Wide Area Wireless Network Synchronization Using Locata

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BIOGRAPHIES

Edward D. Powers:

Edward Powers is a native of Hot Springs Arkansas. He is a 1984 graduate of the University of Arkansas at Little Rock, where he earned a BS degree in electronics engineering technology and in 1987 he graduated from the University of Arkansas Graduate Institute Of Technology with a MS in Instrumental Science.

Mr. Powers began his civil servant career in 1987 working at the Naval Research Laboratory developing and testing GPS satellite atomic clocks. He provided support for the Navy PTTI program including work supporting the development of HP5071 Cesium clocks, GPS timing receivers and other Navy timing systems. Mr. Powers worked with various agencies on the development of remote deployed timing systems supporting the highest level user requirements. Mr. Powers was lead test engineer on the DISA Loran replacement program during which GPS timing systems were developed for deployment at over 400 remote DoD telecommunication sites. Mr. Powers was responsible for maintaining and upgrading all NRL PTTI clock measurement systems. Mr. Powers worked with the GPS joint program office assisting in development of the NAVWAR program, special research studies and various GPS user equipment test programs.

In 1997, Mr. Powers joined the USNO Time Service Department providing expertise in the area of precise time transfer with a focus of GPS. Mr. Powers continue his advisory duties to the GPS program office supporting space atomic clock development, modernized GPS III navigation message design, GPS accuracy improvement studies, GPS UE development and test support to name a few. Working with DISA the USNO NTP program was moved to a dedicated DISA network circuit. Mr. Powers served on numerous technology readiness/assessment panels including GPS IIIA satellite program and the AEHF FAB-T program, both with a focus on atomic clocks and advanced time keeping systems.

Mr. Powers is presently the GNSS and Network Time Transfer Operations Division Chief with a staff of 5 civil servants and 1 contractor. The GNSS Operations Division is charged with providing the UTC reference used by GPS as part of the GPS UTC timing service. He is also a member of the US Working Group on GNSS interoperability, with a focus on making the navigation time scales of each GNSS system interoperable. Over the past ten years, agreement on navigation and UTC time scale interoperability has been reached with QZSS, Galileo and GLONASS.

Arnold Colina:

Arnold Colina is a graduate of Florida International University (FIU), where he earned a BS degree in Electrical Engineering in 2010. During his tenure at FIU, he worked on electronics projects that included a brain-computer interface. In 2014, Mr. Colina began his civil servant career and joined the USNO Time Service Department working under Mr. Edward Powers as an Electronics Engineer. As a member of the GNSS and Network Time Transfer division, he is tasked with providing accurate UTC reference through GPS and to perform calibration tests on various GNSS receivers.

ABSTRACT

Many critical modern systems such as 4G mobile phone networks, banking, and electricity grids demand high-accuracy time and frequency stability across specified areas. In fact, precise network synchronization is critical for nearly all digital networks, and more stringent network stability requirements are expected to emerge as the user base for these applications continues to grow. To date, the preferred method to achieve this performance is via synchronization from the Global Positioning System (GPS). However, the vulnerability of GPS signals remains a growing concern among industry experts, and many are actively seeking alternative means of providing precise time transfer and frequency stability across wide areas.

Previous technical papers have reported that Locata Corporation’s radio-based Position, Navigation, and Time (PNT) technology—which uses a patented “TimeLoc” process—enables network synchronization at the nanosecond level. Furthermore, they also show that Locata’s network time can be aligned to external references, such as GPS [1] or an atomic clock [2], providing exceptional time transfer and frequency coherence across wide rural areas. These results suggest that Locata could also be used to provide comparable performance across large urban areas.

This paper details experiments conducted by the United States Naval Observatory (USNO) in Washington, DC which investigate the frequency stability of Locata networks (LocataNets) under multiple network configurations in urban environments. Details include specific test parameters and equipment configuration used to determine frequency synchronization across tested LocataNets. The paper further discusses how the Locata transmission signal can be extended—by "cascading" TimeLoc from one Locata transceiver to another—to cover substantially larger areas as required for user applications extending over a wide region.

These USNO demonstrations confirm earlier published results and provide additional independent insight into the frequency synchronization capability of Locata's TimeLoc process. For local areas ranging from small campuses to city-wide user situations, TimeLoc technology offers a relatively easy means of supporting exceptionally high precision time and frequency distribution over broadcast areas.

BACKGROUND

Time and frequency synchronization between remote locations is crucial for many important applications, including mobile phones, all digital communication systems, electrical power grids, and financial networks, to name only a few. Additionally, many aspects of military operations require increasingly accurate and reliable time information. Modern navigation systems, such as GPS, depend on the availability and synchronization of highly accurate clocks. In the intelligence fields, time synchronized activities are essential.

The combination of the above existing systems with emerging technologies such as Machine-to-Machine (M2M) innovations represent what industry experts are calling the "Internet of Everything" (IoE), which stands to revolutionize not only access to data and information but also the global economy. [3]

Typically, these applications require accurate time synchronization ranging from 10 microseconds (μs) down to 100 nanoseconds (ns) and Stratum 1 telecommunication frequency accuracy of $1x10^{-11}$. Over the past two decades, the free availability of GPS time has enabled a plethora of time-dependent applications, not only leading to significant capability advancement, but also cost savings for companies that depend on precise time. However, reliance on GPS for critical timing applications poses two significant problems:

1. Although capable of high accuracy, GPS is vulnerable to interference and is unreliable indoors, under dense foliage, and in some urban environments. Maintaining required time accuracy during GPS outages necessitates the use of expensive oscillators. [3]
2. GPS, with typical timing accuracy of 100ns [3], may actually be limiting our ability to improve time transfer and frequency stability beyond current capabilities, stagnating the growth of time/frequency transfer technologies. Efforts to demonstrate significantly improved time/frequency transfer has proven to be a daunting task.

Despite continuing GPS modernization efforts focused on satisfying advanced PNT requirements with signal robustness, GPS remains vulnerable to interference, degradation, disruption, or denial in every environment, both at home and abroad, by natural and man-made means. According to the 2001 Volpe Report, "the consequences of loss of the GPS signal can be severe (depending upon its application), both in terms of safety and environmental and economic damage to the nation, unless threats are mitigated" [4]. Notwithstanding these concerns, our critical reliance on GPS for time transfer continues to escalate, leading experts to identify or create not just a GPS companion, but also a PNT alternative.

Alternative PNT technologies such as chip scale atomic clocks (CSAC), precision time protocol (PTP), and enhanced long range radio navigation (eLoran) are proposed or in limited operation today, with each working towards serving different markets. Obviously, synchronization requirements are dependent upon the application and technology they need to support.

Meanwhile, timing needs for wireless protocols continue to increase with the proliferation of mobile phones and other wireless communication devices. To accommodate a growing user base, wireless spectrum must be managed thoughtfully to improve bandwidth and channel efficiency. It is well-known that wireless communication performance is fundamentally dependent upon precise time and frequency, so improvements in highly accurate timekeeping methods will permit better spectrum utilization, which in turn permits more users and more bandwidth per user. [3]

Certainly, with these goals in mind, advanced wireless synchronization has been an extremely important topic among industry and academic experts. However, it has proved very challenging to realize, as the timer in each network node is derived from an independent oscillator which is affected by long/short term frequency drifts and jitter, and many alternative timekeeping methods present limitations in terms of precision or network size. [5]

Locata Corporation, a privately-owned Australian company with a US subsidiary, has invented a new radiolocation technology that provides precise PNT in many environments where GPS coverage is marginal, unavailable, or actively denied for modern applications. Locata technology breakthroughs provide ground-based PNT capabilities that deliver positioning advances which, in many scenarios, far exceed the performance and reliability available from space-based GPS signals. Locata creates terrestrial networks—"LocataNets". These function as "local ground-based replicas" of the traditional space-based GPS position and timing services and they can be designed to reliably deliver a powerful, controllable, tailored signal as required by different user applications. [2] [6] [7]

The easiest LocataNet layout to describe consists of a single "Master" LocataLite transceiver and one or more "Slave" LocataLites. However, more complex network configurations have also been deployed in commercial systems in use today. The patented process by which Slaves are synchronized to the Master (or other Slaves) is known as TimeLoc. Although most attention to date has been focused on the position and navigation portion of Locata's PNT solution, all LocataLites are precisely synchronized via TimeLoc, so network synchronization is a natural extension of Locata technology's core capabilities.

In late 2013, Professor Chris Rizos and his team from the University of New South Wales (UNSW) demonstrated that Locata's radio-based PNT technology provided accurate time transfer (~5ns) and frequency stability (~1 ppb) across a large 73 km (45.4 mile) area. This significantly outperforms GPS for wireless time transfer. [1] Given this demonstrated radius of transmission in a rudimentary configuration, Locata can supply nanosecond accurate time to a 146 km (90 mile) diameter circle (which covers 16,750km^2 (6,360 mi^2), an area 200 times the size of Manhattan. Ranges could be greatly increased if required for safety-of-life, military or Government-mandated systems.

Accomplished without the use of atomic clocks, this coverage represents a completely new league in precision network synchronization of this scale. It could conceivably serve as a potential GPS augmentation or back-up solution over wide areas for critical applications that depend on precise time.

Encouraged by these results, the USNO conducted several independent frequency synchronization experiments using Locata in multiple network configurations. The results continue to be promising—suggesting that sub-nanosecond time transfer using Locata may be possible over wide urban areas.

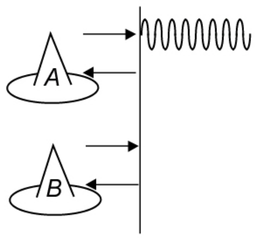
TIMELOC

Since Locata technology was originally developed as a high-precision non-GPS-based positioning and navigation solution, the time synchronization accuracy requirements for a LocataLite transceiver are very high. If sub-centimeter positioning precision is desired for a Locata receiver, every small fraction of a second is significant, e.g. a one nanosecond error in time equates to an error of approximately thirty centimeters (due to the speed of light).

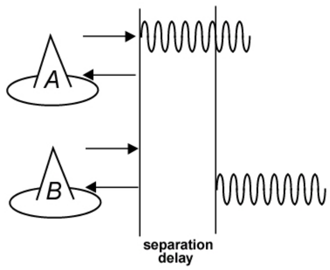
TimeLoc is a patented high-accuracy wireless synchronization method developed by Locata Corporation. TimeLoc allows LocataLites to achieve high levels of synchronization without atomic clocks, without external control cables, without differential corrections, and without a master reference receiver. The TimeLoc procedure is described in the following steps for synchronizing two LocataLites A and B (Figure 1):

1. LocataLite A transmits a unique signal (code and carrier).
2. The receiver section of LocataLite B acquires, tracks and measures the signal generated by LocataLite A.
3. LocataLite B generates its own unique signal (code and carrier) which is transmitted, but importantly, it is simultaneously received by the receiver section of LocataLite B as well.
4. LocataLite B calculates the difference between the signal received from LocataLite A and its own locally generated and received unique signal. Ignoring propagation errors, the differences between the two signals are due to the difference in the clocks between the two devices, and the geometric separation between them.
5. LocataLite B adjusts its local oscillator to bring the differences between its own signal and LocataLite A to zero. The signal differences are continually monitored and adjusted so that they remain zero. In other words, the local oscillator of B follows precisely that of A.
6. The final stage is to correct for the geometrical offset (range) between LocataLite A and B, using the known coordinates of the LocataLites. When this step is accomplished, TimeLoc has been achieved.

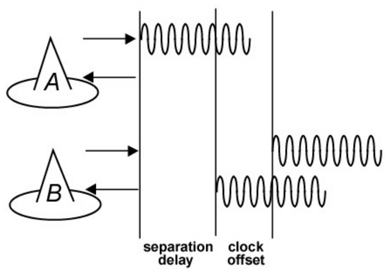
In theory, there is no limit to the number of LocataLites that can be synchronized together using the TimeLoc procedure as described. Importantly, the TimeLoc procedure allows a LocataNet to propagate into difficult environments or over wide areas. For example, if a third LocataLite C can only receive the signals from B (and not A) then it can use these signals for time synchronization instead. Moreover, the only requirement for establishing a LocataNet using TimeLoc is that LocataLites must receive signals from one other LocataLite. This does not have to be the same 'central' or 'Master' LocataLite, since this may not be possible in difficult environments or when propagating the LocataNet over wide areas. This method of "cascading" TimeLoc through intermediate LocataLites has been proven in a growing number of



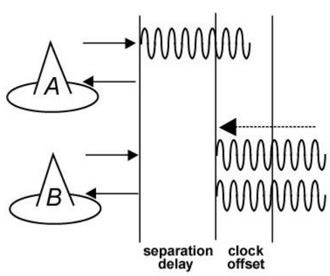
Step 1. LocataLite A transmits a unique signal.



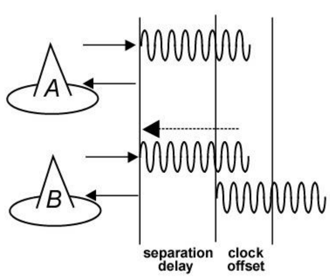
Step 2. LocataLite B receives signal from A.



Step 3. LocataLite B transmits a unique signal.
Step 4. LocataLite B computes difference (clock offset) between transmitted and received signals.



Step 5. LocataLite B makes difference (in step 4) zero.



Step 6. LocataLite B corrects for A & B separation delay

Figure 1: The TimeLoc Process

operational LocataNets, including a network in use by the U.S. Air Force which is configured to cover up to 2,500 square miles (6,500 square kilometers) of White Sands Missile Range in New Mexico. [2]

The complete TimeLoc process is described in detail in the Locata TimeLoc Patent (US Patent #7,616,682). [8]

USNO EXPERIMENT DESIGNS

The USNO has developed one of the world's most accurate and precise atomic clock systems—used by systems requiring highly precise time. In fact, the USNO operates the "Master Clock", which provides precise time to the GPS satellite constellation run by the USAF, and it is also the time standard for the U.S. Department of Defense. Thus, the USNO's clock system must be at least one step ahead of the demands made on its accuracy, and innovative methods of transferring precise time and frequency must continually be anticipated and supported.

To this end, the USNO desired to independently test Locata's TimeLoc methodology as a possible technology for maintaining precise frequency synchronization across an urban network—the foundation for supporting precise time transfer. To accomplish this, the USNO conducted a series of experiments to measure and evaluate the stability between Master and Slave LocataLite 1-pulse per second (1PPS) signals in several urban LocataNet configurations, many of which leveraged TimeLoc's cascade capability.

Figure 2: Two LocataLites under Evaluation at USNO

Locata signals were broadcast in the Industrial, Scientific and Medical (ISM) 2.4GHz radio band at (often referred to as the Wi-Fi band) with a total radiated power of 200 – 500 mW. LocataLites and their respective antennas were installed at locations that permitted line-of-sight between units, according to the specific LocataNet configuration being evaluated at the time. In each configuration, the Master LocataLite, designated as LocataLite 1, was synchronized to the USNO Master Clock so that the Master Clock's time would be propagated through the LocataNet. Both the Master and Slave LocataLite 1PPS signals were collected into a time interval counter and the time difference between their rising edges was measured.

When tracking radio frequency signals over a significant distance, tropospheric delay becomes an important error source for measurements used in the timing solution. Using standard atmospheric parameters, the unmodeled tropospheric delay is approximately 280 parts per million (ppm), which equates to nearly one nanosecond over each kilometer of transmission. Obviously, as transmission distances increase, tropospheric error can become a substantial factor, so devising methodologies for mitigating the effects of tropospheric error becomes increasingly important.

To help solve this problem, Locata has developed new tropospheric models that make use of relatively inexpensive meteorological (MET) stations that measure temperature, pressure and relative humidity at the LocataLite sites. This modeling alone is able to mitigate the tropospheric effects to within a few parts per million.

In large networks where extremely high synchronization accuracies are required, it may be useful to incorporate meteorological sensors at each LocataLite to monitor the change in weather over considerable distances. This is the case for long-range systems such as the USAF LocataNet installed at the White Sands Missile Range, where distances of over 35 miles (50km) can be found between LocataLites. However, for the purposes of these USNO experiments where the longest point-to-point transmission distance was 1.8mls (2.897km), it was assumed that weather parameters were virtually identical at all LocataLite locations. Therefore, only one MET station (collocated with the Master LocataLite) was employed in the entire network.

The initial experiment employed two LocataLites with their respective antennas on the roof of USNO Building 78. In this initial configuration, the antennas were positioned 50ft (15.24m) apart. This is referred to as the 2-node setup. A diagram of this configuration is shown in Figure 3.

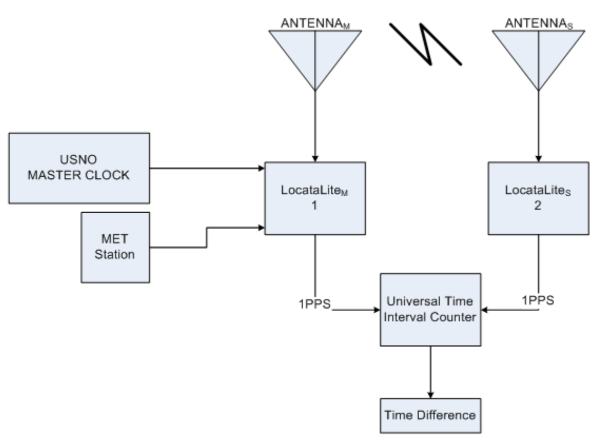


Figure 3: 2-Node Setup (Total Range, 50ft/15.24m)

Second and third experiments demonstrated Locata's ability to "cascade" the Master 1PPS signal to a Slave LocataLite, which in turn transmits and TimeLoc's to a third LocataLite. This LocataNet configuration is referred to as the 3-node setup. A diagram of the setup is shown in Figure 4.

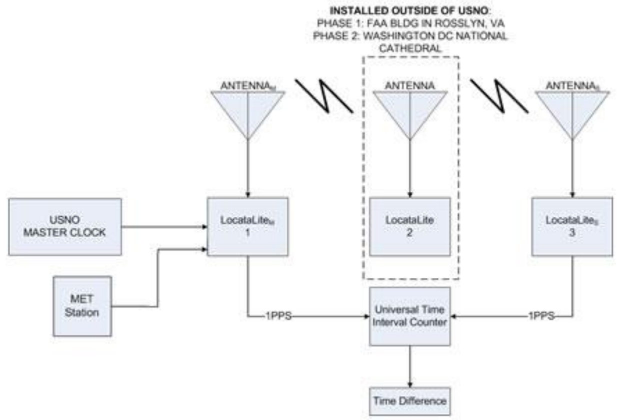


Figure 4: 3-Node Setup (Total Range, 3.6mi/5.794km & 1.49mi/2.401km)

This experiment was conducted twice using two different intermediate LocataLite locations. The first intermediate location was indoors on the top floor of the FAA Building in Rosslyn, VA (Figure 5). The distance between the Master/Slave antennas to the intermediate antenna in the FAA building was approximately 1.8mi (2.897km), but since the signal was propagated through a tinted window, the received signal strength was weakened, effectively simulating an even longer transmission distance. The second intermediate location was from the balcony of the National Cathedral's Ringing Chamber. The distance between Master/Slave to the intermediate antenna in the National Cathedral was approximately 0.74 mi (1.183km).

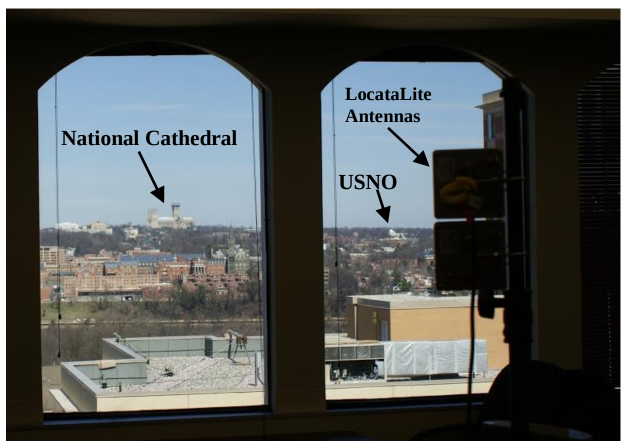


Figure 5: Intermediate LocataLite Antennas inside Conference Room of FAA Building in Rosslyn. In the distance (outside the windows), both the USNO and the National Cathedral are visible.

In both cases, the distance between Master and terminal Slave antennas was 10ft (3.048m), but they were intentionally not TimeLoc'd to each other so that the timing signal would need to be routed through the intermediate LocataLite.

A fourth experiment included yet another intermediate cascade where the TimeLoc signal was transmitted from the second to a third antenna and LocataLite before arriving at the fourth LocataLite in the chain.   This LocataNet configuration is referred to as the 4-node setup. A diagram of the setup is shown in Figure 6, and it leveraged locations at the National Cathedral and USNO Building 1 for the intermediate LocataLites (Figure 7). The distance between the Master antenna (antenna 1) at USNO Building 78 and antenna 2 at USNO Building 1 was approximately 140ft (42.672m). The distance between antenna 2 and antenna 3, USNO Building 1 to the Washington National Cathedral, was approximately 0.71 mi (1.144km). The distance between antenna 3 and antenna 4, Washington National Cathedral to USNO Building 78 was approximately 0.74 mi (1.183km). In this configuration, LocataLites 1 and 4 are intentionally not TimeLoc'd to each other, forcing the 1PPS signal to be routed through LocataLites 2 and 3.

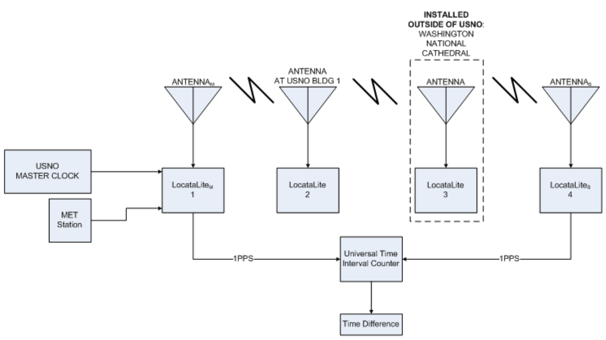


Figure 6: 4-Node Setup (Total Range, 1.5mi/2.413km)

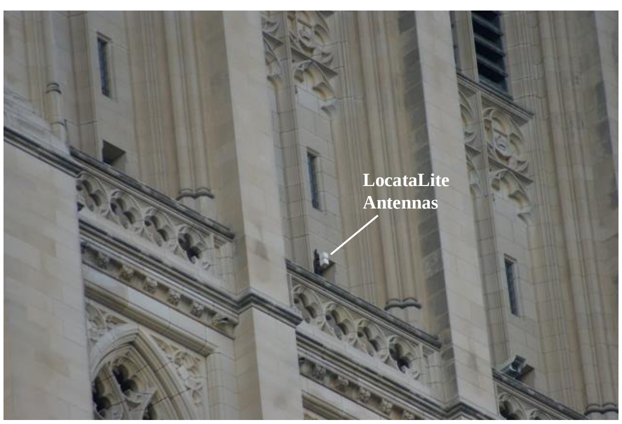


Figure 7: LocataLite Antennas outside the Ringing Chamber of the National Cathedral

A fifth experiment included yet one more LocataLite and antenna at USNO Building 1, totaling cascaded TimeLoc among five LocataLites and their respective antennas. This is referred to as the 5-node setup. A diagram of this setup is shown in Figure 8. In this configuration, LocataLites 1 and 5 are intentionally not TimeLoc'd to each other, forcing the 1PPS signal to be routed through LocataLites 2, 3, and 4.

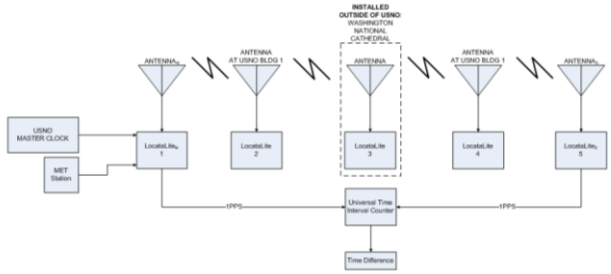


Figure 8: 5-Node Setup (Total Range, 1.51mi/2.427km)

Figure 9: LocataLite Antennas at USNO Building 1. The National Cathedral is visible in the background.

MEASUREMENT METHODOLOGY

A measurement of time difference between Master and Slave LocataLite 1PPS readings was done using a Stanford SR620 universal time interval counter. The rising edge of the 1PPS signals were inspected at 1-Volt trigger level. A 10 MHz reference was provided to the counter from USNO's Master Clock. Channels A and B on the counter were designated to the Master and Slave 1PPS signals respectively. Data were collected from the counter through serial connection to a PC. The length of each experiment was time-limited in some way because of limited access to facilities, such as the FAA building or National Cathedral. However, a minimum of at least 30,000 seconds (8.33 hours) of data were collected for each test to characterize the overall stability of the 1PPS signals between Master and terminal Slave LocataLites.

COLLECTED DATA

The following charts show the normalized 1PPS time difference between the Master LocataLite and the terminal Slave LocataLite. Normalization effectively removes errors due to unsurveyed antenna locations and uncorrected cable delays; hence, it highlights the frequency coherence of the network.

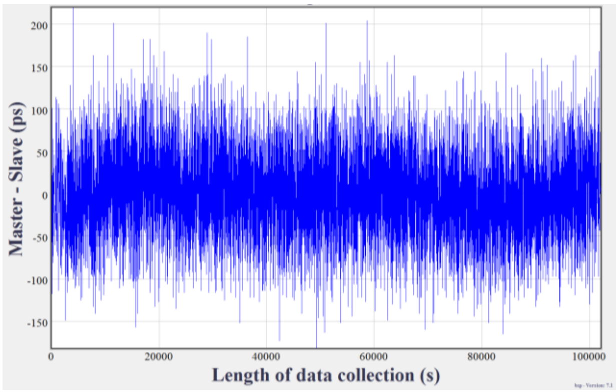


Figure 10 – 2-node setup at USNO building-78 rooftop, collected for 1 day from MJD 56948.756 to 56949.937

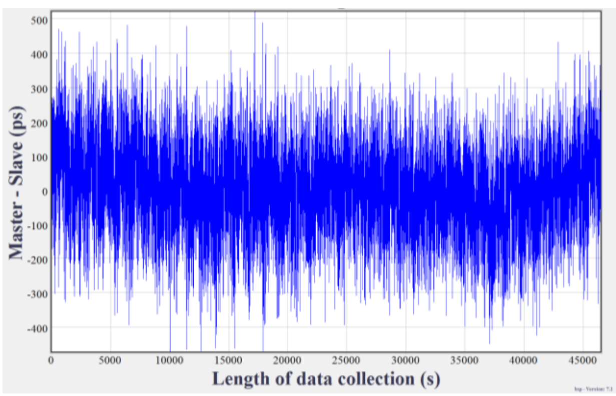


Figure 11 – 3-node setup at USNO and FAA Building in Rosslyn, collected for over 12-hours from MJD 57104.044 to 57104.583

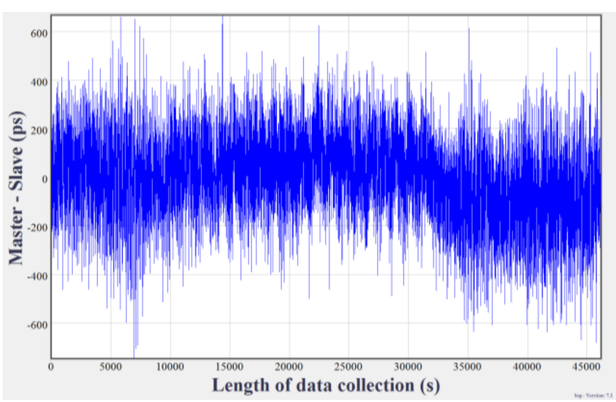


Figure 12 – 3-node setup at USNO and National Cathedral, collected for over 12-hours from MJD 57161.922 to 57162.457

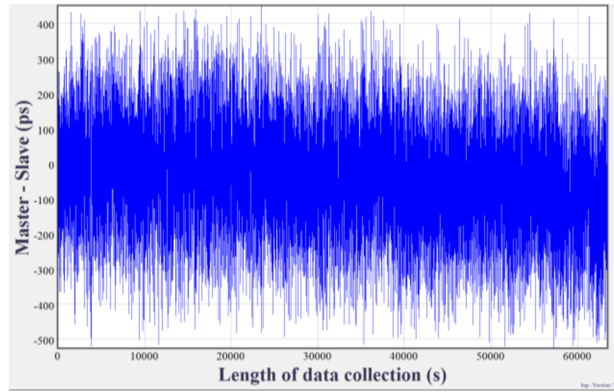


Figure 13 – 4-node setup at USNO with cascades at National Cathedral and USNO building 1, collected for over 17-hours from MJD 57162.848 to 57163.583

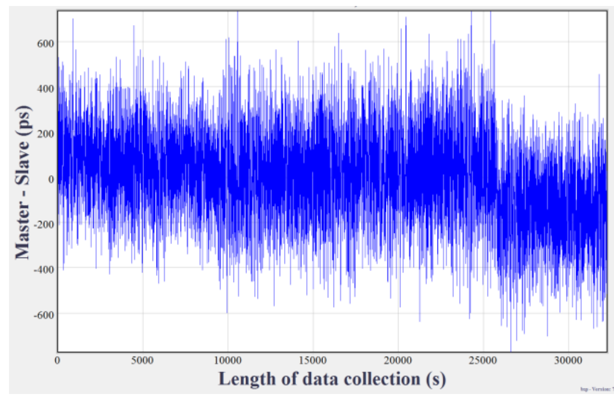


Figure 14 – 5 node setup with cascades at National Cathedral and 2 hops at USNO building 1, collected for over 8-hours from MJD 57164.193 to 57164.566

RESULTS

The results in Table 1 show the 1PPS signal variability for each LocataNet under evaluation. These values represent the frequency coherence between Master and terminal Slave LocataLite 1PPS signals for each experiment.

Setup	Total Signal Distance from Master to terminal Slave LocataLite	Standard Deviation (picoseconds)	Change in RMS from short 2-node setup (picoseconds)
2-node (Fig. 10)	50ft/15.24m	51.095	N/A
3-node (Fig. 11, FAA Bldg.)	3.6mi/5.794km	127.333	76.238
3-node (Fig. 12, Nat. Cath.)	1.49mi/2.401km	171.325	120.230
4-node (Fig. 13)	1.5mi/2.413km	145.247	94.152
5-node (Fig. 14)	1.51mi/2.427km	197.766	146.671

Table 1: LocataNet Frequency Stability

The 2-node setup shown in Table 1 used two LocataLite antennas located within 15.24m (50ft) of each other. The measured precision standard deviation was 51.095 picoseconds. This value is a culmination of the total Locata noise budget, which is expected to consist of TimeLoc noise, residual tropospheric error, multipath change (signal scattering/diffusion), PPS generation, and PPS measurement. This 2-node result can be used as a baseline for Table 1 measurement results over longer distances. The differences are shown in the last column of Table 1. For example, cascading TimeLoc over the 5.794 km (3.6 mile) 3-node setup introduced an additional deviation of 76.238 picoseconds, compared to the 2-node set-up.

The 3-node setup tested the effect of adding a TimeLoc cascade wherein the Locata signal from the Master is routed to an intermediate LocataLite, and then to the terminal Slave. When the Master LocataLite signal was cascaded through the intermediate LocataLite at the FAA Building, the configuration showed a standard deviation of 127.333 ps across a total signal path length of 5.794 km (3.6 miles). Alternatively, when the Master LocataLite signal was cascaded through the intermediate LocataLite at the National Cathedral, that 3-node configuration showed a standard deviation of 171.325 ps across a total signal path length of 2.401km (1.49 miles).

Interestingly, it appears that in the two different 3-node setups, the intermediate cascade to the FAA building (which is 2.9km/1.8miles from the Master and terminal Slave LocataLites) delivered slightly better time transfer performance than the configuration which leveraged the closer (1.183km/0.74 miles) National Cathedral intermediate cascade. It is believed this is attributable to the fact that the line-of-sight between USNO Building 78 (the site of the Master and terminal Slave) and the National Cathedral (the intermediate cascade) was completely obscured by heavy foliage as seen in Figure 9, and that this particular configuration required the signal to pass through the foliage twice when being transmitted back and forth. Not only does foliage introduce multipath, but the properties of this foliage also changed regularly according to wind and moisture—two weather attributes that varied significantly over the course of the week in which those particular experiments were set up and run. This theory seems reasonable, since the 4-node setup (see below) only required the signal to pass through this foliage once, and the recorded performance was better than the 3-node setup - despite the fact that an additional TimeLoc cascade point was introduced.

The 4-node setup included TimeLoc cascades at USNO Building 1 and the Washington National Cathedral. In this configuration, the data from Table 1 shows a standard deviation of 145.247ps across a total signal path length of 2.413km (1.5 miles).

The 5-node setup included yet another TimeLoc cascade between the National Cathedral and Building 1 at USNO before reaching the terminal LocataLite Slave. In this configuration, the data from Table 1 shows a standard deviation of 197.766ps across a total signal path length of 2.427km (1.51 miles)

Frequency stability is best measured over long periods. Because all equipment in the 2-node setup was located on USNO premises, it could run undisturbed for a longer period of time than configurations which leveraged external facilities. Data obtained from the 2-node setup were used to calculate the frequency stability between the two TimeLoc'd LocataLites. The length of this data set was 28 hours, 22 minutes, and 40 seconds. During this period, the approximate one-day frequency stability was measured as $1x10^{-15}$ (which may also be expressed as a drift of approx. 1 part per quadrillion).

To put this measurement into a more practical context: Stratum 1 is defined as a source of frequency with an accuracy of at least $1x10^{-11}$, hence Stratum 1 performance generally originates from an atomic standard. For example, Cesium Beam atomic clocks typically provide better performance than this, with one day Allen deviation stabilities in the mid-Ex10-^{14} (usually stable to between $3x10^{-14}$ to $6x10^{-14}$). Rubidium clocks are typically never more stable than $1x10^{-13}$ and MASER clocks are typically stable to mid-to-low $Ex10^{-15}$ over one day.

Locata's link stability—which is achieved without the use of atomic clocks —is capable of distributing Stratum 1 frequency and precise time without substantially degrading the reference clock stability. This measured performance is significant, because a stable network is an essential prerequisite for precise time and frequency transfer. Moreover, for many traditional timing applications and developing applications, stability is more important than accuracy; just as for most advanced technology applications, frequency is more important than time of day. [10]

CONCLUSIONS

The five USNO experiments suggest that the variations of the measured frequency synchronization between Master and terminal Slave LocataLites were not inevitably attributable to the distance between LocataLites, but rather governed by (1) the number of nodes or "cascade points" in the LocataNet configuration, and (2) LocataLite signal quality. Each signal cascade through an intermediate LocataLite introduced ~25ps of jitter into the solution. [Table 1]

Additionally, it was noted that transmitting TimeLoc signals across an urban environment did not always allow for perfectly clear line-of-sight or completely open-sky environments. For instance, some of the LocataNet configurations required the signal to travel through dense, leafy trees which appeared to slightly affect overall frequency stability. Additionally, one FAA configuration required the signal to travel indoors through a tinted window which ultimately affected received signal strength.

These USNO tests highlighted the capability of the LocataLite as a viable option for a stable 1PPS distribution setup within an urban environment in support of applications like cell tower synchronization in "GPS-challenged" environments. All tested configurations demonstrated frequency synchronization of less than 200 picoseconds, which is significantly better any other known wireless network synchronization methodology, including GPS.

Furthermore, if clear line-of-sight is available between a Master and Slave LocataLite, precision has been shown to be on the order of 50ps, and it is stable to $1x10^{-15}$. These results, reinforced by those which the UNSW previously reported, suggest that distance between nodes is not a significant factor, provided that sufficient signal quality is maintained. Thus, there are no theoretical or technical problems with scaling LocataNets to very large areas. In fact, this has clearly been demonstrated at the White Sands Missile Range where the USAF has deployed a network that covers up to 2,500 square miles (6,500 square km) — an area 80 times the size of Manhattan. [2]

The USNO trials reported here have clearly demonstrated TimeLoc's relative picosecond-level synchronization of independent Locata networks. If this highly-stable network capability were not in place, precise time transfer would not be possible. The next step is to now demonstrate how well a LocataNet can deliver absolute time transfer of the USNO's Master Clock time to any other network node across similar areas of urban Washington DC.

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DISCLAIMER

Though particular vendor products are mentioned, neither official USNO endorsement nor recommendation of any product is herein implied.

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