OVERVIEW

WORLD-FIRST CONFERENCE PAPER ON LOCATA TIME SYNCHRONIZATION CAPABILITY

Presented by the University of New South Wales at the US Institute of Navigation's
Precise Time & Time Interval Conference, Seattle – December 2-5, 2013

BACKGROUND

- For many years Locata has been focused mainly on the Position and Navigation portions of GPS technology's essential Position, Navigation and Time (PNT) components.
- Nevertheless, the "T" component – time transfer and synchronization – is at the very heart of Locata via the TimeLoc™ invention which creates Locata's core network technology.
- UNSW researchers wanted to specifically test a Locata network's real-world long-distance time transfer capability. As a performance benchmark comparison they used today's most demanding IEEE synchronization standard for next-generation 4G mobile phone networks.
- Therefore, in November 2013, the UNSW set up two independent research experiments designed to quantify – for the first time – Locata's long range time transfer capabilities.
- Many critical modern systems (4G mobile phone networks, banking, electricity grids, etc) demand high-accuracy time and frequency stability across specified areas, as set out in IEEE specification standard 1588. Today's desired minimum performance levels are:
    - Synchronization: ±1.5 to ±5μs (millionths of a second)
    - Frequency stability: 16 - 50ppb (parts per billion)

  These levels of precision are difficult to achieve. They represent the cutting edge of real world technology performance and require specialised, dedicated infrastructure.
- The preferred way to achieve this IEEE-specified performance within critical systems is via synchronization from GPS or other space-based positioning systems. But, as stated clearly throughout industry literature: *"the vulnerability of GPS signals is of growing concern"*. [https://www.aventasinc.com/whitepapers/WP-Timing-Sync-LTE-SEC.pdf]
- Governments and companies around the globe recognize their deep dependency on time distribution and have begun to demand "backup to GPS" systems. Any alternate to radio-based time distribution (e.g. fibre optics) is very complex, infrastructure intensive and costly. Locata's radio-based system is therefore attracting much attention as a potential solution.

PERFORMANCE

- UNSW ran two different systems to demonstrate (a) Locata networks "locked to GPS time" and distributing that *external* time base, and (b) Locata's *internal* synchronization (i.e. Locata's own inherent network time transfer capability, independent of GPS time). These tests covered transmission distances up to 73km, but much longer distances are certainly possible. The UNSW Conference Paper is attached for a reader that wants to learn more.
- **The real world high-level overview results** are:
    - (a) Locata locked to *external* GPS time, across a 73km transmission distance:
        - Synchronization: ±2.5 nanoseconds (billionths of a second)
        - Frequency stability: 1ppb
    - (b) Locata *internal* relative time transfer, across a 56km transmission distance:
        - Synchronization: ±2.5 nanoseconds (billionths of a second)
        - Frequency stability: 0.07ppb

CONCLUSION

- This performance speaks for itself. Locata is now *clearly* showing the world it has single-handedly invented essential new technologies which will revolutionize many components of PNT in the future. As our partners begin to roll out new devices based on Locata inventions, they will forever change what is possible with positioning technology.

Time Transfer Performance of Locata – Initial Results

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BIOGRAPHIES

Joseph Gauthier is a Graduate Research Student in the School of Electrical Engineering & Telecommunications, at UNSW (the University of New South Wales), Sydney, Australia. He received a BSc in Aerospace Engineering (with High Honors) from the University of Texas at Austin in 2011. While an undergraduate student in Austin, he worked for two-and-a-half years at the Applied Research Laboratories in the Space & Geophysics Laboratory, primarily on the GPS Toolkit (GPSTk). His current research interest is precise timing with GPS.

Dr. Eamonn Glennon is a Senior Research Associate at the School of Civil & Environmental Engineering, UNSW. He received a BSc in Computer Science in 1988, a BE (Hons) in Electrical Engineering in 1990, a MEngSc in Electrical Engineering in 2000, and a PhD in GPS signal processing in 2010, all from UNSW. Before joining UNSW in 2010 he was a Principal Engineer (Algorithms) at SigNav Pty Ltd, where he worked for 15 years on GPS embedded firmware and algorithm development. He also worked at Auspace for 3 years as a Software Systems Engineer.

Chris Rizos is Professor of Geodesy and Navigation, School of Civil & Environmental Engineering, UNSW. Chris is president of the International Association of Geodesy (IAG), a member of the Executive and Governing Board of the International GNSS Service (IGS), and co-chair of the Multi-GNSS Asia Steering Committee. Chris is a Fellow of the IAG, a Fellow of the Australian Institute of Navigation, a Fellow of the U.S. Institute of Navigation, and an honorary professor of Wuhan University, China. Chris has been researching the technology and applications of GPS since 1985, and is an author/co-author of over 600 journal and conference papers.

Professor Andrew Dempster is Director of the Australian Centre for Space Engineering Research (ACSER) at UNSW. Andrew has a BE (Hons) and MEngSc from UNSW, and a PhD from University of Cambridge in efficient circuits for signal processing arithmetic. His current research interests are in satellite navigation receiver design and signal processing - areas where he has six patents - and new location technologies.

ABSTRACT

Accurate and precise frequency references and timekeeping systems are required for a wide range of applications, such as stock market trading, power generation and distribution, and telecommunications. Over the years, the Global Positioning System (GPS) has become the “go-to” solution for time transfer.

This paper details the initial time transfer capabilities of Locata, a localized GPS-like technology. In order to investigate this capability, two time transfer experiments were conducted using two configurations of LocataNets. A LocataNet consists of a single master LocataLite transceiver and one or more slave LocataLites. The process by which the slaves are synchronized to the master (or other slaves) is known as TimeLoc.

The first experiment, demonstrating external time transfer, consisted of a master and two slave LocataLites. Each LocataLite was located at an independent site. The master was synchronized to GPS Time (GPST) via the pulse per second (PPS) signal output by a co-located GPS receiver. The first slave was TimeLoc’d to the master with a site separation of 45km. The second slave was TimeLoc’d to the first slave with a site separation of 28km, providing a total time transfer distance of 73km. The time difference between the PPS signals output by the second slave and an independent, but co-located GPS receiver was measured. The mean and standard deviation of the time difference were both on the order of a few nanoseconds. The frequency difference, as derived from the time difference, had a standard deviation of approximately 1 part per billion (ppb).

The second experiment, demonstrating internal time transfer, also consisted of a master and two slave

LocataLites, albeit in a different configuration. The first slave was TimeLoc'd to the master with a site separation of 28km and the second slave was adjacent to the master, though TimeLoc'd to the first slave 28km away, providing a total time transfer distance of 56km. The time difference between the PPS signals output by the master and the adjacent second slave was measured. The mean and standard deviation of the time difference were on the order of a few nanoseconds and a couple of hundred picoseconds, respectively. The frequency difference, as derived from the time difference, had a standard deviation of less than 0.1ppb.

The purpose of the external and internal synchronization experiments was to demonstrate the absolute and relative time transfer performance of Locata, respectively.

INTRODUCTION

Our reliance on GPS for time transfer is staggering. 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" [1]. As such, our understanding of its vulnerabilities must be enhanced and alternative or backup time transfer systems must be developed.

Technologies such as chip scale atomic clocks (CSAC), precision time protocol (PTP), and enhanced long range radio navigation (eLORAN) are proposed or operational today, with each working towards serving different markets. Obviously, synchronization requirements are dependent upon the application and technology. Furthermore, within each application, the requirements and results are dependent upon the technology used. For example, in the case of telecommunications, the most stringent time and frequency requirements specified by the IEEE at this time are ±0.5 to ±1.5µs and 16-50ppb, respectively [2].

Although Locata has traditionally focused on the navigation portion (position and velocity) of the position-velocity-time (PVT) solution, given that the LocataLites are synchronized via TimeLoc, time transfer is a natural extension of the technology. This paper represents the first experiments conducted for time transfer using Locata, and the results are promising. The external synchronization experiment had a time difference with a mean and standard deviation of -5ns and 4.2ns, respectively. The frequency difference, as derived from the time difference, had a standard deviation of 1.03ppb. The internal synchronization results were much better, with a mean and standard deviation of 5.9ns and 300 picoseconds, respectively. The frequency difference, as derived from the time difference, had a standard deviation of 0.07ppb. This level of performance far surpasses even the most stringent requirements for technologies in the telecommunications area at this time.

TIMELOC

The purpose of TimeLoc is to synchronize one LocataLite to another. In the case of absolute time transfer (both external and internal synchronization), the master LocataLite must be synchronized to GPST. When this is done the PPS signals output by the master and its slaves are aligned with the one second boundary of GPST. In the case of relative time transfer (internal synchronization only), this is not required and so there is no guarantee that the PPS signals output by the master and its slaves are aligned with the one second boundary of GPST. The results of the absolute time transfer experiment demonstrate the combination of the external and internal synchronization performance. Similarly, the results of the relative time transfer experiment demonstrate the internal synchronization performance alone.

A brief overview of the TimeLoc procedure presented in [3] for two LocataLites, B TimeLocing to A, follows:

i. LocataLite A transmits its code and carrier.
ii. LocataLite B transmits its code and carrier.
iii. LocataLite B acquires, tracks, and measures the code and carrier transmitted by LocataLite A and by itself.
iv. LocataLite B computes the code and carrier differences between signals from LocataLites A and B and compensates for the geometric range between the two.
v. LocataLite B adjusts its own transmit signals to minimize the code and carrier differences between itself and LocataLite A.

The difference between the code and carrier transmitted by LocataLite A and generated by LocataLite B is composed of the separation delay, tropospheric delay, and propagation errors. The separation delay is dependent upon the geometric distance between LocataLites A and B. The tropospheric delay is also dependent upon the geometric distance between LocataLites A and B as well as the atmospheric conditions (temperature, pressure, and humidity) along the line-of-sight path between the two. For more details see [3].

EXPERIMENTAL DESIGN

Two time transfer experiments were conducted over the course of two days using two configurations of LocataNets.

The locations of the three sites used are shown in Figure 1.

Figure 1. Locations of the three sites used. For the sake of orientation, the capital city of Australia, Canberra, is shown. It is located approximately 100km to the north.

The three sites were NTF South, Mount Roberts, and Brothers South. A short description of the site setup follows.

SITE SETUPS

Each site had a variety of equipment, much of which was the same from site to site. All three sites had the following standard equipment: (i) LocataLite and transmit and receive antennas, (ii) meteorological station, (iii) 3G modem and transmit/receive antenna, (iv) solar panels, and (v) deep cycle batteries.

A short description of each site setup follows.

NTF SOUTH

The Numeralla Test Facility (NTF) South site served as our base of operations for both experiments and is shown in Figures 2 and 3:

Figure 2. NTF South site—overlooking the rest of the NTF.

Figure 3. NTF South site—in the direction of the Mount Roberts site.

As shown in Figures 2 and 3, the NTF site has three dishes that were used for the experiments, all of which were pointed towards Mount Roberts. The middle and bottom dishes (transmit and receive) were used during both experiments. For the external and internal synchronization experiments, they were the antennas for the second slave and master, respectively. The top dish (receive) was only used by the second slave for the internal synchronization experiment. The second slave transmit antenna was a patch antenna mounted just above the top dish. All other visible antennas were preexisting and were not used. The temperature and relative humidity sensors of the NTF South met station are also shown in Figure 2. The GPS antenna used in the external synchronization experiment is not shown.

MOUNT ROBERTS

The Mount Roberts site is shown in Figure 4.

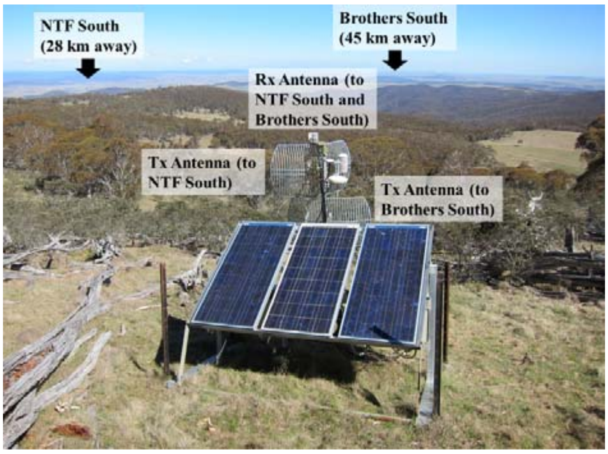

Figure 4. Mount Roberts site—in the direction of the NTF South and Brothers South sites.

The Mount Roberts site has three antennas. The top and bottom transmit dishes are pointed towards NTF South and Brothers South, respectively. The receive patch antenna mounted above the top transmit dish is pointed between NTF South and Brothers South.

BROTHERS SOUTH

The Brothers South site is shown in Figure 5.

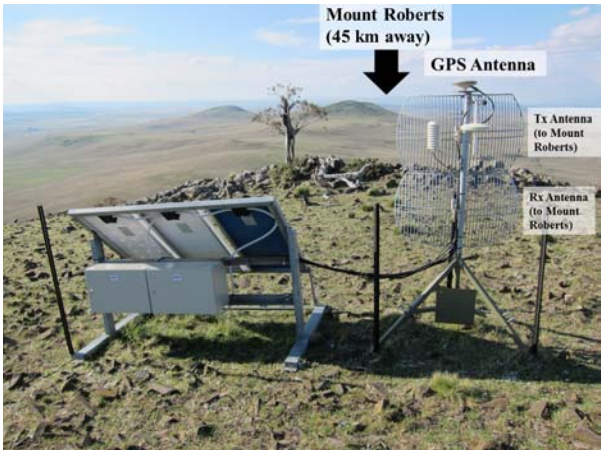

Figure 5. Brothers South site—in the direction of the Mount Roberts Site.

The Brothers South site has two antennas. Both antennas are pointed towards Mount Roberts.

EXPERIMENTAL SETUPS

EXTERNAL SYNCHRONIZATION

The setup for the external synchronization experiment is shown in Figure 6.

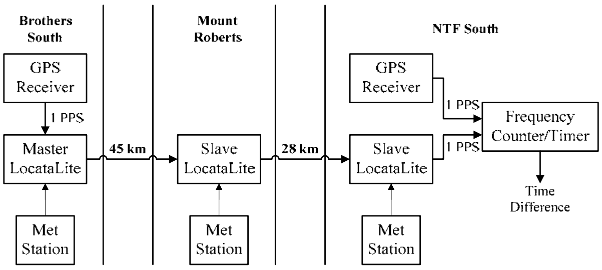

Figure 6. Setup for external synchronization experiment.

As shown in Figure 6, the LocataNet for the external synchronization experiment consisted of a master and two slaves, with each LocataLite located at an independent site. The master (at Brothers South) was synchronized to GPST via the PPS signal output by a co-located GPS receiver. The first slave (at Mount Roberts) was 45km away from the master and the second slave (at NTF South) was 28km away from the first slave. The first and second slaves were TimeLoc'd to the master and first slave, respectively. Additionally, an independent met station was located at each site. The time difference between the PPS signals output by the second slave and an independent, but co-located GPS receiver was measured at NTF South. The total range over which time transfer was performed was 73km.

INTERNAL SYNCHRONIZATION

The setup for the internal synchronization experiment is shown in Figure 7.

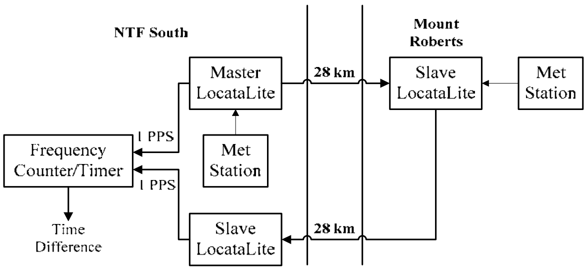

Figure 7. Setup for internal synchronization experiment.

As shown in Figure 7, the LocataNet for the internal synchronization experiment consisted of a master and two slaves. The first slave (at Mount Roberts) was 28km away from the master (at NTF South) and the second slave was adjacent to the master, though TimeLoc'd to the first slave. Additionally, an independent met station was located at each site. The time difference between the PPS signals output by the master and the adjacent slave was measured at NTF South. The total range over which time transfer was performed was 56km.

MEASUREMENT SETUPS

TIME DIFFERENCE

In order to determine the initial time transfer performance of Locata, the time difference between two PPS signals was measured. A two-channel time difference is shown in Figure 8.

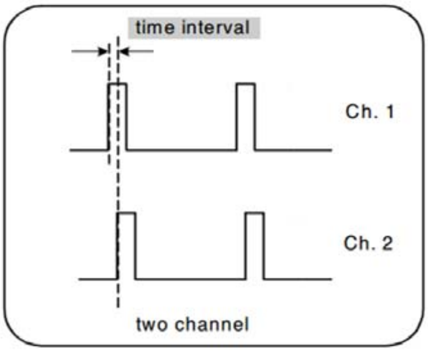

Figure 8. Two-channel time difference.

For the external synchronization experiment, channels one and two were the GPS receiver and slave LocataLite at NTF South, respectively. For the internal synchronization experiment, channels one and two were the master and adjacent slave LocataLites at NTF South, respectively.

As shown in Figure 8, a time difference is a measurement of the time interval between a start condition and a later stop condition. The start and stop conditions correspond to the left-hand and right-hand dashed lines, respectively. Although the signals on channels one and two resemble rectangular functions, they are not. The unit rectangular function is defined as:

$$rect(t) = \Pi(t) = \begin{cases} 0 \ if \ |t| > \frac{1}{2} \\ \frac{1}{2} \ if \ |t| = \frac{1}{2} \\ 1 \ if \ |t| < \frac{1}{2} \end{cases} \qquad 1$$

where t is time. Equation 1 implies an infinitesimal change in time results in a finite change in the value of the function at $t = 1/2$. However, a finite amount of time is required for the signals in channels one and two to change by a finite amount. Thus, the start and stop channel level settings should be selected carefully based upon knowledge of the PPS signals output by the master, slave, or GPS receiver.

The measurement fidelity of the frequency counter/timer was estimated by measuring the time difference between the same PPS signal on two different channels. The PPS signal on one of the channels was delayed slightly by using a slightly longer cable. The measurement fidelity was approximately 50ps. The additional noise in the time difference for the internal synchronization experiment in the results is attributable to variations in the rise times of the PPS signals. Such variations were measured using the frequency counter/timer.

RESULTS

EXTERNAL SYNCHRONIZATION

The external synchronization performance of Locata is shown in Figures 9 and 10.

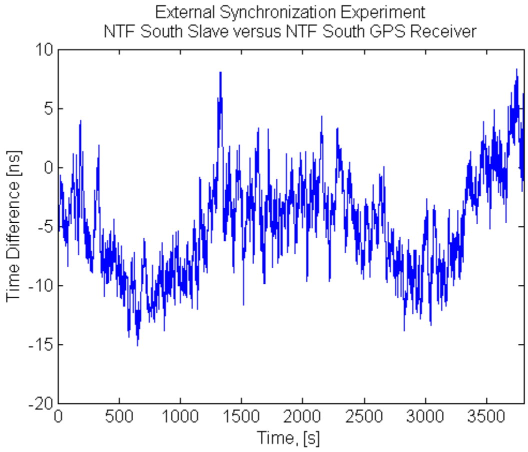

Figure 9. External synchronization performance of Locata—NTF South slave versus co-located GPS receiver.

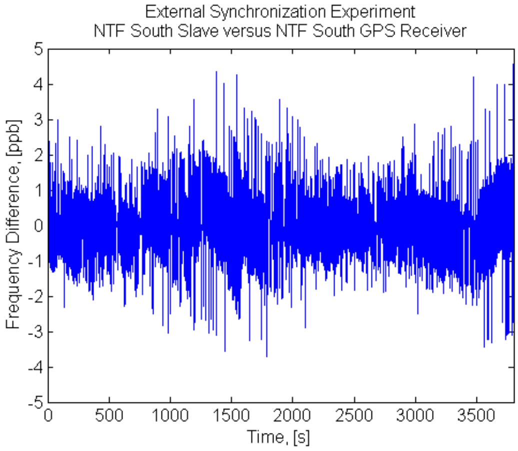

Figure 10. External synchronization performance of Locata—NTF South slave versus co-located GPS receiver.

As shown in Figures 9 and 10, the external synchronization performance of Locata was on the order of a few nanoseconds, with a mean and standard deviation of -5ns and 4.2ns, respectively. The frequency difference, as derived from the time difference, had a standard deviation of approximately 1.03ppb. Most of the error in the time difference may be attributed to two sources: (1) imperfect synchronization to the PPS signal output by the GPS receiver on the part of the master LocataLite, and (2) imperfect synchronization of the PPS signals output by the GPS receivers at Brothers South and NTF South.

INTERNAL SYNCHRONIZATION

As mentioned previously, the external synchronization performance of Locata was limited by its imperfect synchronization to GPS as well as the imperfect synchronization of the two GPS receivers. The master LocataLite at Brothers South was synchronized to the

GPS receiver at Brothers South, but the PPS signal output by the slave LocataLite at NTF South was compared with the PPS signal output by the GPS receiver at NTF South. To demonstrate the actual internal synchronization performance of Locata, a second experiment was conducted where the aforementioned problems would no longer be a factor because no GPS receivers were used. For this experiment, the time difference between the PPS signals output by the master and the adjacent second slave LocataLite was measured, after a 56km transmission distance, as shown in Figures 11 and 12.

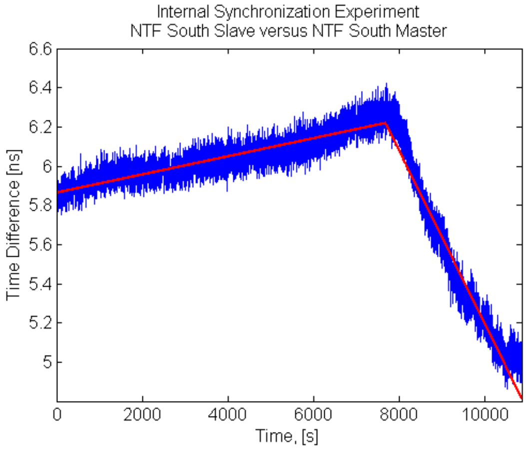

Figure 11. Internal synchronization performance of Locata—NTF South slave versus NTF South master.

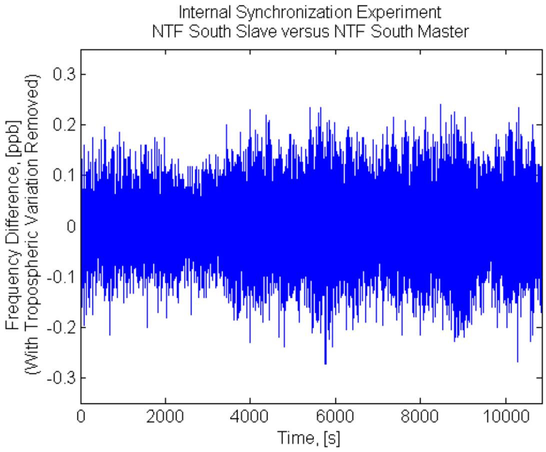

Figure 12. Internal synchronization performance of Locata—NTF South slave versus NTF South master.

As shown in Figures 11 and 12, the internal synchronization performance of Locata was much improved over the external synchronization performance. The mean and standard deviation of the time difference are 5.9ns and 300 picoseconds, respectively. The frequency difference, as derived from the time difference, had a standard deviation of approximately 0.07ppb.

The biases observed in both experiments of approximately 5ns, as shown in Figures 9 and 11, are attributable to multipath, antenna coupling errors, PPS quantization error, and residual tropospheric delay.

One feature of Figure 11 that is not evident in Figure 9 is the noticeable drift of approximately 1.5ns over the course of the experiment. This drift was attributed to the uncorrected tropospheric delay and was clearly correlated with the meteorological data recorded on the day. The improvement in the synchronization performance was to such a point that even minor variations in the tropospheric delay were observable. Such variations in the tropospheric delay are due to the continuously changing meteorological conditions. The temperature, pressure, and relative humidity at NTF South and Mount Roberts are shown in Figures 13-15.

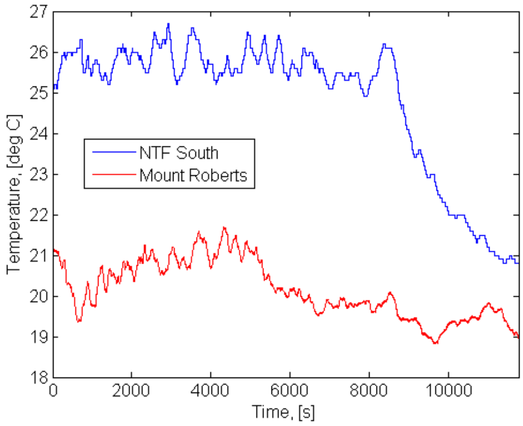

Figure 13. Temperature—NTF South and Mount Roberts.

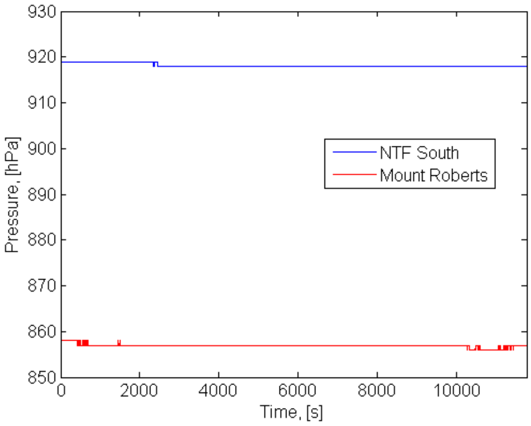

Figure 14. Pressure—NTF South and Mount Roberts.

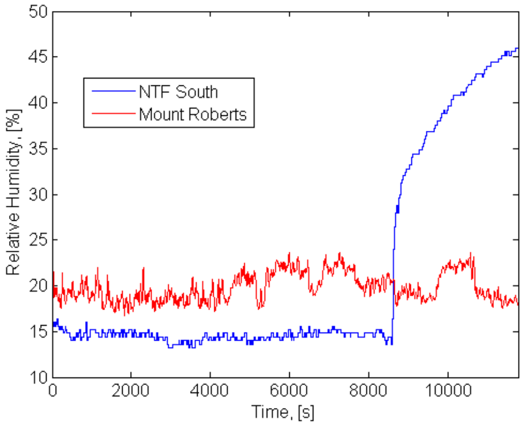

Figure 15. Relative humidity—NTF South and Mount Roberts.

At the beginning of the internal synchronization experiment, a tropospheric delay of 14.444m was calculated (and applied) for the roundtrip from NTF South to Mount Roberts and back. Although this static value accounted for the vast majority of the tropospheric delay, it did not capture the smaller, dynamic variations of the tropospheric changes.

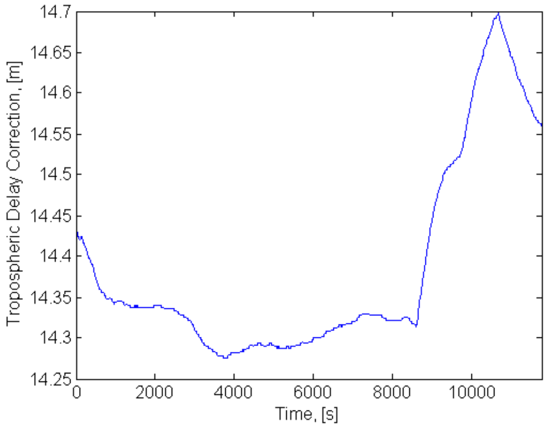

Figure 16. Tropospheric delay—NTF South to Mount Roberts and back.

As shown in Figures 13 and 15, the temperature dropped and the relative humidity rose at NTF South near the end of the experiment. These changes occurred approximately two hours prior to sunset. The tropospheric delay was calculated after the fact using the temperature, pressure, and relative humidity for each site, as measured by its met station, and is shown in Figure 16.

The rise in the tropospheric delay in Figure 16 coincides with the drop in temperature and rise in relative humidity in Figures 13 and 15, respectively. The integrated carrier phase residual for both the static correction (14.444m) and when the calculated dynamic correction is applied, is shown in Figure 17.

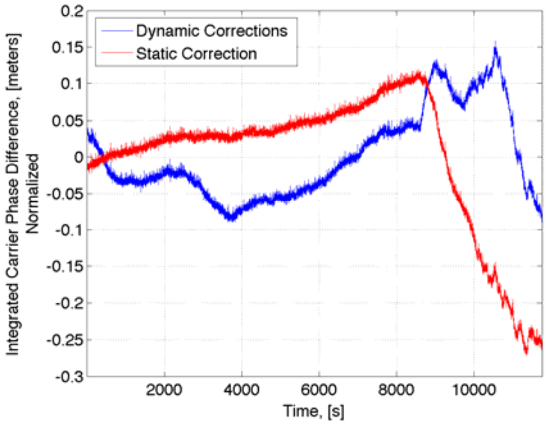

Figure 17. Integrated carrier phase difference with dynamic and static corrections for tropospheric delay—NTF South slave versus NTF South Master.

As shown in Figure 17, the application of dynamic corrections for the tropospheric delay would reduce the tropospheric variation from approximately 35cm to approximately 23cm, and subsequently improve the Locata time transfer variation from approximately 1.2 ns picoseconds to approximately 770 picoseconds.

The variations in the tropospheric delay are clearly visible in both Figures 11 and 17. One distinction between the time difference and integrated carrier phase difference is that there is much more noise in the former (approximately 200ps peak-to-peak) than in the latter (approximately 70ps peak-to-peak). The additional noise in the time difference measurements was primarily due to imperfections in the PPS signal output by the LocataLite, and secondarily due to the measurement fidelity of the frequency counter/timer. Variations in the rise time of the PPS signal output by the LocataLite were observed with the frequency counter/timer.

CONCLUSIONS

In this paper, the time transfer performance of Locata was for the first time examined. Two time transfer experiments were conducted using two configurations of LocataNets. The first experiment investigated the external time transfer performance of Locata. For this experiment, the LocataNet consisted of a master and two slave LocataLites, all located at different sites. The master LocataLite was synchronized to GPST via the PPS signal output by an independent, but co-located GPS receiver. The first slave was TimeLoc'd to the master, with a site separation of 45km. The second slave was TimeLoc'd to the first slave, with a site separation of 28km. The time difference between the PPS signals output by the second slave and another independent, but co-located GPS receiver was measured. Time transfer was performed over a range of 73km, with the mean and standard deviation of the time difference equal to -5ns and 4.2ns, respectively. The frequency difference, as derived from the time difference, had a standard deviation of approximately 1.03ppb.

The second experiment investigated the internal time transfer performance of Locata, removing the need for the GPS PPS signals. For this experiment, the LocataNet consisted of a master and two slave LocataLites, albeit in a different configuration. The first slave was TimeLoc'd to the master, with a site separation of 28km. The second slave was adjacent to the master, though TimeLoc'd to the first slave. The time difference between the PPS signals output by the master and second slave was measured. Time transfer was performed over a range of 56km, with the mean and standard deviation of the time difference equal to 5.9ns and 300 picoseconds, respectively. The frequency difference, as derived from the time difference, had a standard deviation of approximately 0.07ppb.

The long ranges over which time transfer was performed necessitated knowledge about the troposphere at each site. Indeed, the static correction for the tropospheric delay applied at the beginning of both experiments was large (>10m). Although this static correction accounted for the vast majority of the tropospheric delay, minor variations remained due to the changing meteorological conditions. The variation in the tropospheric delay became clearly evident from the results of the internal synchronization experiment and shows that, if time transfer is to approach the picosecond level, dynamic corrections for the tropospheric delay must be used.

ACKNOWLEDGMENTS

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