Time Source Options for Alternate Positioning Navigation and Timing (APNT)

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ABSTRACT

Precise time synchronization is an essential element for APNT technologies, such as wide area multi-lateration (WAM) and passive pseudo-ranging. The goal is to provide a time service/source that allows APNT technologies to support a required navigation performance 0.3 (RNP 0.3) and provides the navigation integrity and accuracy for surveillance systems that is required for three-mile aircraft separation. The Global Positioning System (GPS) is the key enabler of these capabilities; however, because of its vulnerability to interference, it is critical that an APNT solution be robust (i.e., able to overcome adverse conditions) in the event of GPS outages and interference. The availability of precise and trusted time synchronization is integral to achieving the navigation accuracy performance. This paper outlines the ongoing efforts by the APNT Team investigating technologies capable of providing the precision and widespread delivery of time needed for the APNT goals.

OVERVIEW OF APNT TIMING

Precise time synchronization is an essential element for APNT technologies, such as wide area multi-lateration (WAM) and passive pseudo-ranging. Precise time synchronization is key to achieving the required navigation accuracy and surveillance performance needed to support required navigation performance 0.3 (RNP 0.3) and allow three-mile aircraft separation. It is imperative that the alternative timing system not fail in a manner that reduces the performance or capacity of its supported APNT even in the presence of deliberate jamming and interference of GPS. Hence, the goal of APNT timing is to provide a time service that allows APNT technologies to support targeted goals while being robust to GPS outages and interference.

A precise, robust time system could also provide utility to other aviation assets, such as networking and communications. Precise timing is also needed to support surveillance operations using multilateration to provide verification and redundancy for the automatic dependent surveillance broadcast (ADS-B) system. Networks coordinate communications by precise synchronization to a common time standard such as Coordinated Universal Time (UTC), often using GPS. An APNT timing capability, synchronized to UTC, would provide a high quality, robust source of time for these functions.

Requirements

APNT timing design is driven by the need for a highly accurate and a highly robust time synchronization capability. Additionally, an internal clock that provides holdover in the event of an outage of the synchronization source can supply short-term robustness and redundancy. These are the current focal points of our investigation. As the technologies mature, other issues such as continuity and integrity will be examined.

Time synchronization is required to maintain all components in the APNT system on the same clock reference. In a basic implementation, the clock time reference can be any time source, such as the internal time of the system. For example, WAAS network time (WNT) is an internal time reference – it is derived from GPS measurements across the network when available. Maintaining time to a common standard, such as UTC, provides more flexibility and allows for synchronization using multiple sources as long as they are referenced to the same standard. Two primary time scales are supplied in the US – UTC instantiated from the

National Institute of Standards and Time (NIST) in Colorado [termed UTC(NIST)], and UTC from the US Naval Observatory in Washington, DC [termed UTC(USNO)]. The time difference between these two sources is very, very small and negligible for APNT applications. While GPS synchronizes to UTC (USNO), APNT could synchronize to either GPS or UTC (or both) without impact to its capabilities or timing issues related to transitioning from a GPS-based solution to APNT.

Requirements on timing accuracy derive from the need to supply APNT technologies with timing accuracy commensurate for supporting navigation and possibly surveillance (RNP 0.3, surveillance for three mile separation). Current results show that our pseudo-ranging and multi-lateration signals provide a signal-in-space accuracy of approximately 30 meters (m) at maximum range. The implied time synchronization requirements are shown in Table 1. Currently APNT timing does not have a frequency stability requirement other than it must be sufficient to support the accuracy targeted.

Operation	Position accuracy required	Range accuracy required (HDOP 2.8)	Signal accuracy (estimated)	Derived time accuracy required
RNP 0.3	307.2 m	111.2 m	30 m	347.9 ns
Surveillance (3 mile separation)	92.6 m	32.7 m	30 m	43.7 ns
RNP 1.0	1852 m	654.8 m	30 m	2110.9ns

Table 1. Relationship between position accuracy and time accuracy (95%). RNP position accuracy requirements use FTE accuracy of .25 nm

The calculation of the derived timing accuracy uses with the position accuracy requirements of the targeted operations along with an assumed worst-case horizontal dilution of precision (HDOP) of 2.828, and ranging signal accuracy of 30 m. Overall range accuracy required is derived from the position accuracy required by dividing by the worst case HDOP. For RNP 0.3, the position accuracy is 0.3 nautical miles (nm) less the contribution of flight technical error (FTE) – in this case 0.25 nm. Range accuracy the root sum squared (rss) of time and signal accuracy and so time accuracy required is the square root of the range accuracy required minus signal accuracy as seen below:

Timing Accuracy Required = (Range accuracy required^2- Signal accuracy^2)$^{1/2}$

Timing Accuracy Required (RNP 0.3, FTE = .25 nm) = $[(307.62\ m/2.8)^2 - (30\ m)^2]^{1/2}$ = 104.36 m (347.9 ns)

We also consider the area over which different levels of time synchronization are required. Synchronization of all components within the approach and terminal regions of an airport should meet the most stringent (RNP 0.3 and surveillance) requirements. However, the extent of this synchronization coverage is unclear. It may be necessary to provide this level of synchronization between any two stations that can be used simultaneously by any given aircraft. For example, an aircraft at altitude can receive two stations that are separated by 300 miles. Even if the aircraft is not in the terminal area, en route use may still require 3- or 5-mile separation, which requires a similar high level of synchronization. This would drive us to the conclusion that the most accurate synchronization needs to be provided over a wide area. However, if these stations only need to be synchronized to provide RNP 1.0, the synchronization accuracy could be relaxed. This topic will be further explored.

Robustness to interference and outages, particularly GPS radio frequency interference (RFI), is a critical element of the APNT effort and is needed to prevent wide spread outage of navigation. While the specific requirements for availability under GPS RFI depend on the threat (strength, number and type of jamming), there are several scenarios that any viable APNT system solution should, at a minimum, handle. The first is the scenario is "a strong GPS jammer (100 – 2.5 kilowatt (kW) jammer) at distance (> 75 km) operating over an 8-hour period." This scenario derives from ongoing US Department of Defense (DoD) GPS jamming exercises known as NAVFEST [17]. The second scenario is "an intermittent RFI from one or more low power jammers (~1 milliwatt (mW)) at short distances (~ km)." This scenario has been experienced near Newark Liberty Airport (EWR), where so-called personal privacy devices (PPD) (mobile jammers readily available on the Internet) operating on the New Jersey Turnpike have denied GPS reception on the adjacent airport property.

The timing technologies being examined achieve robustness to GPS RFI either by attempting to be completely independent of GPS or by strengthening the ability to use GPS under interference. The former is challenging as GPS is a "stealth" utility and has been incorporated into many parts of our infrastructure, i.e., many users are unaware that their applications rely on GPS to support their applications. Therefore, careful examination is needed to ensure there are no unseen dependencies on GPS that could impact safety or security or cause significant economic impact. The latter is about making sure a strong interference event can, at most, only affect a small local area (i.e., one transmitter) rather than a large region. One means to achieve this is to have greater rejection to jamming. Table 2 shows that with 30 dB of jamming resistance, the effective radius of a 100 W jammer drops from 500 kilometers (km) to 15 km. With 50 dB of rejection, a jammer would need to be within 1.5 km of a user to cause an outage. For a powerful personal privacy device, 50 dB of rejection means that the jammer would have to be within 15 m of the GPS antenna to have any effect on GPS use.

Jammer Power	Outage Radius (nominal)	Outage Radius (30 dB rejection)	Outage Radius (50 dB rejection)
100 W	500 km	15 km	1.5 km
10 mW	5 km	150 m	15 m

Table 2. Jammer power impact radius

Internal clocks are fundamental part of any timing system and can vary significantly in terms of performance. An internal clock while a necessary component of a timing solution is not sufficient alone as the APNT team cannot assume that the source of interference to GPS will be located and disabled quickly, a source of external time synchronization is being sought that will allow for open-ended operation.

Selection of clocks depending on mission criticality, required performance, and associated costs. The selection of the "right" clock or oscillator is critical as it can supplement the synchronization timing and provide holdover should outages in the timing signal occur. For space-based time synchronization, these outages could be jamming that denies the satellite signals. The performance characteristics of the internal clock and the required time accuracy determine the hold over time. Several measures can be used to assess the holdover performance with the most significant ones being Allan variance (depends on random fluctuations $\varepsilon(t)$), aging (At^2), frequency offset (R_0t), and initial synchronization error (T_0). Time synchronization error ($T(t)$) as a function of time t is a function of these values using the equation below [13] which also includes environmental effects ($E_i(t)$) :

$$T(t) = T_0 + \left(R_0 t + \tfrac{1}{2} A t^2 + \ldots\right) + \int_0^t E_i(t)\,dt + \varepsilon(t)$$

The terms that are most relevant to consider are Allan variance, aging, and initial offset. The frequency offset will be presumably mostly calibrated out when our time synchronization is available while the initial synchronization error depends on our source (see Table 6). For example, examine a Rubidium (Rb) or Rubidium crystal oscillator (RbXO). Figure 1 shows the approximate root Allan variance for various classes of oscillators. For Rb or RbXo with half part in a trillion ($5\text{x}10^{-13}$) root Allan variance ($\sigma_y(t)$), the random fluctuation error (as measured by Allan variance) will be 50 ns in 10^5 seconds (50 ns/$5\text{x}10^{-13}$), or a little more than a day. A comparable error source is aging. For Rb or RbXo with aging of $2\text{x}10^{-10}$ per year, this works out to be conservatively to $5\text{x}10^{-13}$ per day, which then contributes 50 ns in 10^5 seconds (a little over one day). Initial offset depends on the time synchronization system and its errors are shown in Table 6. The first two effects indicate that, with small contributions from other errors sources (such as initial offset), a Rb/RbXO should maintain less than 50 ns, one standard deviation to approximately half a day.

The clock stability (as indicated by Allan variance) and aging for different classes of internal clocks is given in Table 3. Several classes of crystal

	Crystal Oscillators (XO)			Atomic Oscillators		
	TCXO	MCXO	OCXO	Rb	RbXO	Cesium
Stability, $\sigma_y(\tau)$ (τ = 1s)	1×10^{-9}	3×10^{-10}	1×10^{-12}	3×10^{-12}	5×10^{-12}	5×10^{-11}
Stability, $\sigma_y(\tau)$ (τ = 1000s)	1×10^{-10}	-	1×10^{-12}	1×10^{-13}	1×10^{-13}	3×10^{-14}
Aging/Year	5×10^{-7}	2×10^{-8}	5×10^{-9}	2×10^{-10}	2×10^{-10}	0
50 ns time	< 1 min	minutes	~ 1 hr	~ ½ day	~ ½ day	> 1 month

Table 3. Stability and Aging for Different Oscillators (based on [13])

oscillators (XO) are represented: temperature compensated XO (TCXO), Microcomputer compensated XO (MCXO), and oven-controlled XO (OCXO). As seen in Figure 1 and in the two stability rows, the stability is different at different times for each class of oscillators. The last row is a derived result using stability from Figure 1 and the aging values from the table. It is an order of magnitude approximation as different implementations can vary by a factor of 2 or more.

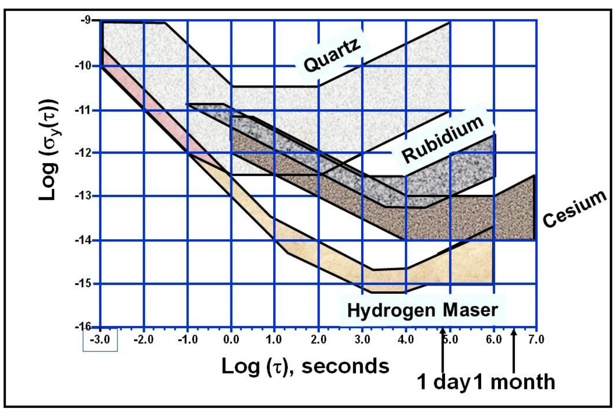

Figure 1. Allan Variance plot for different classes of oscillators [13]

Rubidium clocks seem to be a reasonable internal clock for holdover for APNT. Table 4 presents specifications from a SRS PRS10 that retails for $1500. Future developments in low cost atomic oscillators, such as the chip scale atomic clock (CSAC), have the potential of improving performance and lowering costs. The first commercial CSAC, the Symmetricom SA.45, is now available at $1500 per unit [20][21]. The APNT team is tracking this development.

Short Term Stability, $\sigma_y(\tau)$			Aging	
1 s	10 s	100 s	Monthly	Yearly
< 2×10^{-11}	< 1×10^{-11}	< 2×10^{-12}	5×10^{-11}	5×10^{-10}

Table 4. Stability and Aging for PRS10 [19]

TIME SYNCHRONIZATION AND TIMING ALTERNATIVES & OVERVIEW

Potential solutions

Three primary potential solutions have been considered for time synchronization. One would be to leverage robust, wireless, space-based time synchronization methods. Other options are wired (network) and wireless terrestrial solutions.

Robust space-based timing uses satellite signals such the Wide Area Augmentation System (WAAS) geostationary (GEO) satellite, GPS/GNSS medium Earth orbit (MEO), and low Earth orbiting (LEO) satellites, along with adaptive beam forming, null steering controlled reception pattern antenna (CRPA) array to significantly mitigate RFI or provide anti-jam (A/J) performance. Space-based time transfer is the most popular means of precise time transfer due to its accuracy and cost effectiveness. For example, GPS accuracy relative to UTC is specified to less than 1 microsecond (µs) (without UTC offset), though in actuality accuracy of better than 15 nanosecond (ns) can be achieved. One-way space-based methods are cost effective as they derive time only from reception of satellite broadcasts. However, satellite broadcast signals are susceptible to interference due to their low received signal power.

CRPA technology allows for the use of satellite signals for precise timing and synchronization even in the presence of strong RFI by 1) making outages much more difficult to cause and 2) limiting outages to a small, local area. CRPA enable beam steering and adaptive null forming which focuses more of the desired signal energy while rejecting more interference than conventional antennas. Coupled with other anti-jam technologies, jam resistance can be improved by a factor of 1000 or more over conventional GPS receivers. The CRPA concept for APNT will be discussed in detail in the next section.

Network timing provides time synchronization using standardized protocols developed and supported by network equipment. Two candidates are precise time protocol (PTP) described in the IEEE 1553 standard and J.211. PTP is a protocol being developed and built in router and switching hardware to enable precise time transfer over Internet connections using internet protocol (IP). While there are many flavors of PTP, the most stringent current target for a wide area network (WAN) is 1 μs aimed at supporting telecommunications. PTP timing performance is limited by its use of Ethernet lines that operate different lines for the incoming and outgoing traffic. These incoming and outgoing lines will typically have small percentage differences (0.15%) in length that result in timing errors. For example, over 50 km, 0.15% error equals 75 m or 250 ns of error. The error increases over distance and cannot be easily corrected with PTP. To improve performance, J.211 mandates that incoming and outgoing traffic use the same lines to eliminate this difference. However, this requires dedicated lines and has currently only been implemented over relatively small geographic regions. Table 5 summarizes the key characteristics for the major network timing protocols.

	NTP	PTP	J.211
Deployment	All networks	Precision networks	Cable industry
Layer	Software (SW)	PHY (physical layer), MAC (media access control), SW	Hardware, PHY, MAC, SW
Precision	1-10 ms	100 ns-10 μs	100ps-5 ns
Transport	Any, software	Ethernet preferred	CAT 5 cable
Scale	Network (WAN), Internet	Network (WAN and LAN)	Local / dedicated

Table 5. Summary of Network based Protocols Requirements & Capabilities: Network Time Protocol (NTP), PTP, J.211 [10]

Terrestrial techniques use land based RF transmissions for timing. Two techniques are being considered – the use of long-range signals, such as low or very low frequency (LF, VLF), and line of sight (LOS). LF and VLF signals are useful as they can propagate along the earth for very long ranges. One broadcast, such as the WWVB time signal from Fort Collins, CO, can cover much of the conterminous US (CONUS). The time accuracy of the signal is affected by variations in ground propagation delay and skywave multipath that changes throughout the day. This makes sub microsecond timing over a large area using the signal challenging. Line of sight time synchronization is being used in the current MLAT system implemented in Colorado (RefTrans) and in the commercial pseudolite systems, such as Locata's Locatalites. It can perform very precise time synchronization, especially using two-way closed loop control. However, LOS is only viable over a short distance and does not provide absolute time synchronization (unless there is a master that relies time traceable to a primary reference source/master clock such as USNO or NIST).

Table 6 summarizes the accuracy levels of the methods discussed in this section.

Method	Accuracy (to UTC)
GPS Timing Receiver	40 ns[6] (< 15 ns)
WAAS (with WNT-UTC offset corrections)	29 ns
Iridium [11]	1 μs (20 picosecond (ps) for 1 sat)
Radio - Dedicated	10 ns - 10 ms
Radio - WWVB (60 kHz)	0.1 - 10 ms
PTP	1 μs (target)
J.211 (DTI)	< 5 ns

Table 6. Summary of the Accuracy of Precise Time Technologies [6][10][11]

Combinations

These solutions are not mutually exclusive and their elements may be combined to form a more cost effective solution by using existing and less costly infrastructure to provide the "final" mile. For example, a star network with a precisely synchronized central node that distributes to nearby elements could be used. One implementation could be to use satellite timing for the central node and transfer its time over existing line-of-sight or network connections.

Despite the reliance of the space-based systems on GPS/WAAS, the additional infrastructure required for terrestrial options clearly can become overwhelming. Further, given the success of the CRPA antennas for GNSS and interference cancellation, coupled with the fact that the WAAS signal is under the direct control of the FAA, the focus of this effort/paper has been to explore the robust space timing with CRPA interference rejection.

SPACE BASED TIMING USING CRPA

Basic principles and anticipated performance

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 such common view, etc. The challenge, however, lies in the susceptibility of such sources to interference – both intentional and unintentional. It is also well understood that even low levels of interference can cause loss of lock and subsequent time/frequency synchronization issues for GPS. However, for the threat of a single jammer being considered here, CRPA antenna technology is extremely effective. This has been used for military applications and is well understood.

obtain the benefit of individual components. These components are incrementally added to our prototype. For example, using frequency lock loop (FLL) instead of phase lock loops (PLL) will be implemented once the baseline L5 CRPA has been developed.

Table 7 and the associated suppression need to be qualified relative to a specific receiver. For example, a survey grade receiver may have a tracking threshold of a carrier-to-noise ratio (C/No) on the order of 25-30 dB-Hz. Alternatively, a mass market receiver designed for the urban environment is likely to be able to maintain lock until a threshold of C/No on the order of 10-15 dB-Hz and is already employing the bandwidth reductions and frequency tracking. Although the final RFI suppression is relative to the comparison receiver, the CRPA component will provide a significant benefit - greater than a 20 dB margin - against interference. Further, not mentioned above is the dual frequency nature of the final design utilizing both L1 and L5 frequencies with both frequencies leveraging the

Preliminary Link Analysis		
CRPA antenna system	~20-40 dB suppression	• Null steering suppression • Near-horizon signal attenuation
L5 processing gain	10 dB	10x chipping rate vs. L1-C/A
L5 received signal power	3-6 dB	Higher power than GPS L1-C/A
Static Receiver & quality clock	9 dB	Tracking loop bandwidth reduction (15Hz → 2Hz)
FLL vs PLL margin	5-8 dB	Non-coherent tracking of RF carrier
Potential RFI suppression	40+ dB	Combining factors may not realize complete benefit

Table 7. Preliminary Link Analysis

A focal point of this effort is to transition that technology to the civil community and to develop a prototype that can demonstrate the potential solution.

In addition to the CRPA, which is the primary means considered for overcoming the primary threat of interference, GPS/WAAS receiver technology have addition elements that can be leveraged for such an application. To understand the full potential, we look at the link analysis in Table 7 and elements of Table 7. Thus for space-based time synchronization to be denied would require significant power on both frequency bands.

Prototyping and field tests are needed to demonstrate the feasibility of a commercial off the shelf (COTS) system and to validate theoretical predictions. The prototype development is presented below. Field tests of in situ performance will provide deep understanding of CRPA operations and identify hardware effects, such as antenna saturation, that may alter performance.

The prototyping/architecture design uses phased approach by first developing a unique compact CRPA data collection platform capable of logging/storing the 320 MB/sec of digital data generated. The portable data collection platform developed consists of a compact data collection computer with multiple, high write speed (solid state) drives (Figure 2) and four Universal Software Receiver Peripheral (USRP) connected to a different antenna element to convert received signal to digital data at intermediate frequency (IF) (Figure 3). This enables the raw IF data stream from the CRPA to be captured and stored and processed offline. Then the CRPA algorithms, which are fundamental to the performance gains and the key research area, can be developed and refined in post processing, moving to a real time prototype once finalized. Currently, we have implemented a real time prototype that can perform CRPA processing and data collection simultaneously based on the data collection platform.

Figure 2. Portable Data Collection Computer

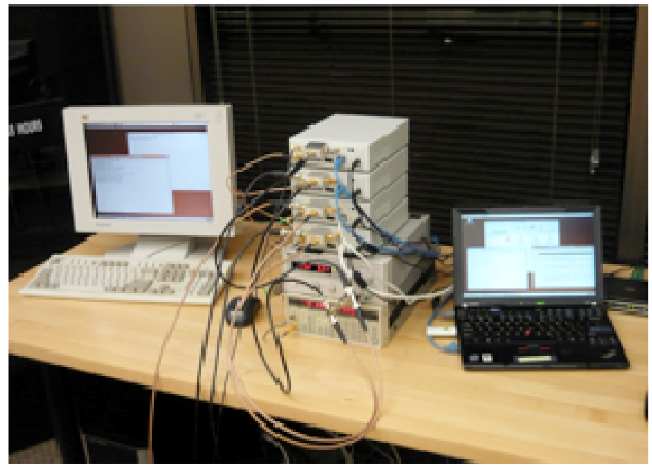

Figure 3. 4 Universal Software Receiver Peripheral (USRP) Data Collection Front End (Middle)

Development timeline

To date, the portable CRPA data collection platform has been used for four official campaigns to collect raw IF GPS samples in the presence of live interference. Since GPS resides in a protected frequency band and any transmissions, even for test purposes, are illegal, such data collection campaigns are essential to the overall effort. Two campaigns collected data during various GPS L1 jamming exercises; the first at the 2011 NAVFEST conducted by the USAF 746th Test Squadron (which is restricted as For Official Use Only (FOUO))[17] and the second in conjunction with the Swedish military at the Vidsel Test Range in Northern Sweden. One campaign has provided GPS L5 jamming which is a data collection in close proximity to the Woodside, CA DME transmitter, which put strong-pulsed RFI (1173 MHz) directly into the L5 frequency band (1176.45 MHz center, 20 MHz wide). The real time system was tested in the June 2012 GPS jamming exercise at White Sands sponsored by the Department of Homeland Security.

Throughout 2012, these data sets will be processed and the CRPA algorithms will be refined fully demonstrating the interference rejection capabilities of the design and quantifying the performance. Although the algorithms are being developed in a post-processing environment, they have been designed capable of real time operation.

The real time prototype CRPA receiver operates on L1 C/A code, 4-element running on a personal computer (PC) architecture (currently Intel Core i7) has been built and demonstrated. By the end of

2012, an L5 wideband 4-element CRPA real time receiver running on a PC architecture will be demonstrated/functional. Some tested four-element arrays are seen in Figure 4.

Figure 4. Four Element Antenna for Testing: L1 (DLR) and L1/L5 using Trimble Zephyr Antennas

This year (2012), the focus of these development and prototype efforts is on the RFI suppression capable technologies based on our measurement campaigns.

In 2013, we expect that the prototype designs will be furthered by integrating a Rb atomic oscillator. The atomic time base will be steered using the 1 pulse-per-second (PPS) signal from the CRPA design and fall back to coasting on the Rb timesource should GPS not be available. Performance metrics, such as allowable coasting time and errors sources, will be the focus of the testing.

Next, the final prototype will be fielded and tested. This will be the integrated GPS L1/L5 CRPA design integrated with the Rb atomic oscillator. The design will feature dual frequency operation driving the Rb timebase and coasting should GPS be denied. This final prototype is expected to serve as a design model for the timing needs of APNT.

and what is needed in the receiver to achieve that performance.

Time synchronization from GPS/WAAS

One-way time transfer involves multiple time scales: satellite, system, and UTC, all of which are different. Of interest for time synchronization is the accuracy of the calculated time to the internal system time and UTC. The internal ground system time for GPS is GPS system time and WAAS is WAAS network time (WNT).

Given the different time scales (calculated, system time), there are several accuracy values associated with a given satellite system. For GPS, there is the accuracy of GPS system time to UTC and the accuracy of UTC derived from GPS as calculated when applying the GPS to UTC offset parameters. When GPS closely follows UTC and the UTC offset parameters are nearly zero, these two time scales are essentially the same. If, on the other hand, GPS time were to drift from UTC, as permitted by the GPS specification, the application of the UTC offset parameters might become significant.

WNT performance is currently specified relative to GPS time. Without WNT-UTC offset parameters WNT is only close to UTC when GPS time is close to UTC. While GPS is typically close to UTC, broadcast of WNT-UTC offset parameters allows users to have an accurate estimate of UTC even if GPS time drifts from UTC. Further improvement may be had if the WNT-UTC offset is determined directly from a UTC source (e.g., UTC(USNO)) thereby eliminating the UTC-to-GPS time error.

Source	Specification	Current Capability
GPS Time	1 ms	< 15 ns
UTC derived from GPS	90 ns	< 4 ns
WNT accuracy to GPS	50 ns to GPS	25 ns to GPS
WNT accuracy to UTC	None explicit (1000 + 50 = 1050 ns)	25 + 15 = 40 ns
UTC Derived from WNT	None explicit	None, needs MT-12
UTC from WNT with GPS offset parameters	None explicit (90 + 50 = 140 ns)	Not demonstrated 25 + 4 = 29 ns

Table 8. GPS/WAAS Time accuracy to UTC

WAAS NETWORK TIME AND SYNCHRONIZATION TO UTC

Accurate one-way time transfer from GPS satellites or WAAS geostationary satellites is a key consideration. In this section, we cover the performance of the time transfer based on WAAS

While the WNT-UTC offset parameters are not currently broadcast, they can be transmitted using WAAS Message Type 12 (MT 12), as discussed later. Table 8 shows the specified and actual accuracy of various time standards derived from GPS and WAAS. The key result is that time derived from GPS is very closely synchronized to UTC (< 15 ns) and WNT is reasonably synchronized to GPS and UTC. Additionally, WAAS timing users may have improved synchronization to UTC with MT 12.

An issue with using WAAS for APNT synchronization is the effect of GPS RFI on WAAS time. The WAAS system operates using a large network of WAAS reference stations (WRS), each using three independent receivers. As individual reference receivers are impacted by interference or otherwise unavailable, the accuracy of WAAS will decrease. The impact of each WRS depends on its location and the ability of the other WRSs and on the parameter being calculated. Relative to other estimates (WAAS corrections and error bounds), the ability of WNT to follow GPS time should be less sensitive to the location of supporting WRSs. Instead it is sensitive to the total number of participating WRSs. The impact of regional or wide scale interference events on WAAS and WNT is difficult to predict.

WAAS Message Type 12 provides three notable benefits in addition to WNT-UTC offset. It is the only WAAS message that has an explicit epoch time included in the message. Therefore it provides the time epoch when the only signal available is the WAAS geostationary (GEO) signal. Second, it contains the leap second offset for the conversion between GPS time and UTC. Third, it provides the offset parameters, which could be significant if the difference between UTC and GPS Time ever approached the 1 μs specification limit. The ability of WAAS MT-12 to support a given level of accuracy depends in part on the source of the offset parameters. Theoretically WAAS could populate MT-12 with the GPS–UTC offset parameters. This is a relatively simple change to the WAAS system, but might include errors associated with the ability of WNT to follow GPS time.

Achieving Accuracy Timing from GPS/WAAS Receivers

GPS/WAAS timing receivers must mitigate sources of error that degrade time transfer performance to achieve highly accurate synchronization to UTC. Sources of error in single measurements create similar errors in time transfer. These errors include thermal measurement noise, antenna phase center location error, and antenna multipath. Environmental impacts, such as ionosphere and troposphere delay, add additional inaccuracy. The data lines between the antenna and the receiver and the receiver processing cause additional delay. Receiver clock error over the period of the observation contributes further uncertainty.

Many methods are used to mitigate these factors. The user can calibrate and include the data line and receiver delays. The user can site the antenna and modify the environment around the antenna to limit multipath. The user can survey the antenna location. Processing techniques can reduce the random uncorrelated errors, such as use of all in-view satellites. Noise can further be reduced through longer averaging or smoothing. Through the use of dual frequency or the application of WAAS ionosphere delay corrections, the user can reduce the error associated with ionosphere delay. However, some of these techniques might require a higher performance clock to avoid the introduction of additional receiver clock errors. There are many factors under the user's control that can reduce the accuracy of time transfer from either GPS or WAAS.

Current GPS timing receiver manufacturers claim to achieve an UTC synchronization accuracy of 40 ns or better. For example, the Trimble Resolution T specifies a 15 ns (1 standard deviation) accuracy to GPS or UTC in a stationary mode with an over-determined solution. For APNT, it is important to understand conditions needed to achieve that accuracy.

SUMMARY

APNT is considering many options for obtaining precise time and system wide synchronization. The three basic methods are: space-based, terrestrial wireless (line of sight), and network time synchronization. Key considerations for these methods are: 1) synchronization accuracy; 2) robustness to outages, particularly due to GPS jamming; and 3) technology maturity and cost to install/operate. These will be coupled with a prudent selection of a base reference clock/oscillator.

Method	System	Benefits	Drawbacks
Space-based time transfer	GPS/GNSS WAAS	Precise timing in large area	Dependent to GPS signal (CRPA mitigate)
	Iridium	Precise time over satellite footprint Stronger signal than GPS (27 dB) Not GPS frequency	Proprietary system (outside FAA control) Less accurate across large region (multiple satellite area)
Terrestrial RF	Line of Sight	Precise timing in local area May use existing signals	Range limitations Some RFI vulnerability
	LF	CONUS wide coverage	May not be accurate enough
Network	PTP	Almost all new network equipment will support Uses existing Ethernet	Time accuracy limited by use of Ethernet Current target is μsec timing
	J.211	Potential for ns timing	Dedicated lines (potentially high cost)

Table 9. Summary of Methods, Implementation, Benefits, Drawbacks

For wide area synchronization, the only method that can currently achieve required accuracies is space-based. Network timing will need significant improvements in accuracy or area to meet synchronization accuracy between any two nodes in CONUS. All three methods have the potential to serve a local region. The concern with any over-the air signal, particularly with the generally weaker signal used in space-based time transfer, is interference. CRPA technology helps overcome the major drawback for space-based timing and synchronization. However, while the technology has significant potential, to date, its use has been solely military. Hence, its capability and cost effectiveness for civil use is not well understood. The APNT team is focused on developing the technology for civil timing and understanding its limitations and requirements. Specifically, we have developed a prototype system and are incrementally evolving it to add improvements to increase jam resistance.

Understanding the performance trade-offs allows for developing the most effective solution - even if a clear "best" method for APNT is not indicated. Space-based offers high accuracy over a large area but is susceptible to interference. While LEOs, such as Iridium, may offer greater RFI resistance, they will incur additional costs, as they are privately owned and, unlike the current WAAS system, are outside FAA control. Terrestrial methods offer greater resistance to interference, but its time synchronization degrades over a large area. PTP utilizes Internet connections and, as a result, degrades over distance. More accurate J.211 uses dedicated landlines, which are expensive over a large area. Terrestrial wireless time transfer can be accurate, but degrades over distances and also may have susceptibility to deliberate jamming or blockage. Table 9 summarizes the methods examined and the benefits and drawbacks to different systems. The best solution may be to draw upon multiple methods.

ADDITIONAL STEPS

Future development of time synchronization using space-based time transfer was previously described in the "Space based timing using CRPA" section. Terrestrial wireless is being used by current MLAT systems and its performance will be studied. Progress in network technologies will also be tracked.

Another step to developing the APNT solution will be to determine detailed definitions of the threat space and acceptable performance during a threat. The threat space is defined by multiple factors such as the duration, strength, and number of jammers in an interference event. Performance factors beyond meeting timing requirements include holdover capability and acceptable outage area (how widespread or how many stations may be unavailable noting that even under nominal conditions a station may be unavailable due to maintenance or failure).

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