

The Need for a Robust Precise Time and Frequency Alternative to Global Navigation Satellite Systems

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ABSTRACT

Positioning, Navigation, and Timing (PNT) services are key enablers of both essential safety and security applications and economically beneficial capacity and efficiency applications worldwide. Whether users are ground-based, sea-based or in the air, their primary/go-to source of PNT has become a Global Navigation Satellites System (GNSS), with the US Global Positioning System (GPS) being the most widely used. Starting in 2001, with the publishing of the landmark Volpe Transportation Systems Center's GPS Vulnerability Report and leading up to the Department of Homeland Security sponsored GPS Interference Testing in 2012, the world has become much more aware of the vulnerability of GNSS-based services – especially in 2011, as the result of significant interest in using the spectrum directly adjacent to GPS for mobile communications services. This was an important wake up call to the world. But while users of GNSS positioning and navigation services are usually at least cognizant of the source of their services, many users of GPS precise time and frequency are oblivious to both the source of these services and their inherent vulnerability. In fact many time and frequency users are not even aware of how GNSS-provided time is crucial to their operations.

The Federal Aviation Administration (FAA) has initiated an Alternate Position, Navigation, and Timing (APNT) program to research various alternative strategies. These strategies are necessary to ensure a safe, secure, and effective transition of the US National Airspace System (NAS) to the Next Generation Air Transportation System (NextGen). While discussing some of the position and navigation aspects of this program, this paper concentrates on the need for a robust time and frequency alternative to GNSS that will support aviation and have the potential to provide robust precise time and frequency services to other user communities. Alternative strategies to be explored include use of existing NAS ground-based navigation aids, high power ground waves, antenna technologies, and alternative satellite constellations.

INTRODUCTION

To discuss the need for “a robust precise time and frequency alternative,” we must first define what is meant by “robust.” Although a number of alternative definitions can be found, the one preferred by the authors, as this is a systemic issue, is “the ability to overcome adverse conditions.” By extrapolating this basic concept, we provide the following basic axiom: *Robust Time and Frequency Services* denotes the provision of strong, sturdy precise time and frequency services that are able to withstand or overcome adverse conditions, and as we are dealing with radionavigation signals, the adverse conditions we must overcome can be categorized as interference.

Radio frequency interference (RFI) comes in many “flavors.” It can be intentional or unintentional; predictable or unpredictable, manmade or environmental, crude or sophisticated (jamming or spoofing); and/or widespread or localized. When we speak of a harsh radionavigation environment, we envision one in which we must overcome some type of interference to arrive at the accuracy, availability, integrity, continuity, or coverage required by our specific applications.

So why is “good” time so important? Because time is the means by which we precisely position and navigate, the means by which we can safely and efficiently separate airplanes in flight. Recently it has become increasingly apparent that it is through the denial or manipulation of good time that spoofers intend to adversely affect GNSS position and navigation users.

The problem is clear – current GNSS time and frequency are not robust, many users are not aware of their dependence on GNSS time and frequency, and GNSS time and frequency services support the vast majority of critical infrastructure/key resource (CIKR) sectors. Figure 1 lists the 18 CIKR Sectors recognized by the US Department of Homeland Security (DHS) and shows that 15 of the 18 rely on GNSS provided time. As a part of the Transportation sector, the FAA clearly recognizes the need for precise time and has maintained a significant non-GNSS based infrastructure to ensure the safety and security of the NAS;

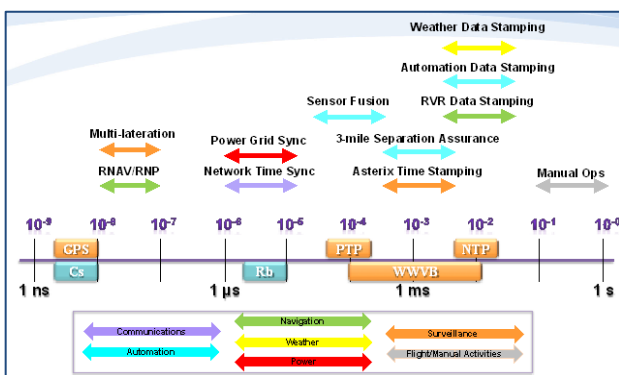
however, as the NAS migrates to NextGen, the need for precise PNT services, and hence the need for robust alternatives, will only increase.

Figure 1. Critical Infrastructure/Key Resource Sectors

Critical Infrastructure/Key Resource Sector	Uses GPS Timing?	
	Yes	No
Communications Sector	X	
Emergency Services Sector	X	
Information Technology Sector	X	
Banking & Finance Sector	X	
Healthcare & Public Health Sector	X	
Energy/Electric Power and Oil & Natural Gas SubSector	X	
Nuclear Sector	X	
Dams Sector	X	
Chemical Sector	X	
Critical Manufacturing	X	
Defense Industrial Base Sectors	X	
Postal & Shipping Sector	X	
Transportation Sector	X	
Government Facilities Sector	X	
Commercial Facilities Sector	X	
National Monuments and Icons Sector		X
Agriculture and Food Sector		X
Water and Wastewater Sector		X

Figure 2 shows the “span” of time users in the NAS, from the relatively unchallenging applications for which seconds will suffice down to the most “discriminating” applications requiring time slices measured in billionths of a second (nanoseconds). Certainly the most widespread use of time in the NAS is for the time stamping of data. Every data transmission from radar returns to voice communications is time stamped and retained as a means to review NAS operations and, if necessary, investigate incidents. As the FAA adopts the Asterix surveillance standard, all surveillance data will include a time stamp calculated to tens of millisecond

Figure 2. Current NAS Precise Time Requirements

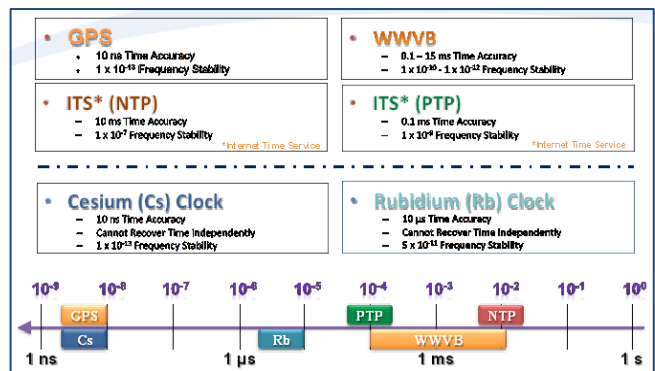


(ms) precision. Communications networks (e.g., SONET) rely on microsecond (μ s) time, as does the electrical power grid. But the most discriminating users are those who utilize time for positioning. Remembering the rule

of thumb that a nanosecond (ns) is approximately equal to a foot (~ 0.98357 feet), ensuring positioning to 10 meters (~ 32.81 feet) accuracy in a time difference of arrival system would require approximately 30 ns accuracy. Historically, systems using this method (e.g., Long Range Navigation (Loran), Distance Measuring Equipment (DME)/Tactical Air Navigation (TACAN) and other secondary surveillance systems) have relied upon internal stable clocks to make less demanding measurements. The innovative solution employed by the developers of GPS to fly precise atomic clocks negated the need of such precision at user equipment. This availability of inexpensive, precise, and highly reliable GNSS time has enabled advances throughout our critical infrastructure. To safeguard these advances, robust alternatives must be sought out and implemented.

Figure 3 shows the various sources of time available to users, starting off with “the gold standard,” GPS. Although GPS’ 10 ns time accuracy far exceeds the

Figure 3. Some Sources of Time and Frequency



requirements of the majority of users, its cost has become so miniscule in relation to other systems components that it has become the most widely used precise time and frequency utility on Earth.

Figure 4. GPS Receiver

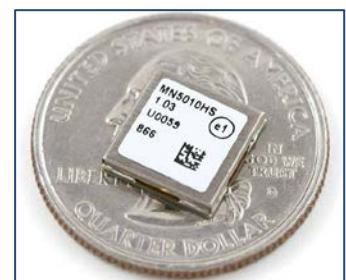


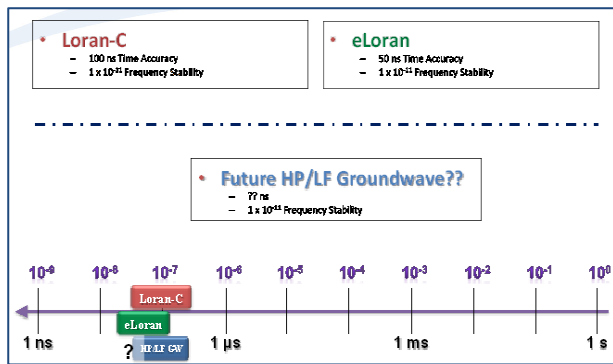
Figure 4 shows one of the typical GPS receiver modules used in today’s electronics. (picture courtesy of Micro Modular Technologies).

WWVB is a 60 kHz radio time service provided by the US National Institutes of Science and Technology (NIST). Its time accuracy at a user receiver is in part dependent on the ability to properly account for the propagation of ground wave, thus the 0.1 to 15ms range in its accuracy. Still, it provides sufficient accuracy to many users. Thanks to the proliferation of the Internet, two means of distributing precise time are

available to users – Network Time Protocol (NTP) allows derivation of precise time from many sources, both government and private sector (e.g., NIST, US Naval Observatory (USNO), Microsoft, Apple, etc.) and the emerging Precise Time Protocol (PTP) described in IEEE Standard 1588. With carefully controlled network architecture time accuracies of 10 ms for NTP and 0.1 ms for PTP can be achieved. Atomic clocks are routinely used throughout the infrastructure to provide precise time references (although not as widespread as many might think). Cesium standards provide time stability equivalent to GNSS’ 10 ns, while Rubidium standards can provide 10 μs. It is important to note that while atomic standards can “flywheel” time quite well, they cannot independently recover accurate time if it is “lost.”

Figure 5 depicts the high power, low frequency ground wave (HP/LF GW) alternatives. While Loran-C is no longer available in North America, there are still many

Figure 5. Other Sources of Time and Frequency



placed in the world that its 100 ns service is still being provided. Some of these locations have enhanced their original Loran-C coverage to provide improved time services that support 50 ns time delivery. A current DHS research effort is exploring if a new HP/LF GW can deliver an even more precise time service. The results of this study have yet to be published, but may yet provide another robust alternative.

THE CHALLENGE OF ROBUST TIME TRANSFER

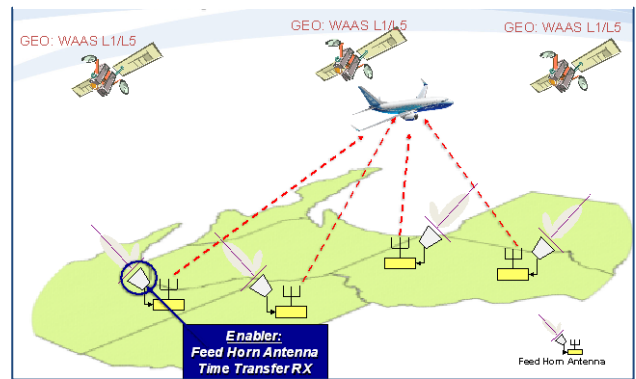
The challenge of robust time transfer, both on the ground and to aircraft involves more than simply precision. As with other aspect of PNT, there is an integrity component of time, i.e., can the information being provided be trusted? Recent demonstrations of spoofing based on exploiting receiver clocks help to highlight the need for both precise and authenticated sources of time.

Precise and authenticated time synchronization is an essential enabling element for two of the alternatives the FAA is exploring in their Alternate PNT (APNT)

initiative – the wide area multi-lateration (WAM) alternative and the passive pseudo-ranging alternative. The goal is to provide a time service/source that allows APNT services to support a required navigation performance 0.3 (RNP 0.3) and to provide the navigation integrity and accuracy necessary for Automatic Dependent Surveillance – Broadcast (ADS-B) systems to support three-mile aircraft separation. GPS is the key enabler of this capability; however, because of its vulnerability to interference, it is critical that a robust APNT solution (i.e., able to overcome adverse conditions) be provided in the event of GPS outages and interference. The availability of precise and trusted time synchronization is integral to achieving the navigation accuracy performance.

In addition to GPS outages and interference, there is a real need to guard against GPS spoofing, which has the potential for impacting safety and security. The availability of a robust PNT alternative that also provides users with precise time both on the ground and in the air can aid in the detection of and mitigation of such impacts.

Figure 6. Robust GEO Satellite Time Transfer



ROBUST TIME TRANSFER ALTERNATIVES

ALTERNATIVE 1A: SPACE BASED TIMING USING HIGHLY DIRECTIONAL (FEEDHORN) ANTENNA

Space-based time/frequency synchronization is well recognized and well understood. There are many ways of using satellites for time transfer based on one-way measurements (e.g., common view). The challenge, however, lies in the susceptibility of such sources to interference – both intentional and unintentional, jamming and spoofing. It is also well understood that even low levels of interference can cause loss of lock and subsequent time/frequency synchronization issues for GPS.

A direct approach to overcoming interference is to “mechanically” prevent them from reaching your receiver, i.e., using a highly directional antennae to focus on the wanted signals and to keep the unwanted interferers at bay.

This would be difficult and rather expensive if the source of the “good” and “trusted” signals were from moving satellites and the antennas had to continuously and precisely track them. Thankfully, there are geostationary satellites (GEOs) that can provide precise time services without the need for elaborate tracking mechanisms. Three of these GEOs are the ones employed by the FAA to provide Wide Area Augmentation System (WAAS) services. WAAS, the US Satellite-Based Augmentation System (SBAS) is working to populate its Time Message – WAAS Message 12, which will allow users “focus” in on one of its three GEOs and derive time services. Figure 6 depicts this potential solution.

ALTERNATIVE 1B: SPACE BASED TIMING USING CRPA BASIC PRINCIPLES AND ANTICIPATED PERFORMANCE

While the use of GEOs may be an acceptable alternative for many fixed-base applications, it becomes problematic if the antenna doing the mechanical filtering is on a mobile platform (e.g., an airplane or ship or truck or person). It would be much better if the antenna itself could identify the source of “good” time sources and filter out the “bad.” For this, Controlled Reception Pattern Antennas (CRPA) are much better suited for prolonging the necessary service performance.

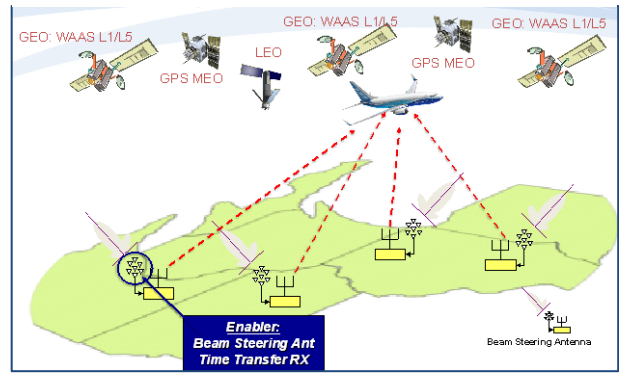
While CRPAs were first developed for military applications, commercially developed CRPAs are now available for non-military customers. For the threat of a single jammer being considered here, CRPA antenna technology is extremely effective. While the military has utilized these applications for some time, some of the technology is now available for civilian applications, as well. Figure 7 shows a numbers of CRPAs currently on the market.

Figure 7. Commercially Available CRPAs



Because CRPAs can reinforce wanted signals and attenuate unwanted ones, this solution is able to avail itself from signals emanating from medium and low altitude satellites (MEOs and LEOs) as well as GEOs,

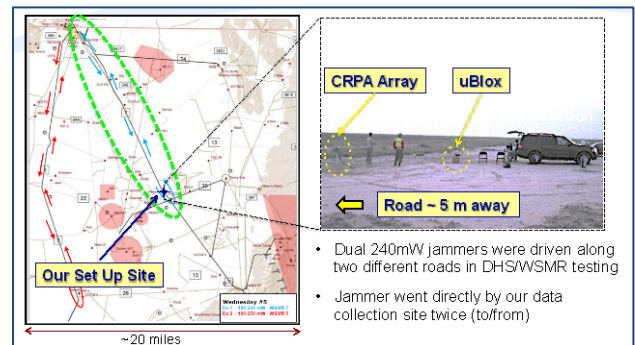
Figure 8. Robust Satellite Time Transfer - CRPA



potentially making it a more robust alternative. Figure 8 depicts this alternative.

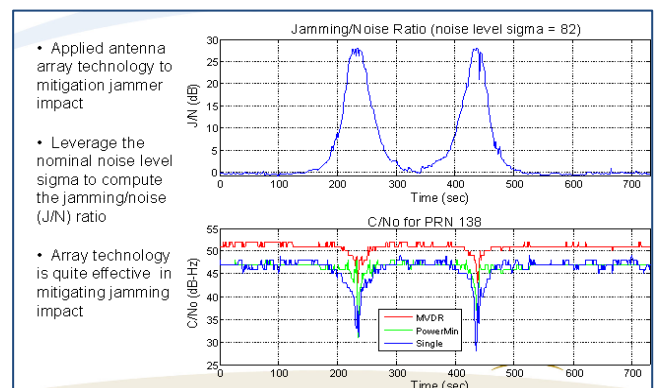
The capability of a CRPA constructed by our Stanford University-based authors was demonstrated during recent

Figure 9. CRPA Response to 250 mW Jammers



trials conducted during a DHS-sponsored GPS Interference event conducted at White Sands Missile Range in New Mexico. Figure 9 shows the location and setup of the trial. A 250 mW jammer was driven down the road circled in green. The Stanford equipment was set up 5 meters from the road. Figure 10 shows the jammer approaching and

Figure 10. 250 mW Jammer/CRPA Results



passing the test setup, turning around and passing it a second time. It also shows the response of the CRPA to the jammer, effectively providing over 30 dB of protection to the receiver.

ALTERNATIVE 2: ROBUST WIRELESS GROUND-BASED SOURCES

Within the NAS there are signals emanating from the ground that have the potential to provide robust time transfer to aircraft. The ADS-B system operates with the L-band proving services via the Universal Access Transmissions (UAT) at 978 MHz and on the Mode S Extended Squitter at 1090 MHz. The UAT signal structure already accommodates time and ranging, but is primarily used by general aviation and business aircraft. Commercial Aircraft use the Mode S ES service, which while better suited to handle multipath due its larger bandwidth, has congestion issues.

Another alternative being explored is the use of ground-based pseudolites co-located with FAA's DME and GBT sites. One means of utilizing pseudolites would be for each to broadcast its time of transmission and allow the aircraft to calculate the time of arrival. As DMEs in their normal mode provide true ranging, the combination of pseudolite and DME shows promise. However, it does require that all ground stations to be precisely synchronized (remember a nanosecond is a foot!). An alternative means of using pseudolites is also being discussed. Proffered by friends at Ohio University, it may be possible to use carrier phase measurements of DME transmitters to derive position without the need to synchronize ground sites. This and other means and other transmissions have not been ruled out.

ALTERNATIVE 3: ROBUST WIRE-BASED SOURCES

As mentioned previously, precise time services (milliseconds down to microseconds) are available through wired sources. Recognizing the need for robust, GNSS-independent time as well as trusted sources, the FAA's Telecommunications Infrastructure (FTI) has introduced both NTP and PTP services to ensure air traffic control facilities will be able to maintain their services in the event of a GNSS outage.

When using wire-based time services, it is important to ensure that the source of the data is trusted and, especially with PTP, the forward and backward communications paths are the same. While an acceptable alternative to most users, wire-based services cannot currently fulfill the needs of nanosecond time users.

LAST THOUGHTS – IMPORTANT!

While concentrating on precision/accuracy, one must not lose sight of integrity. As we have become more and more aware of spoofing, users must ensure that the source of their precise time is from trusted sources, and one of the means to do this is through authentication. One description of authentication (found online from a Duke University source) describes *authentication* as “the mechanism whereby systems may securely identify their users. It provides answers to the questions (1) Who is the user? and (2) Is the user really who he/she represents himself to be?” But in our situation, the “user” is the one needing to authenticate “the system.” Happily, the same principles apply.

For centuries people have used shared secrets to authenticate things – the *secret* password or passphrase or handshake. In the modern era of data transmission, we have migrated to more sophisticated means employing both public (known by all) and private (secret) keys. Because it is important to authenticate the source of time information, we have also begun investigating the means of incorporating both authentication means into our solutions by employing either a private key infrastructure (PKI) or a symmetric key solution. The work is still in its early stages and is mentioned here to ensure that one does not forget to include authentication into the mechanism for achieving time precision.

In summary:

- Time is an important GNSS product, often overlooked;
- Many users are not aware that they are dependent on GNSS time;
- GNSS is vulnerable! GNSS is vulnerable!
- There are robust alternatives – and there is a need to identify and incorporate them into operations to ensure safety and security and to mitigate significant economic impact;
- Precise Time is particularly important to certain ground based and airborne “discriminating” users – in the NAS and elsewhere;
- For many applications authentication is as important as accuracy; and
- Today's status quo may not/will not be an acceptable alternative in the future as GNSS services continue to proliferate and are used to support more and more critical operations.

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