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## Evolution of GPS Systems Architecture and Its Impacts

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### ABSTRACT

*GPS provides many benefits to civilian users. It is vulnerable, however, to interference and other disruptions that can have harmful consequences. GPS users must ensure that adequate independent backup systems or procedures can be used when needed. Interagency GPS Executive Board. GPS Policy, Applications, Modernization, International Cooperation. February 2001.*

### INTRODUCTION

There is no denying the impact that GPS has had on our daily lives both in the United States and worldwide. Far beyond the small screen on the dashboards of automobiles that many drivers have come to rely on in place of the paper road maps we grew up with, GPS is now a ubiquitous technology that is utilized for applications in transportation, financial systems, cell phone technology, air traffic communications, emergency services and many others. Over time, GPS has become something almost like a utility. Civil agencies, commercial firms and many individuals use some type of GPS receiver to navigate from one location to another. Firms in the private sector use the technology to route vehicles, not only in the maritime sector but in mass transit as well. The aviation industry has implemented its use to augment navigation and increase the safety and efficiency of commercial flight systems. The timing signal that GPS broadcasts has become critical various economic activities that include and as diverse as electrical power grids, financial networks and communication systems.



**Figure 1: Military and Nonmilitary Users of GPS Technology (Bogosian, 2003)**

Figure 1 shows military and nonmilitary users of GPS technology reported by Bogosian (2003). Not too bad for a piece of technology that was originally intended for use only as a weapon system, but quite often much of the technology used by the U. S. military today either starts out or ends up as what is called “dual use.” This is not a new idea but in fact represents what has become a long term trend. Unfortunately, the very fact of GPS’ utility in so many daily applications is the very reason that the United States Air Force (USAF), the Executive Agent for the

management of the GPS constellation, is presently considering other technologies for its eventual replacement. The fact that it has become so widespread and the signal so open source also has increased its vulnerabilities to the point that many senior leaders in the USAF consider it to be too unreliable for long term use as a piece of a weapons delivery solutions. The situation has become serious enough that the USAF Chief of Staff Gen. Norton Schwartz has addressed the issue directly in his opening remarks at a national security conference in Washington D.C. on January 20, 2010 (Hoffman, 2010), where he stated:

*“Global positioning has transformed an entire universe of war-fighting capability. Our dependence on precision navigation in time will continue to grow,” (Schwartz said in the opening address to the conference, sponsored by the Institute of Foreign Policy and Tufts University’s Fletcher School). “It seems critical to me that the joint force reduce its dependence on GPS aid.”<sup>1</sup>*

General Schwartz went on to speak to the possibilities of an enemy jamming a GPS signal needed by the military or, alternatively and even worse, to make use of some type of spoofing technique to reroute a weapon to a location other than its intended target. This spawns the following questions: How likely are these scenarios? How big a threat is it to U. S. national security?

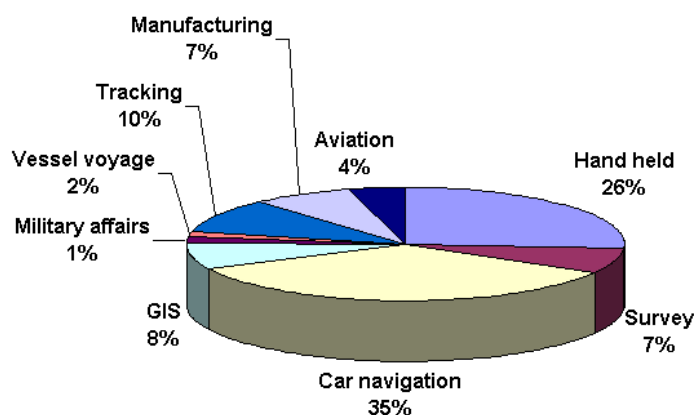


Figure 2: Distribution of GPS Users in the United States (“GPS”, 2006, July)

### CURRENT RESEARCH EFFORTS

The Air Force Institute of Technology (AFIT) is a leading source of research and development for the USAF. Located at Wright Patterson AFB, near Dayton, Ohio, it sponsors and educates the next generation of USAF technical leaders in areas of science and technology critical to the future of the force’s ability to achieve and sustain air dominance. In a review of the list of Thesis titles<sup>2</sup> for work done in the last five years, the examples of an alternative to GPS are many, including in 2010 alone:

- Gravity Gradiometry and Map Matching: An Aid to Aircraft Inertial Navigation Systems.
- An Integrity Framework for Image-Based Navigation Systems.

<sup>1</sup> The Air Force’s top uniformed leader thinks the military is too dependent on global positioning and must develop an alternative to the navigation system to reduce its vulnerability to enemies. Chief of Staff Gen. Norton Schwartz delivered this warning about the government’s satellite constellation January 20, 2010, at a national security conference in Washington, D.C., but also assured his fellow defense leaders that Air Force scientists are working to develop other navigational technologies. Accessed on July 18, 2010, from [http://www.airforcetimes.com/news/2010/01/airforce\\_schwartz\\_012310/](http://www.airforcetimes.com/news/2010/01/airforce_schwartz_012310/).

<sup>2</sup> The Dissertation and Thesis titles can be found at the AFIT website managed by the Advanced Navigation and Technology (ANT) Center located at <http://www.afit.edu/en/ant/centerresearch.cfm?a=thesis>. For the last several years, subjects have included alternatives to GPS reliance which would seem to indicate the depth of the problem as viewed by the current S&T community within the Air Force.

- Satellite-Based Fusion of Imaging Sensors and Georegistered Map Data for Precise Geolocation and Target Tracking.
- Global Navigation Satellite System Software Defined Radio.
- Aiding GPS with Additional Satellite Navigation Services
- Broadcast Vs Precise GPS Ephemerides: An Historical Perspective
- Precision Navigation Using Pre-Georegistered Map Data
- Aiding GPS With Additional Satellite Navigation Services

There are multiple others which demonstrates the fact that the Air Force considers it a big enough issue to begin pouring money into researching potential solutions at this time. Defining the system of technologies as yet immature or even nonexistent that will augment or even completely replace the current system is not a trivial task. *Is the Air Force overblowing the issue?*

### VULNERABILITIES—NATURAL AND OTHER

While there are natural sources such as solar flares that can interfere with a GPS signal, we need to understand that we are not talking about disrupting a very strong signal. *"The strength of a GPS signal is about as strong as viewing a 25W light bulb from a satellite 10,000 miles away,"* said Bob Cockshott, a director of the Digital Systems KTN. *"It's no surprise then that GPS signals are vulnerable to natural and, increasingly, criminal interruptions."*<sup>3</sup>

There are in fact GPS jammers available for sale now on the internet<sup>4</sup>. A recent article by Fox News even provides links to sources where the devices can be purchased at <http://www.jammer-store.com/gj6-all-civil-gps-signal-jammer-blocker.html> and [http://gadget.brande.com/car-cigarette-anti-gps-system\\_p00963c024\\_d001.html](http://gadget.brande.com/car-cigarette-anti-gps-system_p00963c024_d001.html) for as little as \$49 that can be shipped worldwide via UPS. On review of the sites, the capabilities of the devices seems limited to a 10-15 meter range. This by itself should not be too alarming to the AF which can provide a "kinetic solution" dropped from a fighter that will leave a crater twice this size, but there have been tests conducted in the United Kingdom that have demonstrated the ability to jam a signal for a radius as large as 30 kilometers and in fact has been shown to provide a way of "spoofing" the signal to provide erroneous position and velocity information. This research shows that this technology jams the L1/L2 and L5 bands currently broadcast or currently projected for adoption.<sup>5</sup>

The 30 km radius documented in the research combined with the multiband frequencies provide the answer to the question posed earlier about the problem being potentially overblown—we have to conclude that the issues posed by the Air Force do, in fact, present a very real loss of combat capability currently enjoyed and required by the U. S. military.

The GJ6, shown in Figure 3, is advertised to jam all civil GPS frequencies including GPS L1, GPS L2 and GPS L5 systems. After turning on the GJ6 jammer, all civil GPS signals will be blocked. The GJ6 has a cooler fan inside the housing. Not all GPS tracking devices are able to work in your car. A more mobile alternative is the car cigarette anti-GPS systems shown in Figure 4. All one has to do is plug in and use—there is no special technique or training needed. The effective range is advertised at approximately 10 meters and works off a car cigarette lighter.

<sup>3</sup> As detailed at <http://www.crossrate.com/news/58/73/Jamming-of-GPS-signals-threatens-vital-services-in-February-2010>, in the Financial Times.

<sup>4</sup> Fox News reported in March 2010 that there were GPS jammers available for sale online for as little as \$49. While the ownership, importation and use of such devices is illegal under current FCC guidelines, that doesn't mean that a federal law will prevent the proliferation of such technology for use by foreign parties who mean us harm. Accessed on July 15, 2010, from <http://www.foxnews.com/scitech/2010/03/17/gps-jammers-easily-accessible-potentially-dangerous-risk>

<sup>5</sup> An article in GPS World in October 2009, detailed the magnitude of the threat posed by this methodology. <http://www.gpsworld.com/defense/security-surveillance/expert-advice-gps-forensics-crime-and-jamming-8986>



Figure 3: The GJ6 GPS Jammer (Jammer-Store, n.d.)



Figure 4: The Car Cigarette Anti-GPS System (Gadget.brando.com, 2011)

Accidental jamming also takes place as demonstrated by Boeing between December 13 and December, 2001. While preparing for an upcoming systems test, a frequency jammer was accidentally left on in Mesa, Arizona and created issues as far as 180 nautical miles of Mesa. The L1 jammer was radiating at 0.8mW and operated continuously for 4.5 days. The impact to Air Traffic Control operations was immediately felt, and although no aircraft were lost, the GPS signal was disrupted as far as Phoenix where out as far as 45nm aircraft performed 35° turn toward traffic to try and recover the signal. A NOTAM was not issued until 2nd day, numerous pilots reported loss of the GPS NavAid and there were reports of hand-held GPS receivers not working either ("GPS", 2006, July).

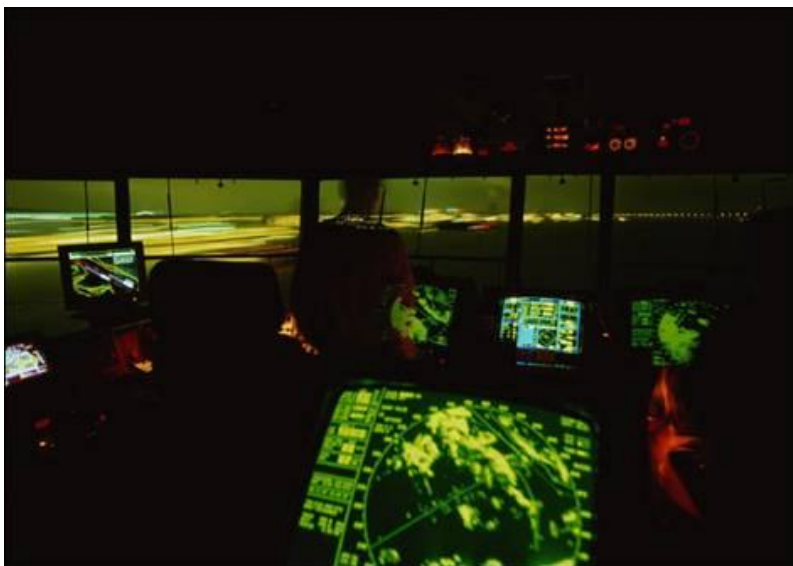
Worse, the case as posed by experts at Cornell University in September of 2008, seem to indicate the possibility of manipulating a weapon in flight to a target.<sup>6</sup> *"The average person doesn't realize how much infrastructure is based on GPS and how vulnerable it is,"* said Brent Ledvina of Virginia Tech, who helped build a spoofer to show

<sup>6</sup> A team of researchers from Cornell University has demonstrated a way to fool the GPS units by sending out a false signal that imitates actual satellite signal patterns. Those signals will be interpreted by the GPS receivers as a genuine signal which causes the wrong position information being retrieved by end users. For normal consumers, it may be still alright but the consequence could be very serious especially when such a scenario happens in military applications. <http://www.mydigitallife.info/2008/09/24/cornell-university-researchers-demonstrated-gps-vulnerability-with-spoofing-activities>

weaknesses in the system. *"It looks exactly like a real GPS signal...everything looks completely normal, but the spoofer is controlling your position in time and space."*<sup>7</sup>

Because our adversaries do not fully operate in the same environment that we do today, U. S. forces currently possess unprecedented opportunities to shape and control the battlespace to achieve national objectives. However, as our adversaries become more capable, this unique ability may erode and as a result, these same capabilities make themselves a target by these same adversaries. Most U. S. kinetic weapons are fully integrated into networks and are accounted for in Network-Centric Operations (NCO). Those that are not, are scheduled for replacement or upgrades to enable such employment.

A technique for sabotaging GPS systems, called spoofing, could cause havoc in the wrong hands, warns researchers. In spoofing, a spoofer creates a false GPS signal that passes as a real GPS signal, sending an incorrect time and location to a certain receiver. Figure 5 is a depiction of a false GPS signal (Bland, 2008, October 2).



**Figure 5: Depiction of False GPS Signal—Spoofing** (Bland, 2008, October 2)

The Tactical Tomahawk (TACTOM) AN/BGM-109E (GlobalSecurity.org, 2010)<sup>8</sup> exemplifies an NCO-enabled weapon that receives, via networks, pre-flight targeting data from national, operational and tactical command centers and real-time in-flight updates from multiple sensors (aircraft, unmanned platforms, satellite, and personnel in the field, tanks, and ships). Equipped with onboard sensors, the TACTOM is also capable of sending sensor data and status information back to the same platforms to feed common operating pictures. If an adversary became able to block or manipulate targeting, guidance or command and control data to turn the TACTOM against U. S. forces or even worse, civilian populations, the enormous advantages of employing such network-capable GPS guided kinetic weapons in an information-dependent environment could become a severe liability. Since these missiles can also be nuclear armed, the implications of relying on GPS navigation for the distant future become dismally apparent—and, in fact, the United States does not use GPS for nuclear weapons guidance due to concerns regarding jamming and

<sup>7</sup> The easiest way to mess with a GPS device is simply to jam it, or create a false GPS signal that overpowers the real GPS signal. In this case, the victim would know about the sabotage right away; often the GPS receiver simply doesn't work. From <http://www.msnbc.msn.com/id/26992456>

<sup>8</sup> For a full description of different variants of the Tactical Tomahawk see <http://www.globalsecurity.org/military/systems/munitions/bgm-109-var.htm>

spoofing<sup>9</sup>. While we have shown that the potential effects of jamming the GPS signal, what about its loss completely due to attack by an adversary? *How vulnerable to attack is the current system?*

Far from the hype posed by the media in 2007 when the Chinese launched a missile to destroy one of their own aging weather satellites, most experts within the U. S. government seem to consider an attempt by both Russia and China to push a treaty outlawing space based weapons as a positive sign.<sup>10</sup> Since everyone sees the advantages of having access to GPS technology enough to warrant wanting their own systems<sup>11</sup> and the benefits such a system engenders, it becomes apparent that a weaponization of space is not a likely alternative.

Block	Designation	IOC	Guidance	Warhead
Block II	TLAM-N	1986	INS, TERCOM	W80 nuclear warhead
Block III	TLAM-C	1994	INS, TERCOM, DSMAC, GPS	1,000 lb unitary warhead
	TLAM-D	1994		Sub-munitions dispenser
Block IV	TLAM-E	2004	INS, TERCOM, DSMAC, GPS	1,000 lb unitary warhead

Source: [http://www.raytheon.com/capabilities/products/stellent/groups/public/documents/content/cms01\\_055764.pdf](http://www.raytheon.com/capabilities/products/stellent/groups/public/documents/content/cms01_055764.pdf)

**Table 1: Tomahawk Cruise Missiles in U. S. Inventory**

Perhaps a version of a “Freedom of the Seas” philosophy can be adopted with respect to space systems that all benefit from. While they do have a military use, the civilian uses have far outstripped the military ones. Indeed, more seems better as we attempt to deconflict different constellations and augment each other’s capabilities<sup>12</sup>. Indeed, the National Space Policy, published by the current administration specifically states,

*“As such, all nations have a responsibility to act to preserve the right of all future generations to use and explore space. The United States is committed to addressing the challenges of responsible behavior in space, and commits further to a pledge of cooperation, in the belief that with strengthened international cooperation and reinvigorated U. S. leadership, all nations will find their horizons broadened, their knowledge enhanced, and their lives greatly improved”* (The White House, 2010, June 28).

While the U. S. reserves the right to turn our GPS systems off, this doesn’t “spoil the ground” for everyone on a permanent basis—other nations can still launch their own and make use of the technology to their individual benefit after any conflict the U. S. military is engaged in has terminated. Beyond the technology to jam the signal, what

<sup>9</sup> The United States has developed two successive generations of Tomahawk missiles (the Block III and Block IV) with improved guidance. One feature has been the integration of satellite guidance using the Global Positioning System. The United States does not use GPS for nuclear weapons guidance due to concerns regarding jamming and spoofing. Although some Block II Conventional Tomahawks remained in the inventory through the 1990s, U. S. regional combatant commanders strongly prefer the newer Block III and IV versions.

<http://lewis.armscontrolwonk.com/archive/2560/why-the-navy-should-retire-tlam-n>

<sup>10</sup> Everyone concerned now seems to understand that destroying another nations satellites only exponentially increases the amount of space born debris that is a hazard to satellites of any nation. With the move towards other nations launching their own comm and navigation systems, agreement on this issue seems to show that reason has won the day. As reported by Reuters on July 13, 2010, and accessed on July, 18, 2010.

[www.reuters.com/article/idUSTRE66C4K520100713?type=politicsNews](http://www.reuters.com/article/idUSTRE66C4K520100713?type=politicsNews)

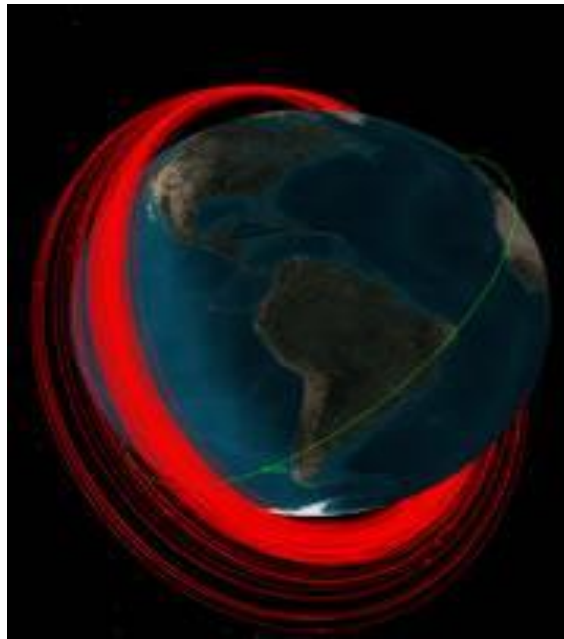
<sup>11</sup> The United States and the European Union (EU) now have an agreement in place that unifies both with bilateral cooperation between the U. S. Global Positioning System (GPS) and the European planned Galileo spaced-based navigation system.” (U. S. + E. U... Positioning Partners (SATCOM). Accessed on August 1, 2010, from <http://www.satnews.com/cgi-bin/story.cgi?number=1014062728>)

<sup>12</sup> The United States and the European Union (EU) announced on July 31, 2010, a bilateral cooperation between the U. S. Global Positioning System (GPS) and the European planned Galileo spaced-based navigation system. (U. S. and the EU to collaborate on usage of Global Navigation Satellite Systems. Accessed July 31, 2010, from <http://wireupdate.com/local/u-s-and-the-eu-to-collaborate-on-usage-of-global-navigation-satellite-systems/>)

might other adversaries attack to deny the U. S. the use of GPS? The obvious answer would be the ground control stations themselves.

The stations are often remotely located and as such are on installations that are minimally manned and perhaps minimally defended. Their remote location, sensitivity and complexity of the equipment, combined with other factors would seem to make them a choice target for exploitation or even destruction.

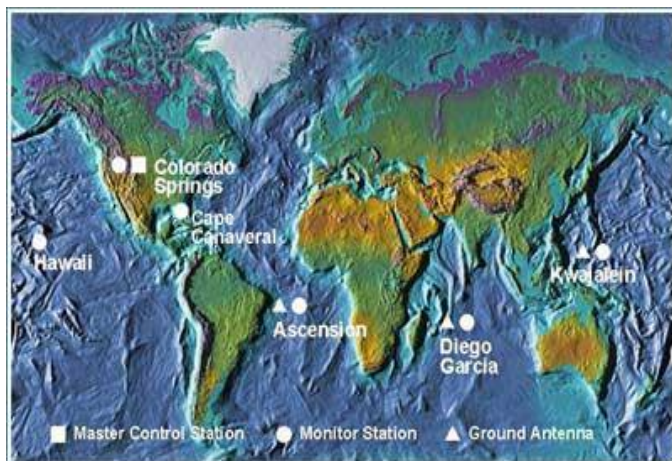
The official debris count from China's anti-satellite missile test has reached 957 pieces big enough to be tracked and NASA's Orbital Debris Program Office is estimating more than 35,000 pieces larger than 1 cm. This makes the January 11, 2007, test the largest debris-generating event in history, surpassing the previous record set in 1996. The following image, shown in Figure 6, illustrates U. S. military's mapping of the debris field ("Chinese ASAT Test", 2011; "Chinese ASAT Test Largest", 2010).



**Figure 6: U. S. Military Mapping Image of Debris Created after Chinese Anti-satellite Weapon Test (Brumfiel, 2007)**

Six monitor stations are located at Falcon Air Force Base in Colorado; Cape Canaveral, Florida; Hawaii; Ascension Island in the Atlantic Ocean; Diego Garcia Atoll in the Indian Ocean; and Kwajalein Island in the South Pacific Ocean. These are shown on the map in Figure 7.a, which was obtained from the USAF. Each of the monitor stations checks the exact altitude, position, speed, and overall health of the orbiting satellites. These unmanned ground stations (shown in greater detail in Figure 7.b) monitor and control GPS satellites, and they continuously update orbital positions and time data received from satellites. The image was also obtained from the USAF.





**Figure 7a. USAF Satellite Monitor Stations—Source USAF**



**Figure 7b. Image of an Unmanned Ground Station—Source USAF**

Such an event was speculated by Ackerman (2009) in an article in *SIGNAL* magazine when he stated, “a team of commandos can disrupt satellite operations by attacking and disabling a key ground station<sup>13</sup>.” While replacement is possible, it would not be necessarily immediate. Replacement units for those shown in Figure 7b are not sitting in a warehouse numbering in the dozens waiting to be installed. They have a manufacturing lead time of several months and as such, the interruption of the signal by their destruction might take months to reconcile. In the interim, the impacts on the economy due to their loss are not easily calculable. So what is the next step in preserving the capability while minimizing the exposure to the U. S. military?

### CURRENT MODERNIZATION EFFORTS

The USAF is taking steps as evidenced by the award of an one contract worth almost \$1.6 billion contract to Raytheon reported in Mar 2010, “which includes a much-needed update for the U. S. air traffic control system by request of the FAA (notice a request from the civilian sector). The contract states that Raytheon will supervise a team of contractors to make expansions and improvements in accuracy to the GPS system nationwide” (Fox News, 2010, March 5), and a second contract in July 2010, reportedly worth up to \$8 billion that will “include sophisticated anti-jamming technologies that are important for cyber security in war” (Gillentine, 2010, June 5).

Not to put all its eggs in one basket, the USAF is also looking at alternative means of navigation as reliable and as ubiquitous as it has historically enjoyed with GPS. We have seen that the dual use nature has made the signal potentially unreliable in an extended conflict and, for this reason, the U. S. military is doing the R&D today in order to eventually move into new technology arenas. Dependence of the civilian sector to the use of GPS technology is well recognized, so any new strategy must be accompanied by a smooth transition so as not to interrupt the U. S. civilian sectors’ dependence on the current GPS architecture. Regardless, access denied to the military is access denied irrespective of whether it is as a result of jamming, ground station compromise or something else. The dependence of our current reliance on GPS for not only navigation of manned systems, but unmanned systems makes the current implementations’ eventual replacement a foregone conclusion. The Chief of Staff of the Air Force

<sup>13</sup> The full quote is as follows, “Other means can be employed against space-based capabilities. Deliberate radio frequency interference, electromagnetic pulses and directed energy weapons such as antisatellite (ASAT) lasers all have been tested in one form or another. Down to Earth, a team of commandos can disrupt satellite operations by attacking and disabling a key ground station. In addition to direct action by an enemy, the U. S. ability to operate its space systems can be challenged by a number of nonhostile causes. These challenges can take the form of increased space traffic, particularly debris, and inadvertent electromagnetic interference, for example.” Accessed August 17, 2010, from [http://www.afcea.org/signal/articles/templates/SIGNAL\\_Article\\_Template.asp?articleid=1970&zoneid=124](http://www.afcea.org/signal/articles/templates/SIGNAL_Article_Template.asp?articleid=1970&zoneid=124)

has addressed the issue of the current over reliance on GPS, research is being done on it as we speak to replace the current capability, and if the reliability of it is in question in time of conflict, it could be argued that it has moved beyond being a weapon system at all and is more properly placed and managed by a nonmilitary government agency if not the civilian sector in totality. At a time when the Air Force is struggling for funds to modernize the fleet of manned and unmanned aircraft, the significant portion of the budget locked into a mandatory overhead expense for GPS becomes an obvious target for outsourcing. If it is no longer a reliable technological contributor to the military's warfighting capability, it is inevitable that very soon it will be time to move on and let someone else take responsibility for its day to day operation, maintenance and upgrades. Being so placed in the civilian sector might in fact make it less of a target than it currently is. The business models for use of satellite technology by the civilian sector already abound (examples include communications, satellite TV and satellite radio) and something as simple as an annual usage fee determined by the accuracy required might be one solution to follow. Alternatively, its mission and architecture could be transferred to another government agency such as the National Geospatial Intelligence Agency (NGA). They already provide satellite imagery on demand for the DoD—it could be argued that the GPS constellation might be better placed within NGA's portfolio.

The U. S. civilian population, let alone the entire world, has become accustomed to getting something for nothing—it may be time to move beyond that if GPS is going to survive. Based on comments of the Chief of Staff of the Air Force, the current trends in R&D, and the well documented system vulnerabilities, the U. S. military seems to be preparing to move ahead to the next set of technologies that will preserve or enhance the capabilities currently provided by GPS. The civilian sector had best start looking at ways to move in that direction as well.

The challenges posed to the USAF with regards to system modernization are not singular in nature. First, there is a fiscal challenge imposed by difficulties in successfully building GPS satellites within cost and schedule goals, particularly in the IIF program. The troubles with the IIF were compounded by a relaxed acquisition strategy that allowed less oversight of the contractors in the areas of contractor moves, contractor merges and overall quality. This has contributed to cost overruns estimated as high as \$870 million and launch delays of almost three years.<sup>14</sup> The first IIF was supposed to be launched in 2007 and was only launched May 28, 2010 ("First GPS", 2010, May 28).

### NOT BACKWARD COMPATIBLE AND NOT PLUG AND PLAY

Replacement of one satellite with another is not as simple as a "plug and play" technology. To say that the overall system is the same from year to year based on the simple metric of the number of satellites is evidence of a naïve or (hopefully not) deliberately misleading release of information. There are significant differences between the GPS IIA, the GPS IIR, the GPS IIR-M, the GPS IIF and finally the GPS III. These differences are often lost in the typical research report or article. While data in the GAO report seemed to imply that all new and planned satellites were in fact backward compatible—meaning that older equipment would continue to function—this may not necessarily be the case.

Buried within the notices section of the September 23, 2008, *Federal Register*, is the following verbiage ("Preservation", 2008):

*The U. S. Government acknowledges global use of GPS codeless and semi- codeless techniques and commits to maintaining the existing GPS L1 C/A, L1 P(Y), L2C and L2 P(Y) signal characteristics until December 31, 2020, when the second and third civil signals (L2C and L5) are planned to be broadcast from a minimum of 24 GPS satellites. After the planned transition date, the characteristics of the L1 P(Y) and L2 P(Y) signals transmitted by any or all GPS satellites broadcasting two or more civil-coded signals may change without further notice and may preclude the use of P(Y) coded signals for high accuracy applications.*

<sup>14</sup> This is well documented in "Global Position System Significant Challenges in Sustaining and Upgrading Widely Used Capabilities," accessed on August 14, 2010, from <http://www.gao.gov/new.items/d09325.pdf>. A preliminary discussion in the Executive Overview on page 3 describes these issues. Essentially, GAO said that due to inadequate planning, poor contractor supervision, diffuse senior leadership, conflicting requirements and a lack of accountability, almost all DoD space programs are either late, over budget or both.

This notice asks for input from the public and private sectors regarding the impact of the potential planned changes in the signals being broadcast from the GPS constellation. In September 2007, the U. S. Government announced its decision to procure the future generation of GPS satellites, known as GPS III, without the SA feature. Doing this will make the policy decision of 2000 permanent and eliminate a source of uncertainty in GPS performance that has been of concern to civil GPS users worldwide for some time.

Satellite evolution and capabilities			
Legacy (1989 - 2002)	Current (2005 - 2012)		Future (2014 - 2023)
GPS IIA/IIR	GPS IIR-M	GPS IIF	GPS III
<ul style="list-style-type: none"> <li>Broadcasts signals for military and civil users.</li> </ul>	Includes IIA and IIR capabilities, plus: <ul style="list-style-type: none"> <li>2nd civil signal</li> <li>2nd military signal</li> <li>Ability to increase signal power to improve resistance to jamming</li> </ul>	Includes IIR-M capabilities, plus: <ul style="list-style-type: none"> <li>3rd civil signal for transportation safety requirements</li> </ul>	Includes IIF capabilities, plus: <ul style="list-style-type: none"> <li>IIIA: stronger military signal to improve jamming resistance and 4th civil signal that is interoperable with foreign signals</li> <li>IIIB: near real-time command and control via cross links</li> <li>IIIC: improved anti-jam performance for military users</li> </ul>

Ground control segment and capabilities		
Legacy (Various versions from 1979-2007)	Current (Came online in 2007)	Future (Planned to come online with initial capabilities in 2011)
Legacy Operational Control System (OCS)	Architecture Evolution Plan (AEP)	Next Generation Operational Control Segment (OCX)
<ul style="list-style-type: none"> <li>Centralized computer mainframe</li> <li>1970s technology</li> </ul>	<ul style="list-style-type: none"> <li>Distributed architecture</li> <li>Enables upgrades to the system</li> <li>Next upgrade will control GPS IIF</li> </ul>	<ul style="list-style-type: none"> <li>Necessary for full operation of GPS IIR-M, IIF, and III satellites</li> <li>Service-oriented architecture</li> <li>Connects to the broader network</li> </ul>

Source: (U. S. Government Accountability Office, 2009)

**Table 2: GPS Satellite and Ground Control Segment Modernization**

As can be seen from Table 2, from the GAO report, from one generation of spacecraft to the next, there seems to be the impression that the follow on satellite would “include....IIxx capabilities.”

And from the preceding May 16, 2008, *Federal Register* (“Codeless”, 2008):

*After the transition date, the characteristics of the Y-code signals transmitted by modernized GPS satellites may change without further notice and may preclude codeless/semi-codeless use of the Y-code signals. However, for those legacy satellites that have no modernized capabilities, codeless/semi-codeless access to Y-code at L1 and L2 will continue until those satellites are decommissioned.*

So while the GAO report perhaps missed the proposed changes, one point seems clear—as downbeat as the GAO report may seem with respect to the program management, it may not have captured all the aspects that have contributed to the potential impacts of the future changes—it will be worse than originally reported by GAO. As documented earlier the federal government was soliciting comments in the *Federal Register* on two separate occasions on the impact of the proposed signal changes planned on being introduced in 2020.

GAO focused on programmatic, such as cost, budget, and schedule. Coming from the Government Accountability Office, the audit, evaluation and, most importantly, investigative arm of the U. S. Congress, formally called the General Accounting Office, they seem to have played to their strength. But they overlooked or neglected to report the possibilities of the impacts on the commercial sector on or after 31Dec2020. From a strictly Project Management perspective, the situation is grim enough<sup>15</sup>—albeit it has been somewhat dismissed by the USAF. They included in

<sup>15</sup> U. S. Government Accountability Office (2009), page 19, shows that GAO is only “counting heads,” not evaluating changes in capabilities.

the appendix, estimates of satellite availability based on actuarial analysis of the design life of the individual satellites in the overall constellation neglecting the actual differences in capabilities of the individual satellites.

In a combined response to the GAO report, the Air Force Space Command and Boeing replied,<sup>16</sup>

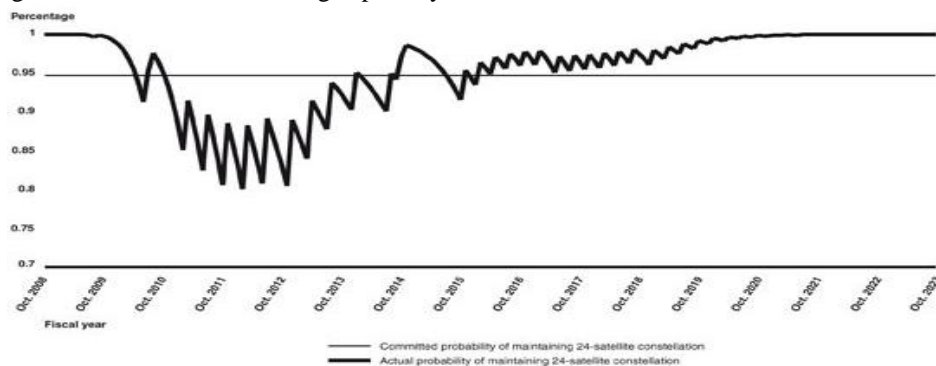
*“Just as it was reported in the Government Accountability Office’s report May 7, AFSPC acknowledged the potential for an availability gap years ago, and has actively pursued and institutionalized procedures and processes to mitigate the potential gap or minimize any impact”*

and

*“GPS IIF will deliver more capability and improved mission performance to military and civilian users. Working very closely with the Air Force and its team, Boeing has taken aggressive steps to resolve the technical issues on IIF with a strong emphasis on Mission Assurance. Design changes were required to ensure performance over the satellite design life.”*

The USAF also released its own assessment of the report when they stated in a news release on May 25, 2009, [Satellite Today 05-26-09] *The U. S. Air Force said that a report released by the U. S. Government Accountability Office (GAO), which claimed that the U. S. military GPS system is experiencing serious degradation, is not accurate, according to a May 25 statement by Air Force Col. Dave Buckman. “The issue is under control,” said Buckman in an online press conference. “We are working hard to get out the word. The issue is not whether GPS will stop working. There’s only a small risk we will not continue to exceed our performance standard.”*

The following chart, Figure 8, is from the U. S. Government Accountability Office (2009). While an interesting chart that takes into account the flow of satellites in the pipeline combined with their projected lifecycle, what is missing is a consideration of the broader impacts of signal changes in the private sector. GAO uses this private sector dimension as one of its arguments, but fails to account for the actual impact due to changes in the signal itself—counting heads rather than measuring capability.



**Figure 8: Probability of Maintaining a Constellation of at Least 24 GPS Satellites Based on Reliability Data and Launch Schedule as of March 2009**

So in reviewing the complexity required in a fair analysis, we can see that although the individual satellite block capabilities are not the same and in fact are not backward compatible in the long run, this issue has not been completely understood nor accurately reported in a consistent perspective. To put in simple terms, on the bright side, the satellites are robust and seem to last longer than their normal design life<sup>17</sup> which can be viewed as a mitigating

<sup>16</sup> You have to notice the caveats in the press release—while acknowledging the potential for a capability gap, the new systems will provide more capability (not necessarily saying it is fully backward compatible with older systems) while implementing design changes required over the satellite life. Accessed August 14, 2010, from <http://www.satnews.com/cgi-bin/story.cgi?number=886073393>

<sup>17</sup> 7.5-year design lifetime; 8.9 year average lifetime, accessed August 14, 2010, from <http://web.mit.edu/jhawk/tmp/gpstalk.pdf>

factor for the GAO analysis (Lockheed Martin, 2010, August 9). On the down side, viewing any satellite from a “all things being equal” approach of just counting the birds in orbit misses the impact on the commercial sector when the older satellites either quit functioning on sometime or about 31Dec2020 (the date advertised in the earlier mentioned Federal Register), when the government (or at least the DoD) simply quits supporting them—as it should, given the earlier established and documented vulnerabilities of the older members of the constellation. This leads us to the next series of questions: Are there parties aware of the impacts of the 2020 cutover that responded to the solicitations in the Federal Register?

### USERS WEIGH IN

The answer is “yes” and the responses seem to fall into two groups—small business users who might be constrained financially to pay for modernized receivers and large business users more capable of absorbing the costs and appreciating the increased benefits from the enhanced capabilities (United States, 2011). The comments from the small business user seem to rally around the logic of “don’t break something that’s working” vs. the large business that is willing to support it and are willing and more able to pass on the costs of in house upgrades that some estimate would run as high as \$40k. In an interview given to GPS World and published in July 1, 2008, Alan Cameron (AC) talked with Jason Kim (JK), senior analyst at the Department of Commerce. Mr. Kim stated (“Leadership”, 2008, July 1):

*We solicited public comments on this matter because it became clear that users had always considered GPS modernization as additive to semi-codeless access, that they were getting these new signals in addition to, not instead of semi-codeless. The idea that these new capabilities were going to replace semi-codeless—they weren’t really aware of that.*

Nor are agencies like the FAA unaffected. They use semi-codeless with Wide Area Augmentation System (WAAS) today to augment other navigation technologies currently in use. It is not accurate enough on its own and they are also in the process of implementing Local Area Augmentation System (LAAS) technologies to give aircraft better response time for take offs and landings. They will eventually go with an L5 signal since the L5 is protected for aeronautical radio navigation services. A discussion of this approach was presented in a paper at the WORLDCOMP’10, The 2010 World Congress in Computer Science, Computer Engineering, and Applied Computing by Sitzabee, Stephaniak, and Feng (2010, July). They also discussed issues such as jamming and spoofing the LAAS technology and the ramifications to civilian air traffic if it occurred. One of the recommendations they made was to maintain the INS systems as a backup in this eventuality.

There is still one aspect of national security to discuss with respect to GPS. As we have noted, there actually is a “slight chance” that the current performance standard will not be met for some periods of time, and per the spokesperson for the USAF on this issue, Air Force Col. Dave Buckman. “*The issue is under control.*” But what exactly does this mean? As reported in Satnews.com on August 1, 2010,<sup>18</sup>

*“The United States and the European Union (EU) now have an agreement in place that unifies both with bilateral cooperation between the U. S. Global Positioning System (GPS) and the European planned Galileo spaced-based navigation system.”*

and

*“Plus, there would be improved robustness to GPS satellite outages. A comparison of GPS, Galileo, and a combo performance for three types of receivers, was also finished. The combined GPS/Galileo would also bring into play various improvements, especially when dealing with partially obscured environments and the use of dual-frequency receivers. The U. S. and the E.*

<sup>18</sup> As reported on August 1, 2010, at <http://www.satnews.com/cgi-bin/story.cgi?number=1014062728>, accessed on August 14, 2010. A working group was designed by the two involved parties to complete an assessment of the global, combined performance for GPS Space-Based Augmentation System (SBAS) receivers using the European Geostationary Navigation Overlay Service (EGNOS) and the GPS Wide Area Augmentation System (WAAS) supporting safety-of-life applications.

*U. will continue their work on issues to improve navigation positioning and service offerings around the globe.”*

So response to outages is a goal of cooperation. The issue here will be whether or not the U. S. military should rely on a system controlled by a foreign power which in a time a political tension might choose to add some sort of dithering to undermine the accuracy of the signal in the event of a disagreement on an international crisis between the parties. Although a substantial number of the members of the EU are also NATO partners, this does not mean that the policies of the EU are always shared by NATO members. In fact, many members of the EU often choose not to affiliate with NATO managed solutions when it might be in their best interest to do so.

### SUMMARY

One thing we can always depend on about the future—it's coming whether we realize it or not and whether we understand it or not. The current use of GPS technology is not apt to change for most users except that it is likely to become more ubiquitous (is this possible?) and cheaper. Even as there are challenges to upgrading the current constellation driven by things as diverse as national security issues to project management and corporate mergers, the changes are still coming. While there may be time to discuss the impacts of the changes on the private sector, the fact is clear that at some point on or after 31Dec2020, the federal government will be relying on (because of security issues) a constellation that shares a heritage with the current one, but whose functionality and capability was only dreamed of by the architects of the original systems. The USAF cannot afford to continue to support legacy systems—it doesn't do so with ground based systems and aircraft and cannot be expected to do so for a legacy satellite constellation system for which it no longer has a requirement or whose time has passed from a strategic perspective. This day will come at some point in the next decade. One day there will be a quiet—perhaps even unheralded moment when the last of the older satellites is simply switched off and the only indication of it will be worldwide, when older GPS receiver units no longer function. Hopefully at that point, investment will have been made by visionary CIOs, CEOs and CFOs worldwide so that both functionality will be maintained and enhanced and disruptions will be minimal. The issues are complex simply because it is a complex system. It is complex because it has expanded into something that is so very useful in so many different sectors of society.

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