The Case for Alternative Position, Navigation and Timing (APNT) Development for Aviation

Douglas Helton, Advanced Aviation Consulting, Inc.
Ariel Scheirer, SELEX Systems Integration, Inc.

Introduction

The world has come to depend on the United States Global Positioning System (GPS), a space-based satellite system, to provide positioning, navigation, and timing (PNT) for a host of civil and military applications. GPS-provided PNT is a key enabler of many of the conveniences that we enjoy today. Not only do the nation's transportation systems now rely on GPS for the safe, rapid, and efficient movement of people and goods, but also for its telecommunications, emergency responders, energy mining and management, agriculture, food production, control and maintenance of electric and gas utilities, and world-wide financial transaction management.[1] Although GPS is currently the only fully functional global navigation satellite system (GNSS), its tremendous value has been recognized and many other countries are currently working to deploy their own similar systems.

GPS signals emanate from satellites in medium earth orbit, approximately 11,500 miles above the Earth. Despite all its strengths, the GPS signal is extremely weak when it reaches the ground, making it highly susceptible to radio frequency interference (RFI). For this reason, U.S. national policy requires that alternative sources of position, navigation and timing services (APNT) be employed as a backup for critical applications and infrastructure.[2] As an element of the Nation's critical infrastructure, our National Airspace System's (NAS) growing reliance on GPS-enable PNT services necessitates such an alternative, and that need will grow as the Next Generation Air Transportation System (NextGen) leverages PNT services to further enhance safety, efficiency and capacity. This article outlines the need for APNT to support NextGen, summarizes ongoing Federal Aviation Administration (FAA) APNT efforts and rationales, identifies aircraft equipage cost considerations, and presents a strong case for accelerating research, development, and implementation of alternative PNT systems.

Background on GPS Interference

Although highly accurate and available, GPS signals are extremely weak and are susceptible to RFI from both natural and man-made sources. This same vulnerability is shared by other existing and planned satellite navigation systems, e.g. GLONASS (Russia) and Galileo (European Union). Although the availability of a new, slightly more powerful GPS civil frequency in the future will help somewhat, and allow aircraft to better model challenges presented by an ever-changing ionosphere, it will not preclude loss of GPS-provided PNT. The

[1] Department of Defense (formerly, National Security Space Office), "National Positioning, Navigation, and Timing Architecture Study, Final Report," September 2008, http://www.acq.osd.mil/nsso/pnt/pnt.htm.
[2] Department of Homeland Security, "Homeland Security Presidential Directive-7: Critical Infrastructure Identification, Prioritization, and Protection," December 17, 2003, http://www.dhs.gov/xabout/laws/gc_1214597989952.shtm.

U.S. National Space-Based PNT Advisory Board has reported that examples of intentional interferences have increased over the last 10 years.[3]

GPS interference may be categorized as environmental, man-made unintentional and man-made intentional with malicious and non-malicious intent, as summarized below:

Types of GPS Interference				
Type	**Example**	**Description**	**Coverage**	**Duration**
Non-man-made	Ionospheric	Solar Flares	Wide-spread, Intermittent	Hours – Days, 11-year cycle
Unintentional	Existing signals	Spurious signals from other types of transmitters	Local (100s ft.- 100s miles)	Hours-Weeks
Intentional, Non-malicious	Military Jamming, Personal jammers	Unscheduled/Accidental	Local-Regional (up to ~100s of miles at altitude)	Hours - Days
Intentional, Malicious	High-power GPS Jammer	Deliberate interference of GPS, ground-based or aerial	Local-Regional (up to 100s of miles at altitude)	Hours – Months (possibly intermittent)

Table 1 Types of GPS Interference

GPS disruptions are well-documented and specific examples of past events include:

- ***Solar flares*** (Non-man-made, Environmental): Solar flares, large "clouds" of charged particles resulting from solar coronal mass ejections (CME), occur at routine intervals. Although of varying intensity, a solar flare may disturb the Earth's geomagnetic field to the extent that the GNSS's radio signals are interrupted. The China Meteorological Administration reported communications disruptions throughout the south of the country following a February 2011 solar flare. Solar flares are cyclical, and therefore somewhat predictable.[4] The U.S. National Space Weather Prediction Center has identified solar maximums at 2010-2013, and then starting again in the late 2020's. Dual frequency GPS receivers help alleviate ioniospheric effects, but do not eliminate them.[5]
- ***VHF/UHF television antenna*** (Man-made, Unintentional): Interference may occur as a by-product of existing signals. In 2001, three VHF/UHF television antenna preamplifiers generated signals in Moss Harbor, California, jamming GPS in a 0.5-mile radius. Locating the source of the intermittent interference resulting from these three antennas required six months of work.
- ***Drivers use GPS jammers*** (Man-made, Intentional, Non-malicious): The prevalence of so-called personal privacy devices (PPDs), which emit a GPS-jamming signal, has become and becoming increasingly problematic, as seen by the FAA in the case of truck drivers in the Newark, NJ area in 2010. Although not intended to affect other GPS

[3] U.S. National Space-Based PNT Advisory Board, "'National PNT Advisory Board Comments on Jamming GPS - A National Security Threat: Recent Events and Potential Cures," November 2010, http://www.pnt.gov/advisory/recommendations/2010-11-jammingwhitepaper.pdf.

[4] National Aeronautics and Space Administration, "Scientists Predict Big Solar Cycle," December 21, 2006, http://science.nasa.gov/science-news/science-at-nasa/2006/21dec_cycle24/.

[5] Datta-Barua, Doherty, Delay, Dehel, Klobuchar, "Ionospheric Scintillation Effects on Single and Dual Frequency GPS Positioning," White Paper, ION Conf. September 2003, http://www.ion.org/search/view_abstract.cfm?jp=p&idno=5208 and U.S. Department of Commerce, "Service Assessment, Intense Space Weather Storms," October 19 -November 07, 2003, http://www.weather.gov/os/assessments/pdfs/SWstorms_assessment.pdf .

receivers, the PPDs interfered not only with the ability of the truck dispatchers to locate truck position, but also with the GPS-based procedures at Newark International Airport, causing multiple disruptions.

- ***Military Jamming Exercises gone wrong*** (Man-made, Intentional, Non-malicious) Conducting communications jamming exercises, U.S. Navy accidentally jammed GPS in San Diego for two hours in January 2007 interrupting automobile navigation systems, cellphone communications, and banking transactions. A military contractor in Rome, NY accidentally left a GPS jammer on over a 3-day weekend in 1997, jamming aircraft navigation over more than a 100-mile radius.
- ***North Korea jams South Korea GPS*** (Man-made, Intentional, Malicious): In March 2011, South Korea reported that GPS-enabled military communications were jammed by North Korea at 5-10 minutes intervals. The South believes that North Korea has modified Russian jamming technology so it can disrupt guided weapons, as well as naval and civilian off-shore navigation.

Position, Navigation and Timing in Aviation

Position, in the context of PNT, generally refers to identifying and tracking the location of aircraft and vehicles, e.g., air traffic surveillance. Radar is the primary source of air traffic surveillance information today and determines aircraft position relative to the radar antenna and other aircraft. There are two types of radar technology used today. Secondary Surveillance Radar (SSR) communicates with aircraft transponders to determine aircraft lateral and vertical positions relative to the radar antenna and to obtain the identification. It is also known as cooperative radar because aircraft must have a transponder in order for it to work. The other type of radar is known as Primary (or “skin paint”) radar, which “bounces” a signal off reflect objects, e.g. metal aircraft. It is also known as non-cooperative radar because no aircraft equipment is required. It is used as a backup when aircraft transponder or the SSR fails. This results in a loss of target information and automation features, which greatly increase controller workload and impact the efficiency and capacity of the NAS. Because the antennas for both radars are generally mounted on the same rotating mast, failures in that portion of the system impact both radar types. Radars update aircraft positions approximately once every five seconds in major airport terminal areas and once every 10 - 12 seconds in en route airspace (long-range radar). The accuracy and update rates support 5-nautical mile (nm) minimum separation for en route airspace, 3-nautical mile (nm) minimum aircraft separation for terminal airspace, and 2.5nm separation on final approach at appropriately provisioned airports

Automatic Dependent Surveillance – Broadcast (ADS-B) leverages GPS by using broadcasts from an ADS-B equipped aircraft that include position, pressure altitude, I.D., and ground speed, to track and separate aircraft. There are two ADS-B systems currently in use – one based on the 1090 MHz Extended Squitter and the other based on the 978 MHz Universal Access Transmitter (UAT). Position and ground speed are derived from GPS and included in an aircraft’s ADS-B message. Broadcasts are received through a network of ADS-B ground stations and provided to ATC. Aircraft also receive broadcasts of similar “flavor” ADS-B receivers (1090ES or Universal Access Transceiver (UAT)). Each ADS-B ground systems also uplinks traffic information to by the aircraft’s ADS-B receiver, e.g., non-ADS-B equipped aircraft (traffic information service – broadcast, or TIS-B), as well as different flavor ADS-B (ADS-R (rebroadcast)). It should be noted that the traffic information uplinks provided by ADS-B is currently only used by pilots for situational awareness.

Weather and NAS information is already uplinked to aircraft over UAT (know as flight information services – broadcast (FIS-B)), and ADS-B is capable of supporting other information, such as trajectory intent information, atmospheric data or anything else the community agrees to implement. Although GPS is not explicitly required by the ADS-B standards, by default it is the only position source that currently meets the standards. ADS-B position is as accurate as the aircraft's onboard sensor system and is updated once per second. Although 0.3nm accuracy is required to support 3nm aircraft separation standards, GPS and augmented GPS are capable of much better. ADS-B is in the early stages of nationwide adoption, and is one of the foundational technologies that will enable NextGen. Radar currently serves, and will continue to serve, as a backup once ADS-B is fully implemented.

Navigation refers to the tracking of one's own position, and calculating and flying the desired path between geographic points. In the case of legacy radionavigation aids (VOR/DME, NDB and ILS), these geographical points are the radionavigation station themselves. An aircraft's position is determined relative to the ground station, which is then visualized by pilots and manually correlated to a position on printed map. Historically airways have been based on these station locations and consequently don't typically provide the most direct routes.

Area navigation (RNAV) provides a geographically referenced position using a geographic coordinate system, which is easily overlaid on electronic moving map displays and very intuitive to the user. These systems enable navigation between two waypoints, normally accessed from an onboard navigation data base, via the most direct route. This form of navigation has been around for some time in various forms including GPS, scanning distance measuring equipment (DME/DME), inertial reference systems, and previously in the U.S., Loran. These RNAV systems normally support track accuracies down to 0.3nm for non-precision approaches, and in the case of augmented GPS systems, down to .1nm for precision approaches. GPS also supports enhance airport surface operations.

Required Navigation Performance (RNP) is an extension of RNAV and adds aircraft conformance monitoring and alerting features to help pilots remain on course. NextGen calls for implementing RNAV capability in all airspace and RNP where needed. Instrument Landing Systems (ILS) will continue to serve as the backup for precision and non-precision approaches for the foreseeable future, thus the backup issue is focused on terminal and en route navigation. When pilots loose RNAV capability, e.g., GPS-provided PNT become unavailable, they must revert back to legacy radionavigation systems. While large aircraft can rely on GPS-independent area navigation provided by multiple DMEs and inertial reference units (IRU) to a great extent, this alternative is not available to many NAS users, such as regional aircraft and general aviation. About 65% of airline/cargo aircraft are equipped with scanning DME and IRU avionics and another 25% is equipped with scanning DME and no IRU, providing crews with backup area navigation capability albeit not as good as GPS. Without GPS or DME updates, IRU position accuracy degrades approximately 2nm per hour. The aircraft in this fleet without IRUs must rely on DME/DME area navigation for their backup. Although these area navigation backup systems are mostly adequate for today's area navigation procedures, they may not support more advanced

NextGen procedures. These systems also do not provide all the integrity information required for ADS-B, and therefore are currently not used for that purpose. GPS interruptions can result in significantly increased pilot workload and loss of efficiency for operators that have no backup area navigation system; such is the case for most general aviation aircraft. They must fall back on VOR/DME where available, or dead reckoning and radar vectors otherwise. This will also greatly increase controller workload when GPS interruptions impact a busy large local or regional area.

Timing is fundamental to position determination when using GPS, but it is also required by other applications, including digital communications and switching, e.g., telephone switching networks, cell phones, the Internet, electric and gas generation and transmission, etc. Air traffic control inter-facility communications rely on telephone networks, which rely on GPS timing as the primary means and utilize atomic clocks to the extent necessary to maintain service during GPS interruptions. NextGen plans call for using digital wireless communications between pilots and controllers, as well as their respective automation systems, to enable trajectory base operations (TBO). It is expected that such systems will utilize GPS timing and will, therefore require some type of backup system that would retain critical automation features. Without alternative timing sources, controllers and pilots would need to fall back to analog voice communications, which would result in higher pilot and controller workload and loss of efficiency-related automation features.

Until the advent of ADS-B, care was taken to ensure that P and N and T systems would be independent of each other. A failure in one could not affect the other two, and special procedures ensured that safety would always be maintained, albeit at a loss of efficiency and/or capacity. Although leveraging GPS for both navigation and ADS-B surveillance greatly improves those capabilities, it also creates a single-string failure mode in which a loss of GPS affects both navigation and surveillance improvements, and requires reversion to less capable legacy systems. Digital communications will be impacted in a similar manner thereby compounding the problem further if and when data link communications becomes an integral part of air traffic management. While a loss of navigation capability in a single aircraft or a single ground station has a limited impact on the system, a GPS service interruption is likely to impact numerous aircraft simultaneously in a broader area, creating a significant challenge for controllers to step in and fill the service void. Such failures will also airport surface operations which are evolving to take advantage for of GPS for traffic management.

As we take increasingly greater advantage of the GPS-enabled PNT capabilities in NextGen to reduce traffic separation, increase capacity and enhance safety, the disparity between legacy and new PNT capabilities will grow, thus making the reversion from new systems to old systems more and more problematic. This could arguably compromise safety in this new NextGen environment. However, the FAA and aviation community will most certainly take steps to ensure that safety is maintained by sacrificing NextGen capacity and efficiency related capabililites. Those compromises would jeopardize NextGen benefits and investments.

If the aviation community is going to achieve its NextGen safety, efficiency and capacity goals and obtain an adequate return on their significant investments, the availability of PNT services must be assured. Given the high cost of adding new technology to the aviation system and the current economic climate, it is important that any APNT solution be affordable, practical, and provide sufficient performance to support diversionary operational modes.

Alternative PNT Solutions

Although there are a number of PNT systems with adequate performance to serve as a backup to GPS, the cost of equipage and infrastructure plays a significant role in identifying a viable alternative. For example, Enhanced Loran (eLoran) was identified as the most viable back-up for GPS in a recent study sponsored by the NextGen Joint Planning and Development Organization (JPDO)[6]. However, the lack of government or industry support for this solution, in part due to the cost of equipage, resulted in the Department of Homeland Security (DHS) terminating Loran-C service. Although the relatively low annual maintenance costs of the eLoran system may still make it a viable backup timing solution for ground infrastructure, the aircraft equipage costs are just too high to be viable. One of the most logical ways to accomplish this is to leverage existing or planned aircraft equipage and ground infrastructure to reduce costs for both operators and taxpayers.

When it comes to equipping aircraft, there are three general "levels of invasiveness." None are necessarily inexpensive, but some have much greater cost and resource impacts than others. Table 2 summarizes types of avionics upgrades and their relative cost and installation impacts.

Implications of PNT Alternatives on Aircraft Equipage			
Implementation	Description	Cost	Ease of Implementation
1. Software-only	Allows existing equipment to be upgraded through software only. It may require additional interface cabling between avionics. Old avionics can be more expensive to upgrade, and may need to be replaced. Ex: Enhanced DME	Low to Medium	Relatively noninvasive to aircraft, faster turn-around time, can be done in conjunction with routine maintenance checks.
2. Software + Black boxes	Requires that new black boxes be installed, but does not require new antennas or associated modifications to airframes. Can require expensive modification to flight deck displays. Ex: uplink of own-ship position through TIS-B.	Medium to High	Somewhat invasive to aircraft, generally takes days and requires new cabling between avionics.
3. Software + Hardware + Antennas	Requires new black boxes and the associated antennae and airframe modifications. Can also require modification to flight deck displays. Ex: an entirely new system specified for APNT.	High	Highly invasive to aircraft, requires modifications to aircraft skin/structure and cabling to antennas and avionics.

Table 2: Implications of PNT Alternatives on Aircraft Equipage

A similar approach is prudent when assessing the associated ground infrastructure. Leveraging existing ground stations is likely to be more cost effective than decommissioning those sites. Environmental and government contracting policies require the FAA to return ground station sites to their original condition when decommissioning those sites. Given the infrastructure present at many of these sites, e.g., environmental shelters, concrete pads, power and communication lines, backup generators, in-ground fuel tanks and security fencing, decommissioning costs could easily outweigh savings. Additionally, PNT systems will likely need similar supporting infrastructure and establishing new sites, further adding to the cost

[6] Satellite Navigation Backup Study, JPDO NextGen Institute, September 17, 2007, http://www.ncat.com/pdf/Back%20up%20SATNAV%20Study-Final.pdf

equation. Fortunately, many PNT technologies have small physical and environmental footprints which afford some flexibility in installation, e.g., ADS-B, pseudolites, and DME stations can be added to current sites and installed on existing towers or buildings.

Currently, the FAA's Navigation Services team is investigating alternatives that attempt to do just that by leveraging existing DME and planned ADS-B equipage. Table 3 includes a summary of each alternative followed by a more detailed description. Each alternative builds upon existing and planned infrastructure and equipage, thus reducing public and private costs.

APNT Solutions: Terrestrial-Based Alternatives	
Alternatives	Description
1. DME-DME	Leverages DME/DME area navigation equipment used by airlines and many business jets by adding more DME ground stations to improve accuracy and coverage.
2. Psuedolite	Adds a GPS-like ranging message, to DME and ADS-B ground station uplink transmissions that are used like GPS.
3. DME-MLAT	Leverages ADS-B ground stations and uses passive multilateration to triangulate aircraft based on their ADS-B radio signals and sends those positions back to the aircraft via TIS-B uplink messages.

Table 3: APNT Solutions: Terrestrial-Based Alternatives

The first alternative expands the use of DME/DME area navigation by adding more DME ground stations to improve accuracy and coverage, and leveraging equipment used by airlines and many business jets. Current, state-of-the-art DME ground stations and avionics actually provide better accuracy than what is being used today. Further refinements in DME are possible and may get close to 0.3 mile area navigation accuracy with no more than minor software upgrades to avionics. This level of performance will support arrivals, departures, non-precision approaches and en route operations, given sufficient ground station line-of-sight coverage.

The second alternative leverages DME and ADS-B ground stations by synchronizing them and transmitting a ranging message similar to that of GPS. That message could be transmitted over a unique frequency, in which case it would potentially require new avionics and antennas. Alternatively, it could leverage ADS-B and DME equipage by adding the pseudo-range message to DME and TIS-B or FIS-B broadcasts. DME and ADS-B station broadcast their signals with powers of hundreds or watts, which make them much less susceptible to interference. Aircraft equipment would require software and, possibly, hardware upgrades, but no new antennae would be required. Regardless of the medium used, the timing accuracy, the number of ground stations and the geometry of ground stations relative to an aircraft would dictate the accuracy/level of precision of this system. The more ground stations that can be leveraged, the better the potential accuracy. An adequate spread of ground stations would yield similar performance to GPS and the number and placement could be tailored to the performance needs. This solution requires that the timing at all the ground stations be synchronized. This could be done through a land-line network or via a radio signal such as eLoran or the Wide Area Augmentation System satellites. The latter example would use a narrow beam antenna pointed at the WAAS satellite to make it resistant to ground-based interference sources.

The third alternative utilizes a system known as multilateration, in which a network of ground stations receive transmissions from aircraft without position information and triangulate its position using angle and/or time of arrival. The "active" version of multilateration uses a request/reply methodology to interrogate aircraft transponders. The passive version would use aircraft ADS-B broadcasts, which would still include aircraft ID and altitude when GPS position was absent. Like the second alternative, precise synchronized timing is required across the ground station network for this alternative to work. Once the ground station network determines an aircraft's position, it would be transmitted back to that aircraft through the TIS-B broadcast, as is done today for non-ADS-B aircraft. The receiving aircraft then could utilize that position in its navigation solution. There is some latency in this method, but it may be sufficient to support a degraded backup mode until GPS service is restored or the aircraft can navigate away from the interference. This alternative would probably be best suited to general aviation aircraft that lack DME/DME equipage. Both DME and ADS-B ground stations offer an opportunity to add passive multilateration receivers.

The FAA maintains approximately 1,100 Distance Measuring Equipment (DME) and TACAN sites and has contracted with ITT to deploy approximately 700 ADS-B sites nationwide. Although there may be some overlap, the value of leveraging these sites and technologies is obvious to maximize benefit while reducing ground infrastructure costs.

Conclusion

Although the need for APNT is significant and the alternatives being considered are sound, it is clear that research and development will be needed to move these concepts into reality. The challenge is completing this work, and developing the avionics standards in time to allow manufacturers to incorporate these capabilities into new equipment before the ADS-B equipage mandate takes effect in 2020. This represents a very aggressive schedule given it often takes the FAA and operators 15 years to fully develop and implement a new technology. It is imperative that prompt action be taken to develop and test alternatives, and establish the necessary requirements and standards in time for a PNT alternative to be integrated into NextGen infrastructure and equipage deployment. This activity is not funded until 2014 in the FAA's budget and must be accelerated if there is any hope to leverage NextGen equipage and infrastructure. Without a viable APNT system in place, the aviation community and country will likely not realize the benefits of NextGen by 2025.