of the GPS signals any interference will have devastating and far-reaching effects. With the operationalization of space and the recognition of space as a warfighting domain,[32] the importance of GPS is even more important. As stated throughout this work, using GPS is woven into the fabric or our society, way of life, and increasingly utilized in everyday technology. The United States will and must protect GPS as the structures and institutions that underpin our way of life.

NAVWAR

The doctrine that the United States and her allies to depend on in order to protect GPS is Navigation Warfare (NAVWAR). Navigation warfare enables the use of GPS and PNT technologies through all domains and all levels of warfare, from permissive to denied operating environments. While NAVWAR falls within the greater electromagnetic (EM) warfare doctrine, GPS and PNT technologies are the cornerstone technologies that enable most other warfighting technologies. While we as a nation are well versed in EM warfare, NAVWAR investment, tactics, techniques, and procedures (TTP) should be further refined and developed to assure access to GPS at any location on the planet.

The ability to protect and enhance our fielded abilities and develop new technologies is dependent on the questions: Can we augment GPS with additional technology essential to assure our ability to operate? What are the alternatives?

ALTERNATIVES

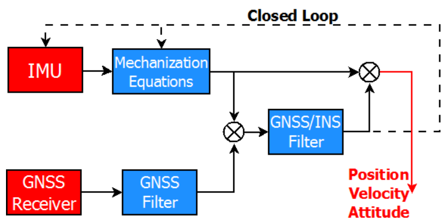
The primary alternative to GPS is the use of other space-based Global Navigation Satellite Systems (GNSS). As discussed in previous sections of this analysis, the advantages of a space-based system offer endless potential and the most important advantage of global 24/7 accesses. While other GNSS systems are not GPS, the first GNSS system and worldwide standard offers similar capability that can be augmented with hardware/software changes. The level of change for any system to utilize more than GPS depends on its ability to be modified, be software reprogrammable, and most importantly that the receivers have the ability to calculate the most accurate solution for PNT applications. The ability to calculate and resolve the difference between systems is the major obstacle to the United States adapting a multi-GNSS solution.

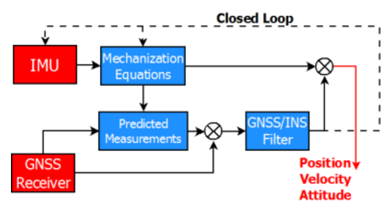
To adapt a multi-GNSS solution requires a level of trust for the data that is being transferred to the receiver level. Other GNSS constellations are operated by foreign governments and in periods of heightened tension, such as minor to major warfare, the ultimate questions remain: What is the adversary's NAVWAR plan going to be? Is the signal at the receiver trustworthy? Is the receiver in a jammed/degraded operating environment? How long has my receiver been in a jammed/spoofed/degraded operating environment? These are some of the primary questions associated with implementing a multi-GNSS solution. Assessing each GNSS and some of the hurdles of incorporation with GPS is important for this analysis.

There are 100 total GNSS and Regional Navigation Satellite Systems (RNSS) in orbit today. Each system has different reference frames, timing standards, different orbit configurations (semi-major axis, eccentricity (tilt of orbit), and inclinations), different signal structures, and modes of tracking which make integration difficult and necessitates mathematical adjustments when combined[33]. An additional consideration for application in a Multi-GNSS environment is how to calculate and integrate the other GNSS/RNSS system. When navigational systems are integrated, they can be loosely coupled (LC) or tightly coupled (TC)[34]. The primary difference between the two is how the series of components outputs a navigational solution.

Loosely coupled or the "decentralized approach" includes a Kalman Filter (KF) to combine INS and GNSS parameters[35]. The primary disadvantage of LC is if there are not enough satellites to compute a standalone solution, the inertial system is not updated which results in higher positioning errors when compared to the TC strategy[36].

Figure 1. Loosely coupled scheme [37] Figure 2 Tightly coupled scheme[38]





The TC strategy also referred to as "centralized" due to it only having one KF and its ability to produce a solution regardless of how many satellites are in track or view, allowing for anytime updates when compared to the LC strategy[39].

The first GNSS satellite system that has real-world integration examples to utilize is GLONASS. The Russian GNSS system has been recapitalized over the last decade and has been mandated into cellphone technology since the iPhone 4 (2011)[40] when the commercial manufacturers of chipsets started incorporating a multi-GNSS solution for faster fix times in their handheld devices. The benefit of GLONASS is that it has been optimized for northern latitudes and has been available to the commercial sector since 2007 as a direct competitor to GPS. One substantive difference for acquisition of GLONASS signal is that it utilizes the FDMA in comparison to other GNSS satellite systems utilizing CDMA. The primary difference between the two signal variations is a difference in employment technique and EM philosophies. With the new generation of GLONASS-K satellites Russia has begun transitioning to CDMA signal structures[41], which will give GLONASS, increased interoperability with all other GNSS systems operating on CDMA.

The integration of GLONASS/GPS is an immediate possibility for a multi-GNSS solution. GLONASS is the only other complete GNSS system. The commercial application and experience of incorporating GLONASS and GPS together has occurred since 2011. Industry best practices and mathematical algorithms have already been written. As stated earlier, the modification to existing systems would depend on their expandability, antenna frequency optimization, and the update to existing software systems that support the end user. The best use most likely for military applications would be to use the tightly coupled solution to optimize the navigational and timing solution. An additional consideration for use of multi-GNSS and the use of GLONASS would include the ability of the receiver to revert to single source GPS or other internal inertial reference gyro or computer. This protects military and critical equipment should adversarial NAVWAR occur during worldwide deployment/fielding.

The GNSS systems for inclusion in military applications will most likely be Europe's Galileo and Japan's QZSS. Both are trusted partners and there is a foundation built on international agreements, treaties, and cooperation. Working with these two entities independently would limit the total potential solution for realized multi-GNSS. The decision space and timing is critical to have interoperability with both systems; thus, requiring combined talks and cooperation so all three systems GPS, Galileo, and QZSS have optimized interoperability in standards, frequencies, power levels, satellite placement, and other capabilities. Combined talks allow the United States to shape the global GNSS discussion as the world leader in PNT.

Another potential solution for alternative PNT is to use computer networks and other non-traditional sources to establish a PNT solution. The use of computer networks is a viable solution, especially those with embedded atomic clocks. Any network solution relies on time synchronization to establish links and pass information. A significant challenge for the A2AD contested operating environment is how to supplement network time to pass time updates through a jammed/denied operating area? The augmentation of PNT weapon systems with network timing assets is an achievable solution as part of a blended solution with GNSS and INUs onboard systems operating at the front line. A2AD operating environments mandate multiple sources and methods for PNT for effective operations. As an independent solution, network time is not enough; it has to be part of the total system construct.

The discussion of multi-GNSS and multi-PNT underlines one important fact: the era of GPS-only is at an end. With 100 GNSS and RNSS satellites in orbit and new developments and advancements in PNT occurring every year, PNT has solidified its role as a vital necessity to our life. The use of GPS-only as a solution in software/hardware applications in the Information age will leave operations limited to permissive operating environments and equipment/software unable to overcome the contested or degraded operating environments of this century. The questions remain: what will it cost to upgrade our current infrastructure and what is the cost for assuring operability?

An additional consideration to assuring PNT access is the benefit of uninterrupted power and utilities. The underlying infrastructures that utilizes GPS include: 1) Power Grid Systems, 2) Banking operations to include the use of ATMs and everyday transactions with our credit card systems, 3) worldwide communications networks, to include the ability for the internet to operate, and 4) worldwide logistics networks that enable our globalized world[42]. Without GPS and without assuring GPS through the use of multi-GNSS or multi-PNT we risk our ability to live in our 21st century information age.

How is the significant cost of upgrading our systems managed? The most likely course of action is to upgrade in a phased manner to take advantage of the benefits of multi-PNT and GNSS. The benefits of upgrading to new PNT systems enable users to overcome cyber vulnerabilities, enhance PNT capability, and phase new software updates/coding in throughout the refreshed lifecycle. This applies not only to the nations critical infrastructure, but to the military, commercial and civilian applications, as well. Remaining a nation dependent solely on GPS could leave the US vulnerable and unable to respond when capability is most critical.

RECOMMENDATIONS

With the discussion focused on multi-GNSS, many critics and decision makers often ask, Can we move beyond GPS entirely? The simplest answer to that frequent question is no, because no other system provides reliable worldwide availability 24/7, on demand and multi-GNSS solutions build upon the successes and reliability of GPS. Aerial augmentation, multi-GNSS, computer networks, and the incorporation of navigational upgrades should be considered and implemented as a new PNT architecture for the 21st Century. A layered approach allows the world to overcome any weaknesses (theoretical, imagined, or real), absorb attacks in depth and have the ability to maintain synchronization to the globally interconnected world.

Multi-Source PNT and GNSS requires multiple sources and systems that are flexible, adaptable, and able to respond in real-time to complicated operating environments and/or attack(s), and support open-architectures that are defendable, protected, and cyber-hardened. Immediate upgrades to existing GPS systems are achievable goal to enhance system resiliency against current vulnerabilities; enabling them to overcome most contested/degraded environments they encounter. Loose and tightly coupled PNT solutions with multiple GNSS systems give flexibility for the system and/or its operating software to adaptable between PNT sources, increasing the likelihood of mission success (by not losing PNT), maintaining accuracy while operating through complicated threat environments. While Galileo and QZSS GNSS systems are the trusted partner systems of the DOD, the use of GLONASS gives worldwide redundancy reducing any adversary's ability to mitigate the overwhelming force the United States presents during military conflict.

Although the Air Force is the lead for GPS programs, it is going to require a whole of government and all-service contribution to remain dominant throughout the 21st century. While GPS has been the primary concern of the Department of the Air Force for the last 40 years, the disparate navigational systems the purview of each individual weapon system, the 21st century requires an integrated full system approach. For navigation dominance, all PNT systems should be designed together in an open architecture with the ability to expand to incorporate future upgrades and developments. An open architecture designed system allows for NAVWAR dominance and gives the United States and her allies the ability to outmaneuver the enemy in this critical underpinning technology.

The Air Force should charter an Enhanced Concept Capabilities Team (ECCT) for PNT. An ECCT is needed to uncover all GPS connections, interdependencies, and to allow the Air Force to make informed decisions when it comes to future PNT applications. The ECCT will result in a PNT flight plan, inform the Department of the Air Force, creating a foundational document that all Information Age acquisitions can reference to build resilient weapon systems with assured timing, navigation, and positioning.

CONCLUSIONS

GPS sets the United States warfighting efforts apart from every other global military power. The Second Offset provided GPS and the information superiority that allowed the American military to be dominant. While GPS's advantages have been fully realized in modern warfare, the contested, degraded operating environment is where the American military is going to have to overcome our adversaries in the future. Like every great groundbreaking technology, expansion and upgrade are inevitable and required. Critics will say that it is time to discontinue GPS and create a new system for the battlefield of the future. Sole-source PNT via GPS is the methodology that is now outdated and needs revision/augmentation. That revision is multi source PNT, whether it is from multiple GNSS constellations, upgrades across all GPS segments (user, satellite, ground system), or the re-imagining what a PNT constellation looks like, all are within the realm of the possible. What is an inexorable truth: PNT needs good management, strategy, and timely decision making so that the United States and her allies never fall behind the new GNSS systems fielded by our fellow nations.

To realize multi-PNT and to move beyond sole-source PNT via GPS, deliberate, articulate decision-making is critical within the Department of the Air Force and the greater Department of Defense. The creation of a central office responsible for PNT development would enable timely decisions and allow for all individual stakeholders to manage across the PNT enterprise and ensure that their efforts aren't being duplicated in the Air Force or the greater DOD. This central office would improve the focus of PNT from being solely space mission focused to PNT as an enterprise. This central office could be located under the new Deputy Chief of Staff of the Air Force for Space, the A11. This new center of excellence would be a central point for the Air Force and the Department of Defense and work in coordination with PNT central offices created in the Departments of the Navy and Army.

NAVWAR will be critical to operations in our next major military operation. The ever-increasing dependence upon the EM spectrum makes GPS and PNT decisions in the near term critical to enable the long-term ability of the United States military to overcome contested, congested, hostile and denied operating environments. GPS and PNT are essential to the ability to conduct operations worldwide. The nation should make the deliberate decision to decrease reliance on GPS alone by investing in multiple PNT and complimenting capabilities. Acquisition for any major defense program often takes 10-15 years; considering that timeline, the critical decisions should be made now to field capability when it is most needed. Additional capabilities on currently fielded capabilities and those coming in the near future are achievable with stable funding. GPS and PNT are worth the investment. The projected net benefit to the economy is $122.4 billion per year and 5.8 million jobs once GPS reaches 100 percent in the commercial GPS Intensive industries[43]. Our military, economy, and way of life depend on reliable PNT provided by GPS, diversification with multi-PNT solutions enables another American century.

[1] By, Rebecca Grant, - Wilson Brissett, Brian Everstine, and Gideon Grudo8/14/2017, -Wilson Brissett, Brian Everstine, Gideon Grudo, and Amy McCullough8/11/2017, and -Wilson Brissett, Brian Everstine, and Amy McCullough8/10/2017. "The Second Offset." Air Force Magazine. Accessed August 13, 2017. http://www.airforcemag.com/MagazineArchive/Pages/2016/July%202016/The-Second--Offset.aspx.

[2] Mansky, Jackie. "Operation Desert Storm Was Not Won By Smart Weaponry Alone." Smithsonian.com, Smithsonian Institution, 20 Jan. 2016, www.smithsonianmag.com/history/operation-desert-storm-was-not-won-smart-weaponry-alone-180957879/. Accessed 20 Aug. 2017.

[3] IBID

[4] Chris Matyszczyk August 11, 2013 8:08 AM PDT @ChrisMatyszczyk. "Truck driver has GPS jammer, accidentally jams Newark airport." CNET. August 11, 2013. Accessed August 13, 2017. https://www.cnet.com/news/truck-driver-has-gps-jammer-accidentally-jams-newark-airport/.

[5] IBID

[6] Downes, L. (2017, June 12). Ligado Is Ready To Launch A New Mobile Network. Will The FCC Let Them? Retrieved August 13, 2017, from https://www.forbes.com/sites/larrydownes/2017/06/12/ligado-is-ready-to-launch-a-new-mobile-network-will-the-fcc-let-them/#24772f793831

[7] "GPS Adjacent Band Compatibility Assessment." Www.gps.gov. December 2016. Accessed July 2017. http://www.gps.gov/governance/advisory/meetings/2016-12/vandyke.pdf.

[8] Springer, T.A. "High Accuracy GNSS Solutions and Services." Global Navigation Satellite System Overview. GLONASS Overview. Accessed August 13, 2017. http://www.positim.com/glonass_overview.html.

[9] Telit Wireless Solutions. "GPS Glonass: Using the Best of Both Worlds." Telit Wireless Solutions. October 2012. Accessed July 2017. http://www.telit.com/fileadmin/user_upload/media/Telit_WP_GPS_Glonass_1211.pdf.

[10] Stachowiak, Sandy, Ben Stegner, and Taylor Bolduc. "GLONASS – The GPS Alternative You Never Knew Existed." MakeUseOf. January 09, 2015. Accessed August 13, 2017. http://www.makeuseof.com/tag/glonass-gps-alternative-never-knew-existed/.

[11] Victor Chebotarev, Victor Kosenko, Vladimir Bartenev. "Replenishment of the GLONASS Constellation." Inside GNSS: Engineering Solutions from the Global Navigation Satellite System Community. Accessed August 13, 2017. http://www.insidegnss.com/node/505.

[12] Couts, Andrew. "What is GLONASS?: A quick guide to the iPhone 4S' Russian navigation system." Digital Trends. October 20, 2011. Accessed August 13, 2017. https://www.digitaltrends.com/mobile/what-is-glonass-a-quick-guide-to-the-iphone-4s-russian-navigation-system/.

[13] Garmin Inc. "Garmin Product Description Page: GPS & Glonass." Www.garmin.com. https://buy.garmin.com/en-US/US/cRunning-p1.html?FILTER_FEATURE_OUTDOORGLONASS=true&sorter=featuredProducts-desc.

[14] "About Trimble | GNSS Technology." Trimble. Accessed August 13, 2017. http://www.trimble.com/Corporate/GNSS_Technology.aspx.

[15] Caverly, R. James. "GPS Critical Infrastructure Usage/Loss Impacts/Backups/Mitigation." NOAA. April 27, 2011. Accessed July 14, 2017. http://www.swpc.noaa.gov/sites/default/files/images/u33/GPS-PNTTimingStudy-SpaceWeather4-27.pdf.

[16] "Error analysis for the Global Positioning System." Wikipedia. July 25, 2017. Accessed August 13, 2017. https://en.wikipedia.org/wiki/Error_analysis_for_the_Global_Positioning_System#cite_ref-10.

[17] "Satellite Navigation - GPS - Policy - Selective Availability." FAA seal. November 13, 2014. Accessed August 13, 2017. https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/gps/policy/availability.

[18] "GPS III Permanently Discontinues Selective Availability." Government Technology: State & Local Government News Articles. Accessed August 13, 2017. http://www.govtech.com/policy-management/GPS-III-Permanently-Discontinues-Selective-Availability.html.

[19] "Directions 2017: The year of Galileo." GPS World. December 09, 2016. Accessed August 13, 2017. http://gpsworld.com/directions-2017-the-year-of-galileo/.

[20] Space Based Positioning Navigation & Timing Executive Committee . "GPS and Galileo...Progress through Partnership." Www.gps.gov. Accessed August 2017. http://www.gps.gov/policy/cooperation/europe/2007/gps-galileo-fact-sheet.pdf.

[21] "Joint Announcement on United States–Japan GPS Cooperation." GPS.gov: 2006 Joint Announcement on U.S.-Japan GPS Cooperation. Accessed August 13, 2017. http://www.gps.gov/policy/cooperation/japan/2006-joint-announcement/.

[22] "TAG: urban canyon." GPS World. Accessed August 13, 2017. http://gpsworld.com/tag/urban-canyon/.

[23] Stokes, Felix Salmon and Jon. "Algorithms Take Control of Wall Street." Wired. December 27, 2010. Accessed August 13, 2017. https://www.wired.com/2010/12/ff_ai_flashtrading/.

[24] IBID

[25] Mary Shacklett | February 27, 2015, 7:35 AM PST. "GPS serves a pivotal role in big data stickiness." TechRepublic. Accessed August 13, 2017. http://www.techrepublic.com/article/gps-serves-a-pivotal-role-in-big-data-stickiness/.

[26] IBID

[27] IBID

[28] "Space." GPS.gov: Space Applications. Accessed August 13, 2017. http://www.gps.gov/applications/space/.

[29] IBID

[30] Alexander, Ken . "GPS Modernization, Interoperability & GNSS Space Service Volume." Www.gps.gov. July 28, 2016. Accessed August 2017. http://www.gps.gov/multimedia/presentations/2016/07/ICG 2016/alexander.pdf.

[31] IBID

[32] Clark, Colin. "Exclusive: War In Space 'Not A Fight Anybody Wins' — Gen. Raymond." Breaking Defense. Accessed August 13, 2017. http://breakingdefense.com/2017/04/exclusive-war-in-space-not-a-fight-anybody-wins-gen-raymond/.

[33] Beutler, Gerard, Ruth Nielson, and Arve Dimmen. "Multi-GNSS: Update, Latest Developments and Science Issues in Transition Document." Www.gps.gov. June 2017. Accessed July 2017. http://www.gps.gov/governance/advisory/meetings/2017-06/beutler.pdf.

---

[34] Angrisano, Antonio, Mark Petovello, and Giovanni Pugliano. "Benefits of Combined GPS/GLONASS with Low-Cost MEMS IMUs for Vehicular Urban Navigation." Www.mdpi.com. April 2012. Accessed July 2017. www.mdpi.com/1424-8220/12/4/5134/pdf.

[35] IBID,12
[36] IBID.
[37] IBID.
[38] IBID.
[39] IBID.
[40] "Glonass Russian GPS coming from Qualcomm & more to boost LBS." SlashGear. Accessed August 13, 2017. https://www.slashgear.com/glonass-russian-gps-coming-from-qualcomm-more-to-boost-lbs-18140844/.
[41] "FDMA vs. CDMA." FDMA vs. CDMA - Navipedia. Accessed August 13, 2017. http://www.navipedia.net/index.php/FDMA_vs._CDMA.
[42] Caverly, R. James. "GPS Critical Infrastructure Usage/Loss Impacts/Backups/Mitigation." NOAA. April 27, 2011. Accessed July 14, 2017. http://www.swpc.noaa.gov/sites/default/files/images/u33/GPS-PNTTimingStudy-SpaceWeather4-27.pdf.
[43] Pham, Nam D., PhD. "The Economic Benefits of Commercial GPS Use in the U.S. and The Costs of Potential Disruption." GPS Alliance. June 2011. Accessed August 2017. http://www.gpsalliance.org/docs/GPS_Report_June_21_2011.pdf.

BIBLIOGRAPHY

By, Rebecca Grant, - Wilson Brissett, Brian Everstine, and Gideon Grudo8/14/2017, -Wilson Brissett, Brian Everstine, Gideon Grudo, and Amy McCullough8/11/2017, and -Wilson Brissett, Brian Everstine, and Amy McCullough8/10/2017. "The Second Offset." Air Force Magazine. Accessed August 13, 2017. http://www.airforcemag.com/MagazineArchive/Pages/2016/July%202016/The-Second--Offset.aspx.

"About Trimble | GNSS Technology." Trimble. Accessed August 13, 2017. http://www.trimble.com/Corporate/GNSS_Technology.aspx.

Alexander, Ken . "GPS Modernization, Interoperability & GNSS Space Service Volume." Www.gps.gov. July 28, 2016. Accessed August 2017. http://www.gps.gov/multimedia/presentations/2016/07/ICG 2016/alexander.pdf.

Angrisano, Antonio, Mark Petovello, and Giovanni Pugliano. "Benefits of Combined GPS/GLONASS with Low-Cost MEMS IMUs for Vehicular Urban Navigation." Www.mdpi.com. April 2012. Accessed July 2017. www.mdpi.com/1424-8220/12/4/5134/pdf.

Beutler, Gerard, Ruth Nielson, and Arve Dimmen. "Multi-GNSS: Update, Latest Developments and Science Issues in Transition Document." Www.gps.gov. June 2017. Accessed July 2017. http://www.gps.gov/governance/advisory/meetings/2017-06/beutler.pdf.

Caverly, R. James. "GPS Critical Infrastructure Usage/Loss Impacts/Backups/Mitigation." NOAA. April 27, 2011. Accessed July 14, 2017. http://www.swpc.noaa.gov/sites/default/files/images/u33/GPS-PNTTimingStudy-SpaceWeather4-27.pdf.

Chris Matyszczyk, August 11, 2013 8:08 AM @ChrisMatyszczyk. "Truck driver has GPS jammer, accidentally jams Newark airport." CNET. August 11, 2013. Accessed April 13, 2017. https://www.cnet.com/news/truck-driver-has-gps-jammer-accidentally-jams-newark-airport/.

Clark, Colin. "Exclusive: War In Space 'Not A Fight Anybody Wins' — Gen. Raymond." Breaking Defense. Accessed August 13, 2017. http://breakingdefense.com/2017/04/exclusive-war-in-space-not-a-fight-anybody-wins-gen-raymond/.

Couts, Andrew. "What is GLONASS?: A quick guide to the iPhone 4S' Russian navigation system." Digital Trends. October 20, 2011. Accessed August 13, 2017. https://www.digitaltrends.com/mobile/what-is-glonass-a-quick-guide-to-the-iphone-4s-russian-navigation-system/.

"Department of Defense Directive on Positioning, Navigation , and Timing." Directives Division. Accessed August 13, 2017. http://www.dtic.mil/whs/directives/corres/pdf/465005p.pdf.

"Directions 2017: The year of Galileo." GPS World. December 09, 2016. Accessed August 13, 2017. http://gpsworld.com/directions-2017-the-year-of-galileo/.

"DOD DIRECTIVE 4650.08 POSITIONING, NAVIGATION, AND TIMING (PNT) and Navigation Warfare." DODD 4650.08 - Positioning, Navigation, and Timing (PNT) and Navigation Warfare (Navwar) | Engineering360. Accessed August 13, 2017. http://standards.globalspec.com/std/9897237/dodd-4650-08.

Downes, Larry. "Ligado Is Ready To Launch A New Mobile Network. Will The FCC Let Them?" June 12, 2017. Accessed August 13, 2017. https://www.forbes.com/sites/larrydownes/2017/06/12/ligado-is-ready-to-launch-a-new-mobile-network-will-the-fcc-let-them/#24772f793831.

"Error analysis for the Global Positioning System." Wikipedia. July 25, 2017. Accessed August 13, 2017. https://en.wikipedia.org/wiki/Error_analysis_for_the_Global_Positioning_System#cite_ref-10.

"FDMA vs. CDMA." FDMA vs. CDMA - Navipedia. Accessed August 13, 2017. http://www.navipedia.net/index.php/FDMA_vs._CDMA.

Garmin Inc. "Garmin Product Description Page: GPS & Glonass." Www.garmin.com. https://buy.garmin.com/en-US/US/cRunning-p1.html?FILTER_FEATURE_OUTDOORGLONASS=true&sorter=featuredProducts-desc.

"Glonass Russian GPS coming from Qualcomm & more to boost LBS." SlashGear. Accessed August 13, 2017. https://www.slashgear.com/glonass-russian-gps-coming-from-qualcomm-more-to-boost-lbs-18140844/.

"GPS Adjacent Band Compatibility Assessment." Www.gps.gov. December 2016. Accessed July 2017. http://www.gps.gov/governance/advisory/meetings/2016-12/vandyke.pdf.

"GPS III Permanently Discontinues Selective Availability." Government Technology: State & Local Government News Articles. Accessed August 13, 2017. http://www.govtech.com/policy-management/GPS-III-Permanently-Discontinues-Selective-Availability.html.

Telit Wireless Solutions. "GPS Glonass: Using the Best of Both Worlds." Telit Wireless Solutions. October 2012. Accessed July 2017. http://www.telit.com/fileadmin/user_upload/media/Telit_WP_GPS_Glonass_1211.pdf.

Space Based Positioning Navigation & Timing Executive Committee . "GPS and Galileo...Progress through Partnership." Www.gps.gov. Accessed August 2017. http://www.gps.gov/policy/cooperation/europe/2007/gps-galileo-fact-sheet.pdf.

"Joint Announcement on United States–Japan GPS Cooperation." GPS.gov: 2006 Joint Announcement on U.S.-Japan GPS Cooperation. Accessed August 13, 2017. http://www.gps.gov/policy/cooperation/japan/2006-joint-announcement/.

Mansky, Jackie. "Operation Desert Storm Was Not Won By Smart Weaponry Alone." Smithsonian.com, Smithsonian Institution, 20 Jan. 2016, www.smithsonianmag.com/history/operation-desert-storm-was-not-won-smart-weaponry-alone-180957879/. Accessed 20 Aug. 2017.

Mary Shacklett, February 27, 2015, 7:35 AM PST. "GPS serves a pivotal role in big data stickiness." TechRepublic. Accessed August 13, 2017. http://www.techrepublic.com/article/gps-serves-a-pivotal-role-in-big-data-stickiness/.

"National Space Policy." Office of Space Commerce. Accessed August 13, 2017. http://www.space.commerce.gov/policy/national-space-policy/. http://www.gps.gov/governance/advisory/meetings/2016-12/vandyke.pdf.

Paziewski, Jacek, and Pawel Wielgosz. "Accounting for Galileo–GPS inter-system biases in precise satellite positioning." SpringerLink. October 08, 2014. Accessed August 13, 2017. http://link.springer.com/article/10.1007%2Fs00190-014-0763-3.

Peres, T. R., J. S. Silva, P. F. Silva, D. Carona, A. Serrandor, F. Palhinha, R. Pereira, and M. Vestias. "MULTI-GNSS RECEIVER FOR AEROSPACE NAVIGATION AND POSITIONING APPLICATIONS." The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, W1, XL, no. 3 (March 1, 2014): 87-92.

Pham, Nam D., PhD. "The Economic Benefits of Commercial GPS Use in the U.S. and The Costs of Potential Disruption." GPS Alliance. June 2011. Accessed August 2017. http://www.gpsalliance.org/docs/GPS_Report_June_21_2011.pdf.

"Satellite Navigation - GPS - Policy - Selective Availability." FAA seal. November 13, 2014. Accessed August 13, 2017. https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/gps/policy/availability.

Soderholm, Stefan, Mohammad Zahidul H. Bhuiyan, Sarang Thombre, Laura Ruotsalainen, and Heidi Kuusniemi. "A multi-GNSS software-defined receiver: design, implementation, and performance benefits." Annals of Telecommunications, 2016th ser., 71, no. 7-8, 399-410. doi:10.1007/s12243-016-0518-7.

"Space." GPS.gov: Space Applications. Accessed August 13, 2017. http://www.gps.gov/applications/space/.

Springer, T.A. "High Accuracy GNSS Solutions and Services." Global Navigation Satellite System Overview. GLONASS Overview. Accessed August 13, 2017. http://www.positim.com/glonass_overview.html.

Stachowiak, Sandy, Ben Stegner, and Taylor Bolduc. "GLONASS – The GPS Alternative You Never Knew Existed." MakeUseOf. January 09, 2015. Accessed August 13, 2017. http://www.makeuseof.com/tag/glonass-gps-alternative-never-knew-existed/.

Stokes, Felix Salmon and Jon. "Algorithms Take Control of Wall Street." Wired. December 27, 2010. Accessed August 13, 2017. https://www.wired.com/2010/12/ff_ai_flashtrading/.

"TAG: urban canyon." GPS World. Accessed August 13, 2017. http://gpsworld.com/tag/urban-canyon/.

Tegedor, J., O. Øvstedal, and E. Vigen. "Precise orbit determination and point positioning using GPS, Glonass, Galileo and BeiDou." Journal of Geodetic Science. January 05, 2015. Accessed August 13, 2017. https://www.degruyter.com/view/j/jogs.2014.4.issue-1/jogs-2014-0008/jogs-2014-0008.xml.

Victor Chebotarev, Victor Kosenko, Vladimir Bartenev. "Replenishment of the GLONASS Constellation." Inside GNSS: Engineering Solutions from the Global Navigation Satellite System Community. Accessed August 13, 2017. http://www.insidegnss.com/node/505.