Advantages of a Combined GPS/Loran-C Precision Timing Receiver

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I. ABSTRACT

In Europe, Asia, and other areas, there is reluctance to depend on GPS as the primary timing reference source (PRS) for a critical part of a nation's infrastructure, hence an alternative PRS, such as Loran, is highly desirable. Essential requirements for that alternative would be the ability to provide timing performance similar to that of GPS and to distribute coordinated universal time (UTC).

Advances in Loran receiver technology, coupled with newer NELS and FERNS chains and planned upgrades to the North American stations, has made Loran as high a quality primary timing reference as GPS, and it can be superior in many circumstances. For example, Loran can provide near Cesium clock quality at the receiver site, can generate UTC, and can penetrate urban environments difficult for GPS reception. When coupled with a rubidium oscillator, GPS receiver, or both, a Loran receiver can be integrated into a system that would provide high timing performance with superior reliability.

Timing data from a new generation Loran receiver will be presented along with predictions of accuracy improvements that will follow implementation of Cesium clock and UTC synchronization updates to the CONUS Loran stations. Timing accuracy of standalone GPS timing will be demonstrated. Finally, performance advantages of integrated Ru/Loran and GPS/Ru/Loran timing systems will be discussed, and implications of encoding UTC in the Eurofix data stream will be reviewed..

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INTRODUCTION

A. Background

Accurate time dissemination plays a critical role in the availability and quality of critical infrastructure systems, including telecommunications networks, Internet and other computer networks, and power distribution networks. GPS has become the primary reference source (PRS) for transferring precise time and time intervals (PTTI).

However, GPS has some disadvantages in these applications. For example, GPS is subject to unintentional man-made (e.g. television transmitter) and natural (e.g. solar) interference; it is subject to intentional interference (i.e. jamming); its performance is degraded by selective availability; and it requires line-of-sight access to satellites, which can be difficult to achieve in urban and other environments.

In addition, there is growing international demand for timing references that can operate independently of the USA controlled GPS system. There is increasing worldwide awareness that critical infrastructures depending on accurate timing should not be vulnerable to a GPS disruption, whatever the cause of disruption.

Europe is an excellent example of international concerns with dependency on a sole means system, particularly when the system is controlled by a single state for civil and military use. Today these concerns have led the European Union to develop a policy supporting a mix of terrestrial and satellite systems and have generated much interest in the Galileo system.

Within this context, Loran provides an excellent means to complement GPS and other satellite systems in timing as well as navigation applications and eliminates many of the above concerns. Loran is a high-power, low frequency signal that is much easier to receive in areas that are problematic for GPS and is not subject to the same types of interference. Loran chains provide coverage over most of the Northern Hemisphere and are independently controlled by various governments and multinational organizations. Moreover, Loran can offer long-term timing performance comparable to GPS and function as an autonomous PRS. Finally, a combined GPS/Loran device can offer complete system redundancy in all timing applications, similar to the way it complements satellite systems for navigation.

B. Network Timing & Synchronization Requirements

In the US, most networks use GPS as the PRS and incorporate a backup. Commonly, quartz or rubidium oscillators provide short-term holdover in the event that GPS is unavailable, and Loran provides long-term backup capabilities. As new network services are offered, such as locating mobile handsets and third-generation mobile radio systems, time and frequency reference requirements will become more demanding. With these new demands, quartz oscillators will not meet performance standards and rubidium oscillators will provide limited holdover capability of approximately one to seven days. In comparison, Loran can provide the necessary performance indefinitely.

As an example of the increasing need for better timing performance, requirements for higher data rate services (144 Kb/s for ISDN 2B+D to 2 Mb/s for ISDN H0) and better spectrum efficiency have led to development of third-generation mobile radio systems. The evolution to higher data rates and on-going support of soft handover continues to tighten the base station timing requirements.

III. TIME SYNCHRONIZATION

Synchronization is the level of precision, measured against some reference, of a specific timing (phase and frequency) relationship between the clocks at two different nodes of a network. In order to synchronize a network, phase-locked loops are typically used, and they are locked to a reference or master clock.

A number of commercially available timing systems are able to transfer PTTI with various degrees of accuracy, stability and precision including quartz and rubidium oscillators, off-air frequency standards (e.g. WWVB in the US, and BBC Radio 4 in the UK), GPS, Loran, Cesium Beam clocks, and active and passive hydrogen masers.

Newer time transfer standards include CDMA based timing references. These CDMA timing receivers, while solving the problem of in-building reception of highly accurate timing signals, do not provide long-term redundancy to GPS unless the CDMA base stations transmitting the signals utilize alternative external transfer standards, such as Loran or GLONASS timing receivers.

A. GPS

GPS satellites are equipped with two onboard atomic clocks (Rubidium or Cesium) that are maintained by ground monitoring and control systems. The US Department of Defense intentionally degrades the accuracy of the GPS signal used by civilians (Standard Positioning Service, or SPS) by either modifying the apparent position of each satellite and/or introducing random dither into each satellite's clock, a process called selective availability (SA). SPS provides time transfer accuracy to UTC within 340 ns at 95% confidence interval (1994 Federal Radionavigation Plan - FRP).

With the correction given in the navigation message, GPS is typically within 15 nanoseconds (ns) root mean square (rms) of UTC (USNO) with SA removed. With SA, the rms error has been about 70 ns.

B. Loran

In contrast to the relatively weak GPS signal, radiated power from Loran transmitters varies from about 200 kW to over 1 MW. Loran transmitters have Cesium Beam Frequency Standards that are synchronized to UTC, and the masters are within approximately ± 100 ns of UTC in the US.[5] The US Naval Observatory (USNO) publishes a Daily Time Difference (Series 4) of UTC (USNO,MC) and the master transmitting station for each of the nine North American Loran chains.

The method and the accuracy used to synchronize a Loran system to UTC is under the control of the country(s) operating the system. However, it should be noted that UTC can be derived from Loran signals by the receiver, so it can also provide this important time reference, just as GPS or other satellite system receivers do. In other words, Loran can offer UTC redundancy as well as timing performance in these applications. Quartz or Rubidium oscillators do not have this capability.

Note it is also possible to provide UTC by a more direct method, for example by sending UTC referenced to part of the Loran pulse and a correction factor for clock errors at the master station. This capability can be incorporated into the Eurofix message, and the Radio Technical Committee for Maritime Services (RTCM) Special Committee (SC-104), which defines differential GPS messages, has established a working group to define the Eurofix message.

The USCG is now in the process of modernizing the US Loran system. The improvements include new cesium clocks, replacement of monitoring receivers, and implementation of Time of Transmission Monitors (TTM). TTMs will monitor the time difference between a Loran master station's transmitted signal and UTC.

As a result of the modernization process, short-term stability of the Loran transmissions will improve and adjustments to UTC will be smaller in the US. Long-term stability of the system will also be improved. Coupled with advanced Loran timing receivers, the performance of Loran time transfer will be comparable, or better, than that of GPS.

IV. LORAN TIMING RECEIVER PERFORMANCE

To demonstrate that Loran is suitable as a long-term complement to GPS in timing applications, two Locus Loran receiver models were tested simultaneously with a high-quality GPS timing receiver at our location in Madison, Wisconsin. Each test ran continually for 24 hours to insure that any diurnal effects were captured. All results presented here use the full 24 hours of data for each set.

Both of the Loran receivers were phase-locked to the 8970M station, which is approximately 400 km away. The GPS receiver was configured to select its own set of satellites to monitor. The GPS receiver was allowed to average its position data for at least 24 hours before each test.

The test fixture used is shown in **Figure 1**. Data were collected by measuring the phase differences between the 1 pulse-per-second (PPS) signals from each receiver and a 1 PPS signal generated from a Cesium reference standard.

Test fixture components:
Fluke PM6681 Timer/Analyzer. Each PM6681 Timer/Analyzer was configured to measure the time elapsed between the rising edge of input A and the rising edge of input B. The PM6681 can resolve this measurement to 50ps. The 5 MHz output of the Cs Reference was used to discipline the internal oscillator of each PM6681.

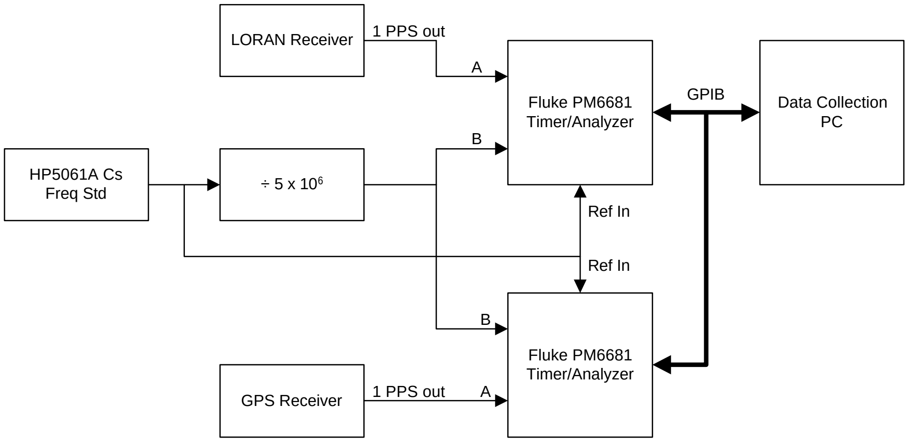


Figure 1: Timing Performance Test Fixture

HP5061A Cs Frequency Standard and Divider. The cesium frequency standard was used as a source to generate a reference 1-PPS signal with the divider, as well as a reference clock to the PM6681 analyzers.

Data Collection PC. Specially developed software was used to collect data via the GPIB bus from the PM6681 analyzers. It was important to be certain that the software did not miss any data, so each data point was time-stamped and then checked after each collection run.

Loran Receivers. Both a Locus LRS II and a Locus LRS III receiver were tested. The Locus LRS III receiver has an optional high performance clock installed. The LRS II has the standard clock.

GPS Disciplined Clock (Receiver). A high quality GPS disciplined clock was used for comparison. This was an advanced, eight-channel device specifically designed for timing applications and included an integrated precision oscillator.

Data and Results

Time Interval Error

The ANSI standard T1.101-1994[1] defines *time delay* (denoted x_i) as "the measured time difference between the significant instants (e.g., zero level crossings) of the timing signal waveform under test and those of a reference signal."

T1.101 also defines *time interval error* (TIE) as "the variation in time delay of a given timing signal with respect to an ideal timing signal over a particular time period."

So, by T1.101, $TIE_i(t) = x_{(i+t)} - x_i$ (where τ is the *observation interval* (units of seconds))

The measurements that were collected are then time delay measurements, or x_i. Since the absolute phase of the divider 1 PPS signal is arbitrary with respect to the absolute phase of the 1 PPS signals from each of the receivers, there is an arbitrary constant in our time delay measurements. However, for the TIE calculations, this constant is removed by the subtraction.

First, histograms of TIE (τ) for τ=1 second, τ=100 seconds, and τ=10000 seconds are presented for the Locus Loran receivers and the GPS receiver in **Figure 2**.

At τ=1s, (**Figure 2A**), the GPS histogram is slightly tighter than the LRSII, and the LRS III is tighter than the GPS (**Figure 2B**). At one-second intervals this result is expected, because the measurement is primarily dependent on the oscillators in all receivers, and the receivers are not fast enough to discipline their oscillators that quickly.

At τ=100s, the LRS II performs better than the GPS (**Figure 2C**), and the LRS III is much better than GPS (**Figure 2D**). At 100 seconds, the receivers are disciplining their respective oscillators with the signals that they are receiving. However, the GPS receiver is starting to see the effects of SA, which degrades its performance.

At τ=10000s, (**Figures 2E** and **2F**), the Loran receivers are still outperforming the GPS receiver. Certainly some of the difference in performance is due to the effects of SA, but as of the moment, we are unable to quantify that difference. Note the LRS II also approaches the performance of the LRS III as the differences between the oscillators become less important.

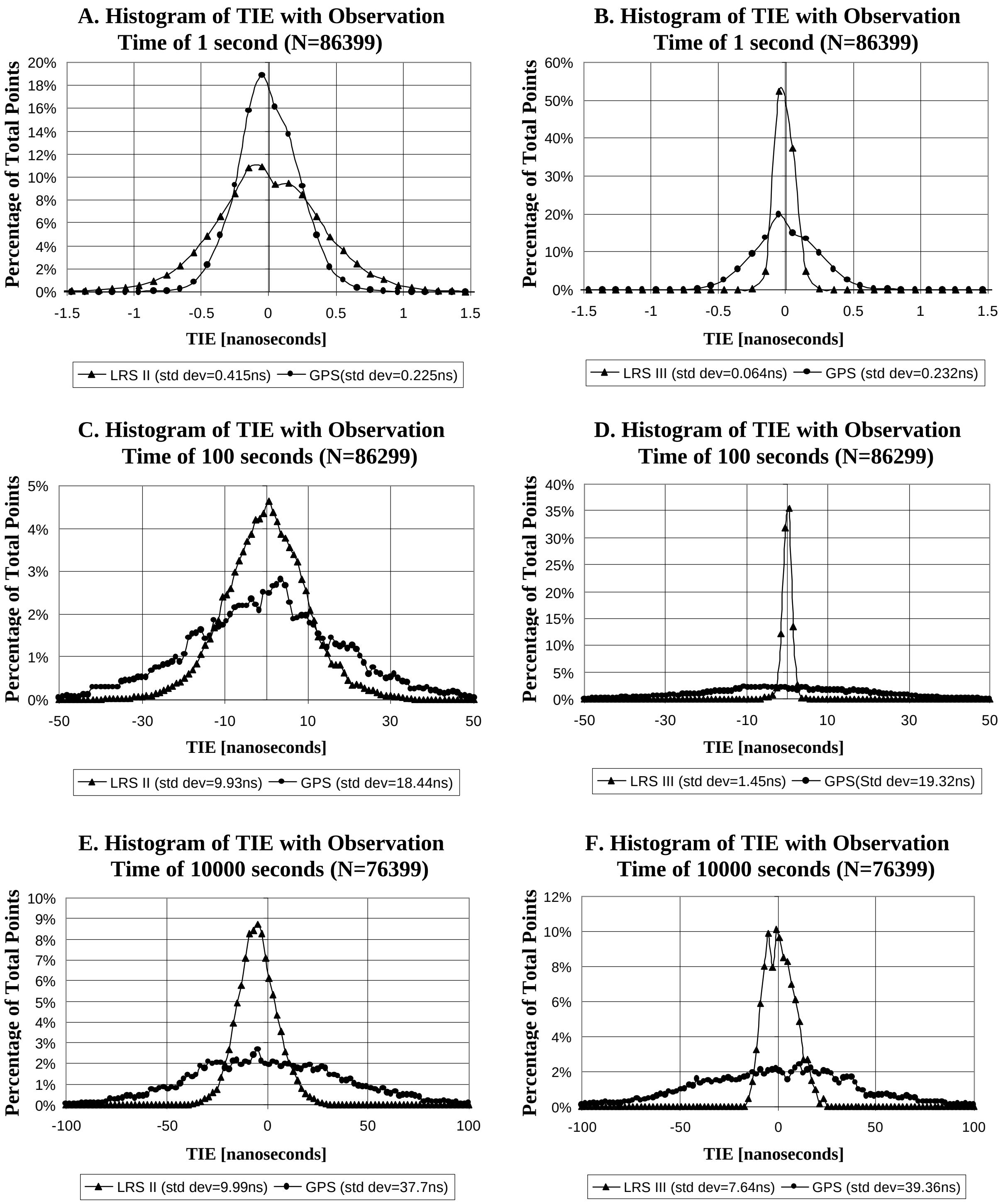


Figure 2. Time Interval Error Histograms at Observation Intervals of 1, 100 & 10,000 seconds.

One of the important performance specifications in the precision timing industry is the level of confidence one has in TIE measurements. In **Figure 3**, a plot is shown of the 99% confidence intervals for different time intervals.

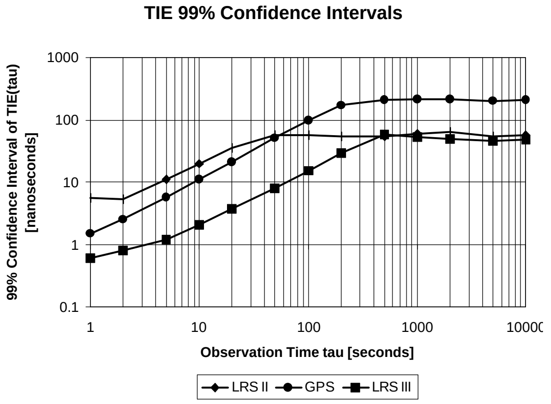


Figure 3. Time Interval Errors at 99% CI

As implied by the histogram and TIE plots, the GPS receiver is slightly better than the LRS II at values of $\tau < 50$ seconds. At $\tau=50$ seconds, however, the LRS II starts to outperform the GPS receiver as SA starts to become a more important factor in the performance of the GPS receiver. The LRS III, with its extra-high quality oscillator, is the best performer up to 500 seconds. Here the LRS II starts to slightly outperform the LRS III. This is due to the fact that the LRS III is optimized for shorter holdover situations and not for long-term wander performance. Note holdover is defined as how long the oscillator can maintain specified timing without any discipline.

Time Deviation

TVAR is defined [1,2] as:

$$s_x^2(t) = TVAR(t) = \frac{\sum_{j=1}^{N-3n+1}\left[\sum_{k=0}^{n-1}(x_{j+2n+k} - 2x_{j+n+k} + x_{j+k})\right]^2}{6n^2(N-3n+1)}$$

TDEV is defined[1] as:

$$s_x(t) = TDEV(t) = \sqrt{TVAR(t)}$$

TDEV is an indication of the spectral content of the phase noise of the signal under test. The TDEV is presented for the three receivers tested in **Figure 4**.

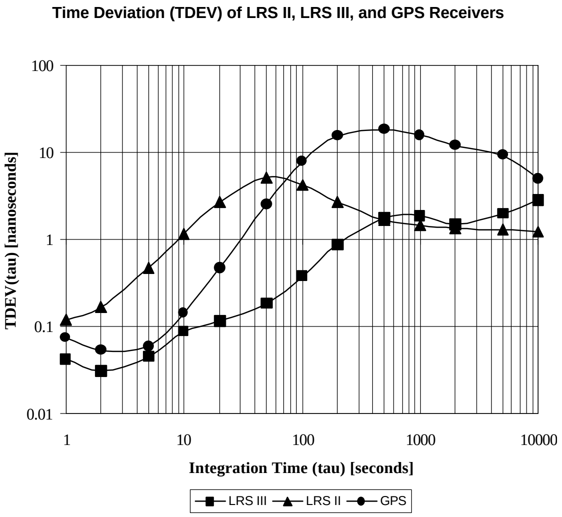


Figure 4. TDEV of Loran and GPS Receivers

The results verify the above discussion. At integration times less than 50 seconds, the oscillators primarily determine the deviation for all of the receivers, but at greater than 50 second integration times, the receivers start to discipline their respective internal oscillators. The TDEV for the LRS II, since it has the most to gain from the clock discipline, starts to decrease until the integration time reaches approximately 500 seconds, where it flattens out. The LRS III again performs the best until the LRS II overtakes it at 500 seconds of integration time, after which they are comparable.

V. INTEGRATED GPS / LORAN SYSTEMS

Modular and flexible systems that include multiple external time transfer sensors and local oscillators can provide a high degree of redundancy to ensure reliability and accuracy of the overall system. Due to their complementary natures, a combined Loran/GPS timing receiver can provide a more reliable timing source than GPS alone. Plus, if one signal is degraded or unavailable, a combined receiver should still operate within overall system requirements.

An established means to improve time scale generation is ensemble time base generation[3], in which various weighting factors based upon the predicted or measured accuracy and stability of various different time sources are taken into account to provide a disciplined time scale generator. Both Loran and GPS have the long-term stability required to discipline (i.e. steer the frequency and phase into alignment with an external reference source) the ensembled clocks. Utilizing both Loran and GPS as disciplining clocks allows a CPU to monitor the stability of each, and use the most stable disciplining clock or assign weights to be used by the ensembler.

The superior short-term performance of the local oscillator and superior long-term performance of the Loran or GPS signal minimize *jitter* and *wander*, respectively, of the combined, or ensembled, system. (See below for the definitions of these terms.)

VI. SUMMARY / CONCLUSIONS

While GPS is an excellent time transfer standard, it requires a complement to offset some of its shortcomings. The best complement would provide comparable Stratum 1 level (see Definitions) time transfer performance and a UTC reference, offer complete independent redundancy, penetrate areas that GPS cannot, present no common mode susceptibilities, and function under autonomous control. Loran’s modern transmitter infrastructures, inherent performance characteristics, UTC capabilities, and new, high performance receivers make it the best such complement available today.

VII. REFERENCES

[1.] ANSI T1.101-1994, *American National Standard for Telecommunications - Synchronization Interface Standard*

[2.] GR-2830-CORE, Issue 2 Dec 1995

[3.] Zampetti, G.P., "Disciplined time scale generator for primary reference clocks", US Patent 5,666,330.

[4.] U.S. Naval Observatory Time Services Department web site, http://tycho.usno.navy.mil.

[5.] "Specification of the Transmitted Loran-C Signal", USCG, COMDTINST M16562.4A, 1994.

VIII. DEFINITIONS

Atomic Time (with the unit of duration the Systeme International (SI) second): defined as the duration of 9,192,631,770 cycles of radiation corresponding to the transition between two hyperfine levels of the ground state of cesium 133. TAI is the International Atomic Time scale, a statistical timescale based on a large number of atomic clocks.[4]

Coordinated Universal Time (UTC): differs from TAI by an integral number of seconds. UTC is kept within 0.9 seconds of UT1 by the introduction of one-second steps to UTC, the "leap second." To date these steps have always been positive.[4] UTC is typically referenced to the USNO Master Clock, UTC (USNO), or the Bureau International des Poids et Measures (BIPM), UTC (BIPM) or UTC (SU) in Russia. The USNO's 50 atomic clocks contribute ~ 40% of the total weight of the BIPM system (250 cesium clocks in 50 establishments.)

Jitter: short-term variations (phase variations of frequency ≥ 10 Hz) of the significant instants (e.g. zero level crossings) of a digital signal from their ideal positions.[1]

Primary reference source (PRS): timing equipment that provides a timing signal whose long-term accuracy is maintained at $1\text{x}10^{-11}$ or better with verification to *coordinated universal time (UTC)* and whose timing signal is used as the basis of reference for the control of other clocks within a network.[1]

Stratum Levels: defined in T1.101

Specification	**Stratum 1**	**Stratum 2**
Accuracy	$1.0 \text{ x } 10^{-11}$	$1.6 \text{ x } 10^{-8}$
Holdover Stability	N/A	$1 \text{ x } 10^{-10}$ per day

Universal Time (UT): counted from 0 hours at midnight, with unit of duration the mean solar day, defined to be as uniform as possible despite variations in the rotation of the Earth. UT0 is the rotational time of a particular place of observation. It is observed as the diurnal motion of stars or extraterrestrial radio sources. UT1 is computed by correcting UT0 for the effect of polar motion on the longitude of the observing site. It varies from uniformity because of the irregularities in the Earth's rotation.[4]

Wander: long-term (phase variations of frequency ≤ 10 Hz) variations of the significant instants of a digital signal from their ideal positions in time.[1]

Biography

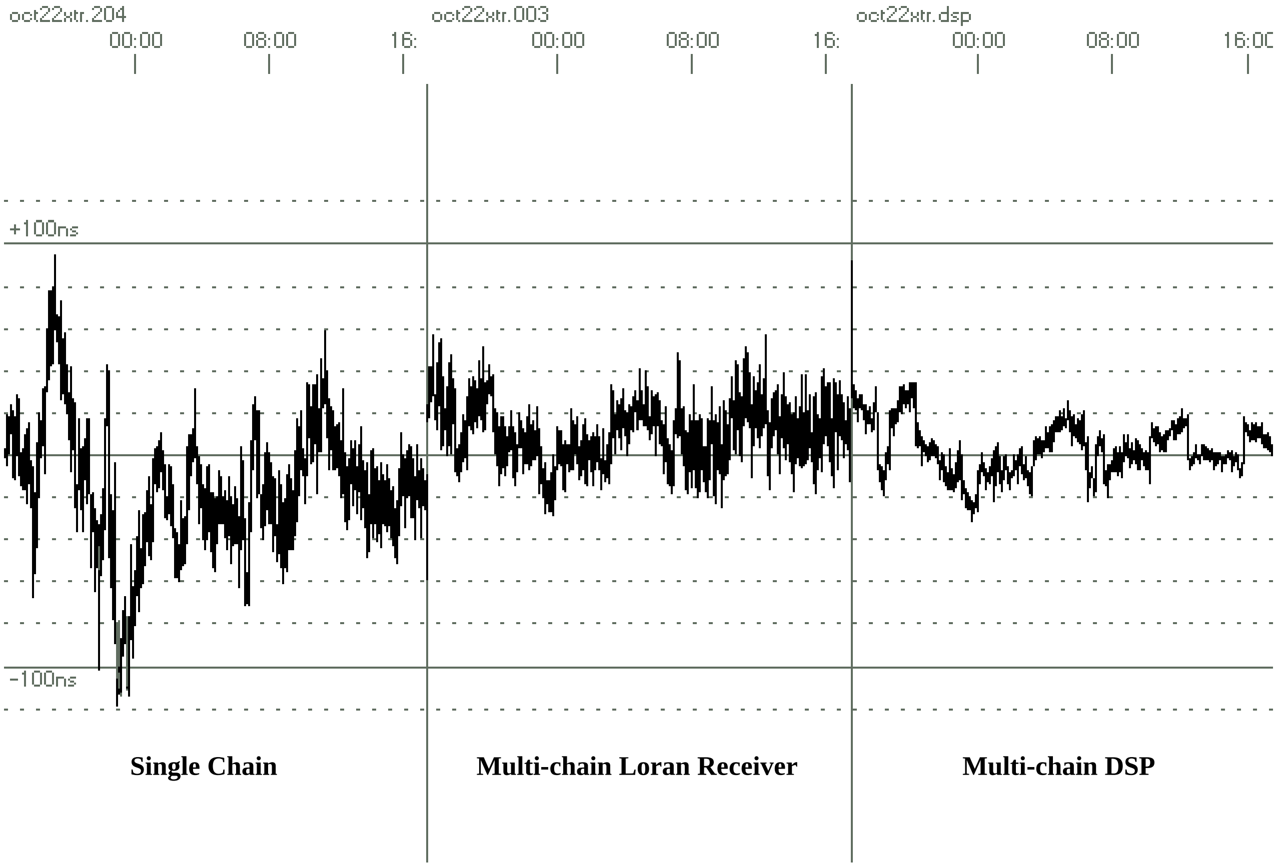
James Jacoby, Project Engineer, Locus, Inc., Madison, Wisconsin.
Mr. Jacoby holds a B.S.E.E. from the University of Wisconsin-Madison. As a project engineer at Locus, he has led the hardware design team for Locus' new DSP-based Loran receiver, as well as other Locus timing and frequency products. Mr. Jacoby is a member of IEEE.

Frank Richwalski, Senior Production Technician, Locus, Inc., Madison, Wisconsin.
Mr. Richwalski's education includes the U.S. Army Signal Corps, Madison Area Technical College, and the Wisconsin School of Electronics. He has over 20 years experience in electronics development and production.

Paul Schick, Senior Project Engineer, Locus, Inc., Madison, Wisconsin.
Mr. Schick is an honors physics graduate of The Cooper Union, New York, and holds a M.S. in physics (E.E. minor) from the University of Wisconsin-Madison. He has led the software development for Locus' linear averaging digital (LAD) Loran and new DSP-based receivers, as well as digital signal processing software for other RF and digital communication systems. Mr. Schick holds several patents.

Kevin Zamzow, Director, Sales & Marketing, Locus, Inc., Madison, Wisconsin.
Mr. Zamzow holds BS Ch.E. and MBA degrees from the University of Wisconsin-Madison. He is responsible for the sales and marketing of Locus' Loran receiver and radio modem product lines. Mr. Zamzow is a member of the International Loran Association (ILA) and the Product Development Management Association (PDMA).

24 Hour Position TDs



Single Chain

Multi-chain Loran Receiver

Multi-chain DSP

Addendum