Enhanced or eLoran for Time and Frequency Applications

G. Linn Roth, Ph.D., Paul Schick, James Jacoby, Chad Schweitzer, Dean Gervasi, and Eric Wiley
Locus, Inc.
Madison, Wisconsin, USA
roth@locusinc.com

Abstract—The US Loran system is undergoing a modernization that will result in an enhanced or eLoran system. As a part of this modernization, three 5071A cesium clocks were installed at each transmitter, and state-of-the-art time and frequency clock measurement and control equipment was installed which uses GPS to steer the ensemble averaged Cs clocks to recover UTC (USNO) within 15 nanoseconds at each transmitter. When the conversion to eLoran is complete, the eLoran system will use time-of-transmission (TOT) control similar to GPS, and add a 9th pulse or Loran data channel (LDC) that will distribute UTC, leap second, and other information from each of the 29 transmitters in North America.

eLoran provides performance comparable to GPS for numerous time and frequency applications, so eLoran can act as a traceable, infinite, and independent backup to GPS in these applications. This paper provides an overview of the eLoran modernization program and new eLoran antenna and receiver technology, and data from recent tests, including preliminary studies of Loran performance using H-field antennas located indoors.

Introduction

There is widespread acknowledgment that it is prudent to provide a backup to GPS and global navigation satellite systems (GNSS) for critical infrastructure time and frequency applications, and a growing recognition that a modern Loran system can provide unique capabilities to fulfill this role for both time and frequency use. In the US, an extensive technical evaluation [1] has confirmed that an enhanced or eLoran system can meet specific criteria for aviation and marine navigation, and provide important benefits to the time and frequency community.

While it has long been known that Loran is a Stratum 1 frequency source, it has recently been demonstrated [2] that eLoran can achieve Stratum 1 performance in less than 30 minutes and better than 2 x 10^{-13} frequency stability in 24 hours. Furthermore, the move toward a modern eLoran system means Loran can also as a UTC source. In other words, the new eLoran system can provide an infinite, traceable, and high performance backup to GPS for both time and frequency applications.

This paper describes the new eLoran system and technology, including practical advantages of eLoran for time and frequency use. The paper also describes recent eLoran frequency tests using outdoor and indoor antenna placements.

The Modernization Toward an eLoran Infrastructure

Over the last several years, the US Congress has appropriated approximately $140 million to modernize the US Loran system, and will approve additional funding for the FY2006 period. To date, these monies have primarily been dedicated to modernizing the Loran infrastructure in the continental US, which is now complete, and the next step is a similar upgrade of the transmitters located in Alaska.

With regard to time and frequency applications, the most important aspects of the eLoran infrastructure modernization are briefly summarized below, and others (see e.g. [3]) have provided more details. These changes are designed to service the great majority of time and frequency users, and the major modernization steps are:

1. Three new 5071A Cs clocks have been installed at each transmitter. Since there are 29 Loran transmitters in North America, these Cs now form the largest distributed primary clock system in the world.
2. The transmitters have been upgraded to solid-state electronics, providing substantially better reliability, and modern time and frequency control equipment (TFE) has been installed.
3. The TFE uses GPS to steer ensemble averaged Cs at each transmitter to provide approximately 15 ns recovery of UTC (USNO) at each transmitter. This TFE equipment also has the capability to utilize all of the Cs clocks in the Loran infrastructure to compute a single timescale.
4. The new eLoran transmission system will utilize time-of-transmission control similar to GPS, so the concept of individual Loran "chains" will be eliminated.
5. A new 9th pulse will be added to Loran transmissions [4]. This will be pulse position modulated, and as shown in Figure 1, this signal will provide UTC, leap seconds, individual station identification, differential Loran corrections, etc. For users, it will mean that acquisition of only one Loran station will provide absolute time.

Time	# bits	Resolution	Range
MSG type	4		16
Time	31	1 msg epoch	97-163 yrs
Leap Secs	6		64
Next leap Sec	1		
sta ID	3		8
Total	45		
dLoran	**# bits**	**Resolution**	**Range**
MSG type	4		16
Time Base Quality	3		
Ref ID	10		1024
Sig ID	3	2	16
Corr # 1	10	2ns	+/- 1.022 usec
Corr # 2	10	2ns	+/- 1.022 usec
Age/Quality	5		
Total	45		

Figure 1. The proposed data format [4] for the 9th pulse in the eLoran system. The definition is now being finalized, and it will take a maximum of 2.4 seconds to transmit a message.

eLoran Receiver and Antenna Technology

Significant technological advances in Loran receivers and antennas [5] actually preceded the eLoran infrastructure modernization, and Figure 2 shows a system now under development that represents the current state of the art. These new eLoran receivers are all-in-view devices, and can track over 40 transmitters simultaneously. By using a variety of DSP techniques and linear signal acquisition, SNR ratios of the signals of interest (i.e. generally signals from transmitters less than 1000 miles from the user) are more than 20 dB better than their antiquated counterparts, and resolution of the Loran signals are greatly improved. Example data from these devices are included later in the paper.

Figure 2. eLoran time and frequency system now under development. This all-in-view (40+ station tracking) receiver will include 9th pulse demodulation, frequency and pulse outputs, two framed DS1 outputs and IRIG output. The unit will also be capable of operating with an E- or H-field antenna.

There has also been significant progress in Loran antenna technology, where small magnetic or H-field and short (< 50 cm) E-field antennas are now available. The H-field antennas have the additional advantage of potentially providing indoor operation, and data from some early tests are presented later in the paper. Figure 3 shows an H-field antenna, and a GPS antenna can also be included in the same radome as the H-field antenna.

Figure 3. eLoran magnetic or H-field antenna. H-field antennas offer the potential of indoor Loran reception, and these small (< 20 cm diameter and 10 cm height) devices do not require a ground, which also simplifies installation.

eLoran Benefits for Time/Frequency Applications

A modernized eLoran system provides substantial benefits for the vast majority of time and frequency users. For example, eLoran will become fully redundant to GPS for both time and frequency needs. Furthermore, since a single Loran signal will provide both and frequency, and since a receiver can simultaneously track many Loran signals, considerable redundancy is provided. The new infrastructure is also extremely reliable, and in combination with new eLoran receiver and antenna technology, eLoran will essentially constitute an infinite backup to GPS.

On a more practical level, eLoran signals will penetrate areas where GPS is unavailable, and enable equipment placement (e.g. cell phone base stations) in locations that would be difficult for GPS. Importantly, H-field antennas now offer the possibility of indoor time and frequency reception, which would be a tremendous economic advantage because of substantially reduced installation and maintenance costs. Data from recent indoor tests are presented later in the paper.

eLoran Performance

Recent Loran tests in the US [6] and Europe [2] have shown have shown Stratum 1 frequency recovery data in approximately one-half hour of averaging. These tests were conducted on CsSync 1000 eLoran receivers, which are configured with ovenized oscillators (OCXOs) that improve the short-term performance of the system. CsSync 1000 receivers can only operate with E-field antennas, and here the antennas were placed on conventional outdoor rooftop mounts. Figure 4 illustrates data taken by the National Physical Laboratory (NPL) in Teddington, UK while a CsSync 1000 was phase locked to the Loran transmitter in

Lessay, France. The 1 pps from the CsSync 1000 was compared to the 1 pps from a NPL hydrogen maser.

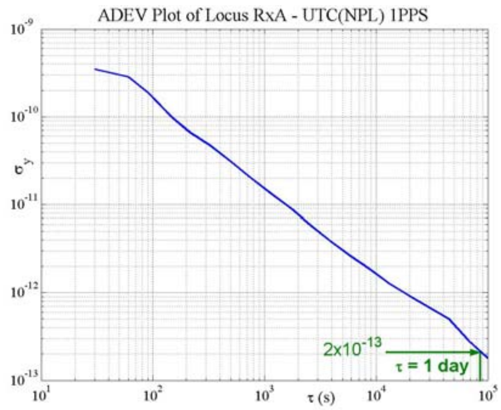

Figure 4. Frequency stability of an eLoran receiver's 1 pps versus the 1 pps from a hydrogen maser. Loran performance reached Stratum 1 with less than 30 minutes of averaging, and was 2 parts in 10^{-13} in 24 hours. From Hlavec and Stacey [2].

Preliminary Indoor eLoran Tests

Loran signal levels are roughly 10,000 times higher than GPS and have a 3 km wavelength. Consequently, they penetrate buildings and urban areas much better than GPS, and present the possibility of indoor placement of antennas for time and frequency applications. Indoor antenna placement can save thousands of dollars in installation costs per site, and can also largely eliminate grounding, lightning, and other environmental problems, so ongoing support costs are substantially reduced as well.

In a preliminary study [7] using an H-field eLoran antenna located inside the Locus building, we demonstrated that it is possible to track many Loran stations indoors (in this case, 16 stations were tracked from Madison, Wisconsin) and that these were groundwave signals originating from transmitters up to 900 miles away. In this evaluation, it appeared that the strength of Loran signals recorded indoors were comparable to those recorded outdoors, but the SNRs were approximately 5-10 dB lower, primarily due to the increased level of interference observed when H-field antennas are located inside buildings. Indoor interference in the 100 kHz Loran band can come from a variety of sources, including electronic equipment, monitors, and lighting ballasts.

In the last two months, additional indoor tests have been carried out in Cedar Park, Texas in order to get a better appreciation of the indoor performance possible when using H-field antennas. For these tests, a CsSync 1030 system was used, which operates with either H-field or E-field antennas and is a newer version of the CsSync 1000. While the CsSync 1030 can utilize an H-field antenna, it is also configured with an inexpensive temperature controlled oscillator (TCXO), so its short term performance is not as good as the CsSync 1000. Nevertheless, obtaining this initial data is important, because it is a straightforward process to integrate a high performance OCXO or Rb oscillator with the CsSync 1030. For these initial CsSync 1030 tests, the H-field antenna was positioned near the ceiling of a room in a small office building, as shown in Figure 5.

Figure 5. Position of H-field antenna for indoor tests in Cedar Park, Texas. The antenna was situated next to a wall and away from windows.

A block diagram of the test setup is shown in Figure 6. Here, the CsSync 1030 was phase locked to the 7980X Raymondville, Texas transmitter, which is located approximately 273 miles away and is the strongest station for this location. The receiver's 10 MHz output was fed into a Symmetricom SSU-2000, and TIE(phase), MTIE and TDEV performance over 24 hours was measured against the SSU's internal Stratum 2E clock, which was locked to a GPS signal with a 9000 second Tau.

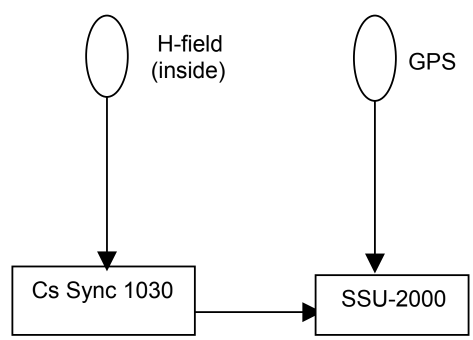

Figure 6. Block diagram of indoor test setup. A CsSync 1030 receiver using an indoor H-field antenna was phase locked to a Loran transmitter 273 miles away (i.e. 7980X, Raymondville, TX), and its 10 MHz output fed to a Symmetricom SSU-2000. Performance was measured against the SSU's internal Stratum 2E clock, which was locked to the GPS signal with a 9000 second Tau. For these tests, the SSU input module took 50 data samples per second, and the data were averaged for 1000 seconds.

Figures 7a, b, and c show the time interval, MTIE, and TDEV results, respectively, from this 24-hour test performed in June 2005. Figure 7a is the time interval (phase) data comparing GPS and indoor Loran using the SSU's 2E clock locked to GPS as the reference. Data are shown with a 1000 second average, and as expected, the Loran phase closely tracks the phase movement of the GPS reference signal. Even with the added noise from the GPS reference, the maximum deviation of the Loran signal is approximately 56 ns over 24 hours (GPS is approximately 46 ns).

Figure 7b plots the MTIE of the Loran during this data set, and the permissible masks for DS1 and PRS [8] are included for reference. As illustrated, this indoor Loran data meets the DS1 MTIE standard for all observation times, but does not meet the PRS MTIE standard for observation times less than 300 seconds. As indicated above, the CsSync 1030 is currently equipped with an inexpensive TCXO. We postulate that most of this short term performance is due to the TCXO, and would substantially improve with a good OCXO or Rb.

Figure 7c shows the TDEV for this data set, and again the DS1 mask is included for reference. Here, the indoor Loran system meets the DS1 standard for all observation intervals.

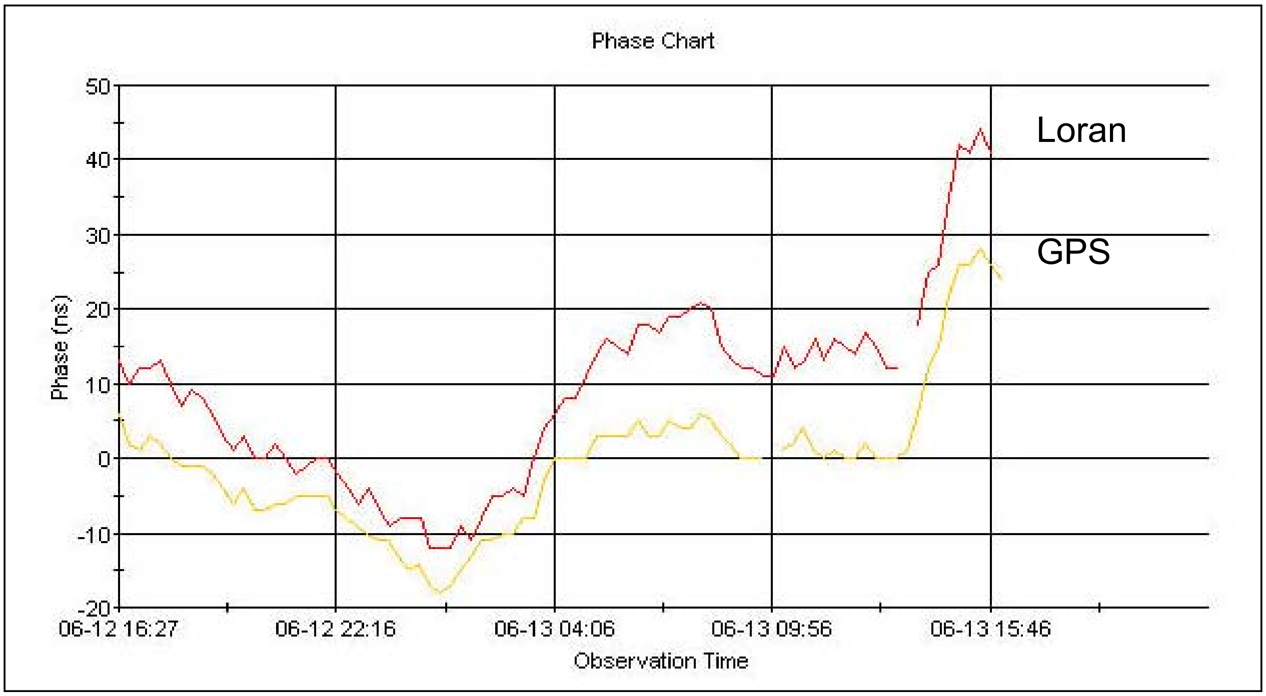

Figure 7a. Phase data of indoor Loran system referenced to SSU's Stratum 2E clock locked to GPS. The Loran phase closely follows the phase movement of the GPS reference signal. Data are shown with 1000 second averaging.

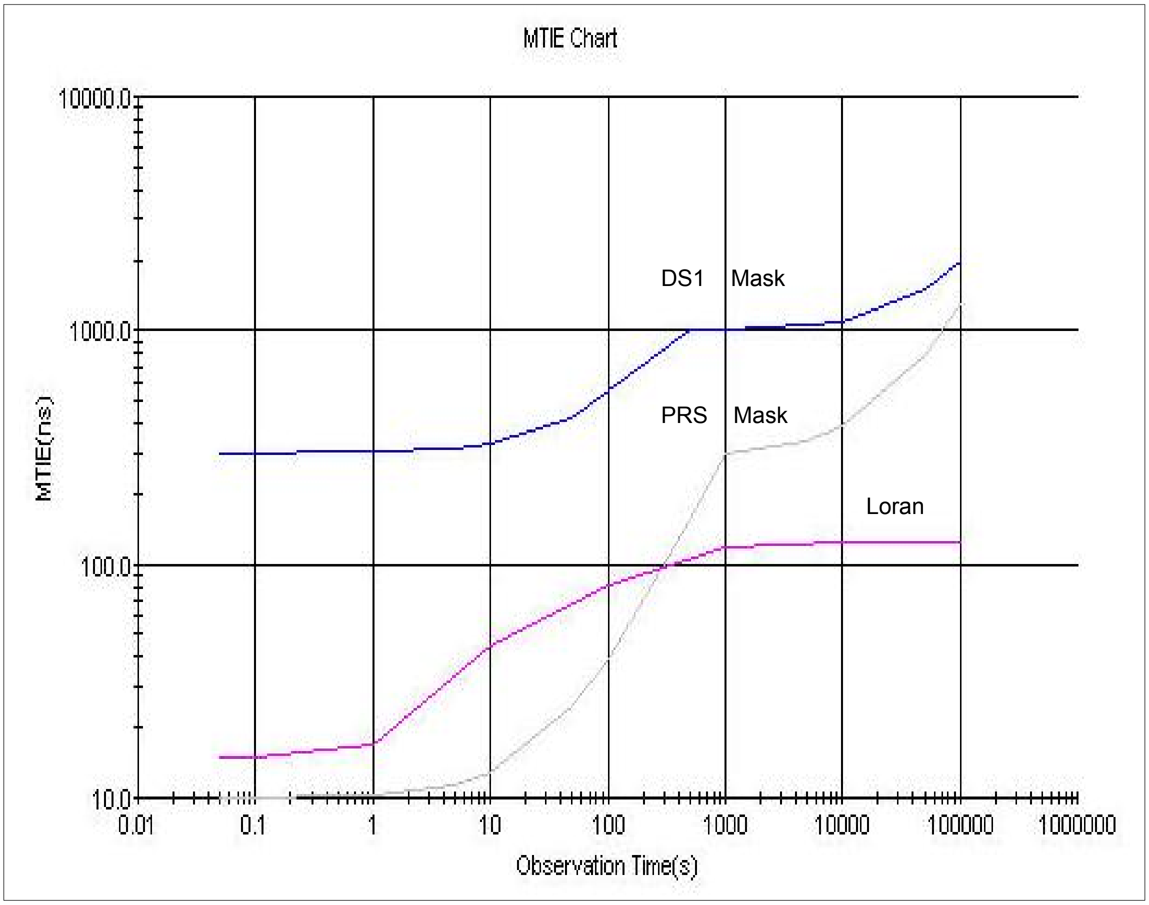

Figure 7b. DS1 and PRS MTIE masks shown with MTIE data of indoor Loran system. The Loran system meets the DS1 standard at all observation times, but does not meet the PRS standard below 300 seconds. This is likely due to use of an inexpensive TCXO in the test Loran receiver.

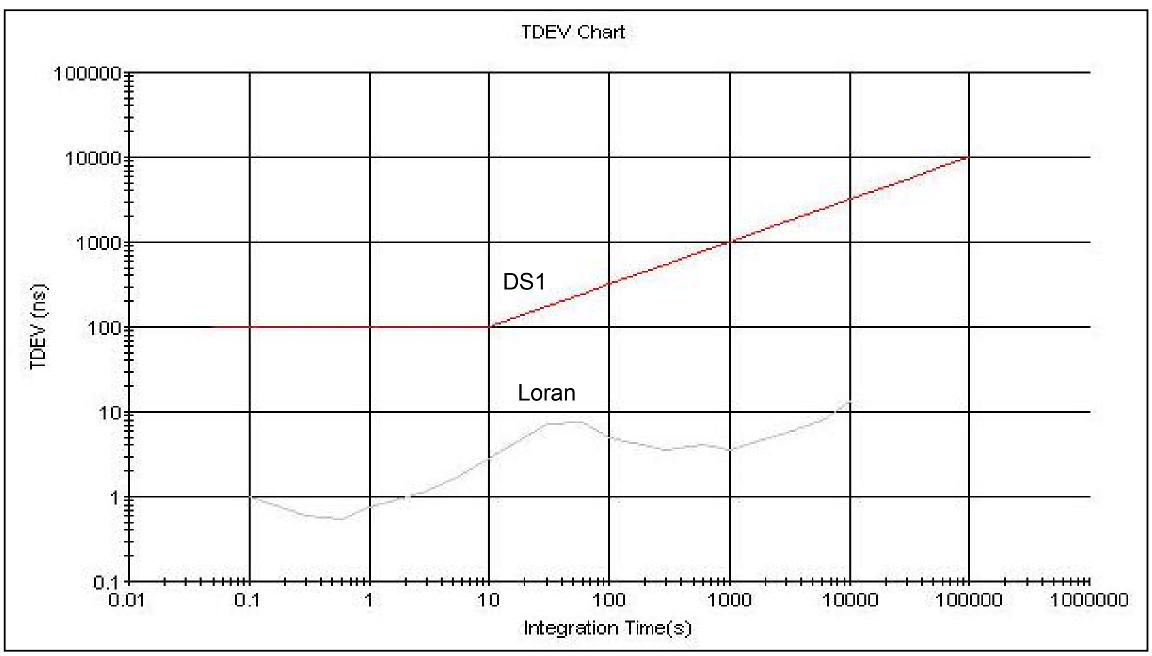

Figure 7c. DS1 TDEV mask shown with TDEV data from indoor Loran system. The Loran system meets the DS1 standard for all integration times.

Additional tests using this same equipment setup were performed from August 16-17, 2005, and these results are shown in Figure 8 a and b. For these tests, the receiver was phase locked to a transmitter 506 miles away (i.e. 9610M at Boise City, OK), and again, MTIE and TDEV plots are shown with the DS1 masks for reference. The results are similar to the results from the June tests, and the indoor Loran meets the DS1 MTIE and TDEV standards over these observation times.

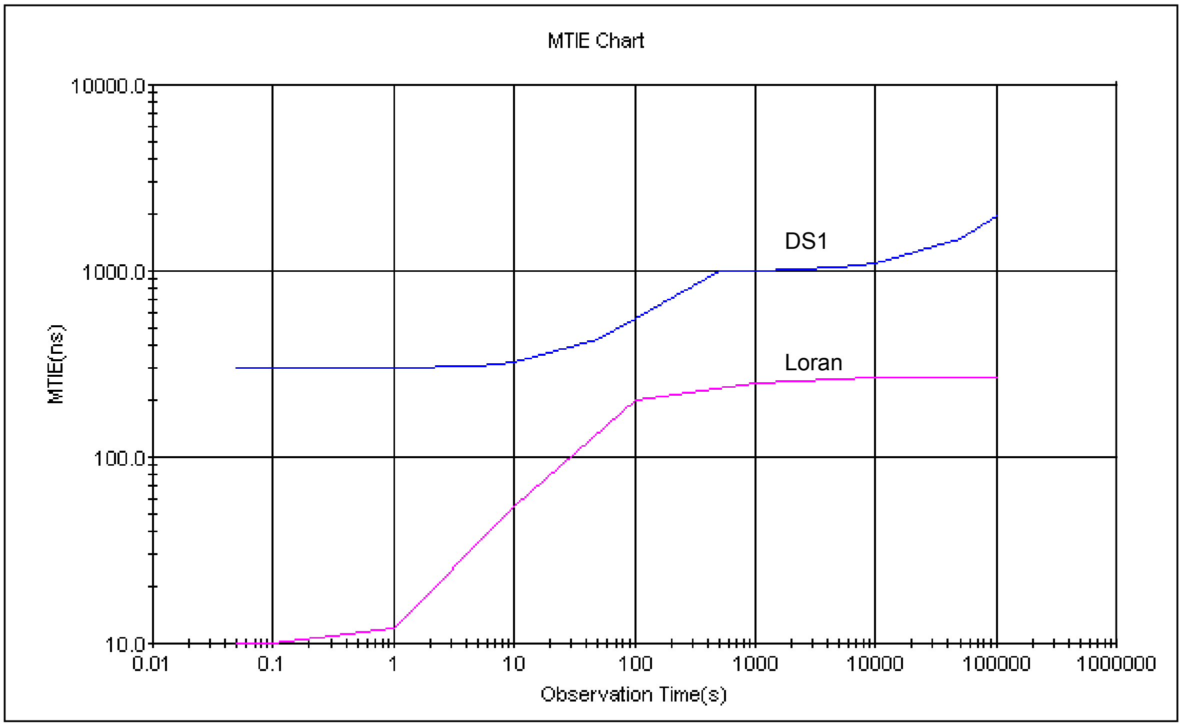

Figure 8a. MTIE data from indoor Loran tests with DS1 mask shown for reference. Here the Loran receiver was phase locked to the 9610M transmitter in Boise City, OK, which is 506 miles from the recording site. Again, Loran meets the DS1 standard for all observation times.

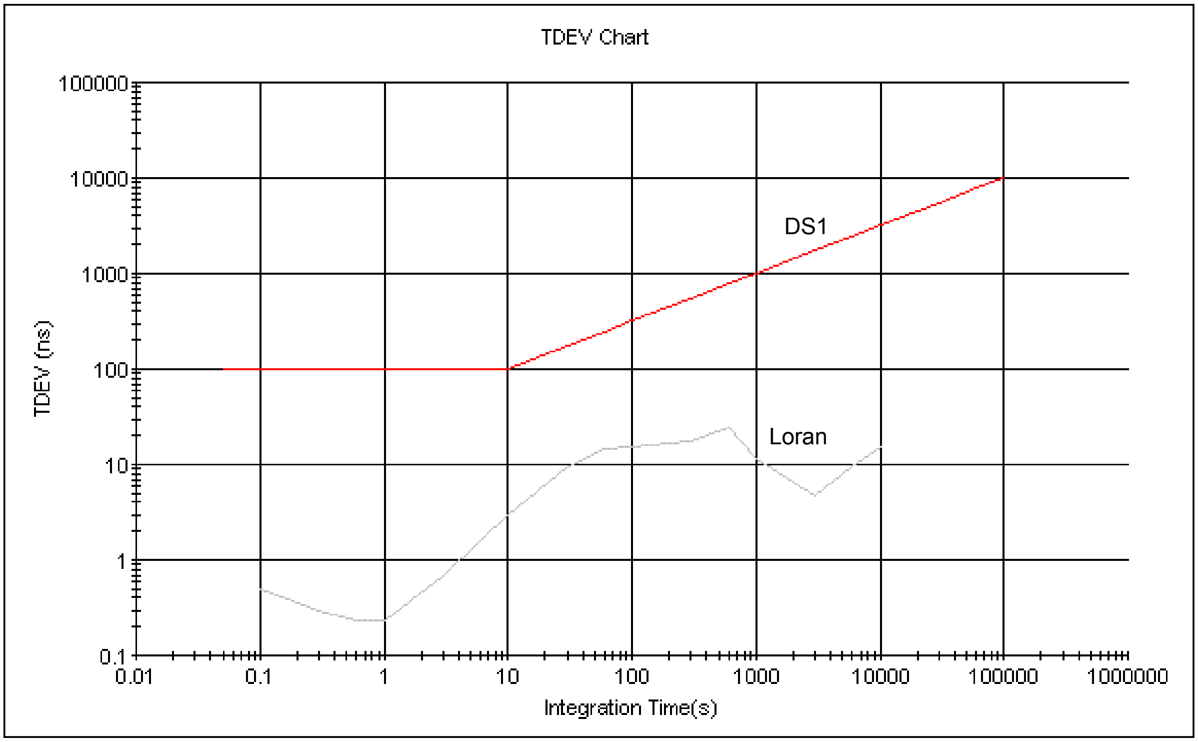

Figure 8b. TDEV data from indoor Loran tests with DS1 mask shown for reference. Loran meets the DS1 standard for all observation times tested out to 10,000 seconds.

The most recent tests using this setup were performed on August 30, 2005, when time interval (phase) between indoor Loran and the GPS was determined using the SSU's 2E clock locked to GPS as the reference. Over this approximately 19-hour trial, the data were plotted using a 100 second average, so they are noisier than the results shown in Figure 7a. The indoor Loran phase data are clearly noisier than GPS, and they follow the phase movement of the GPS reference signal as in the earlier test.

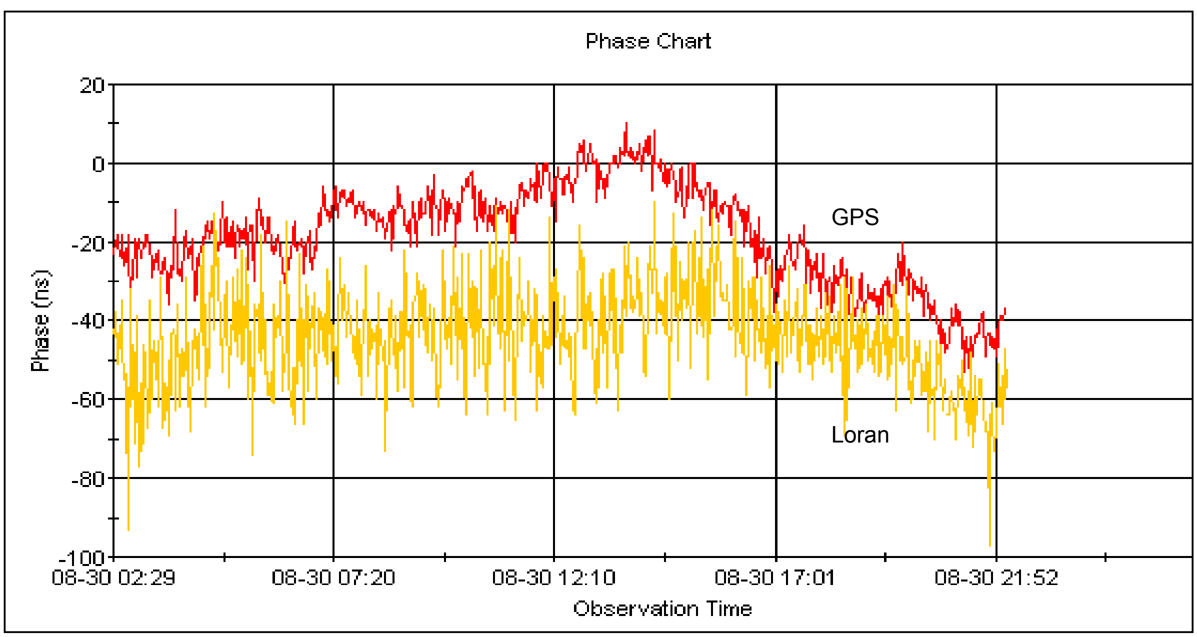

Figure 9. Phase of GPS and indoor Loran when the SSU's Stratum 2E clock is locked to GPS. The Loran phase closely follows the GPS reference signal. Data are shown with 100 second averaging.

Conclusions

The US Loran system is undergoing modernization toward an enhanced or eLoran system that will provide substantial benefits to the time and frequency community. New time and frequency control capabilities will steer all transmitters to within 15 ns of UTC (USNO), will operate with TOT control similar to GPS, and provide UTC and other information on a new 9th pulse. The infrastructure to provide this capability has now been completely installed in the CONUS. Conversion to eLoran operations will mean that users will be able to obtain time and frequency information from a single Loran signal, and that many signals will be available for redundancy.

eLoran receiver and antenna technology has also advanced significantly. Recent tests with a small E-field antenna have demonstrated Stratum 1 frequency performance with less the one-half hour of averaging, and accuracy of 2 x 10^{-13} in 24 hours. New, small H-field antennas can operate without a ground and offer the opportunity of indoor reception. Preliminary tests recording from two different transmitters indicate Loran can meet telecommunication DS1 TDEV and MTIE standards using indoor antennas. While indoor conditions will vary greatly, these tests were performed with an eLoran receiver equipped with a TCXO, so further performance improvements are likely with use of OCXO or Rb technology.

In summary, it appears that the new eLoran system will offer users a high performance system for time and frequency applications, and that eLoran will be an infinite and traceable source of these capabilities.

References

[1] "Loran's Capability to Mitigate the Impact of a GPS Outage on GPS Position, Navigation, and Time Applications," publicly released December 2004. See https://ksn.faa.gov/km/navservices/navserviceslt/tech/Loran_Eval_Report/default.aspx.
[2] R. Hlavec and P.W. Stacey, "Evaluation of Loran Timing Receivers at NPL," Royal Institute of Navigation NAV04, 2004.
[3] J. Macaluso, "Loran-C Modernization Achievements & Plans," Institute of Navigation National Technical Meeting, January 2005.
[4] B. Peterson, K Dykstra, P. Swaszek, and K. Carroll, "Differential Loran," International Loran Association 32nd Annual Convention and Technical Symposium, November 2003.
[5] G.L. Roth and P. Schick, "New Loran Capabilities Enhance Performance of Hybridized GPS/Loran Receivers," Navigation 46(4), pp. 249-260, Winter 1999-2000.
[6] T. Celano, K. Carroll, and M. Lombardi, "Common View Loran-C for Precision Time and Frequency Recovery," International Loran Association 32nd Annual Convention and Technical Symposium, November 2003.
[7] G.L.Roth, "Enhanced (e) Loran in Telecommunication Applications," NIST - ATIS T1X1 Workshop on Synchronization in Telecommunication Systems, February 2004.
[8] American National Standards Institute, "Synchronization Interface Standard – for Telecommunications," ANSI T1.101-1999.