Providing a Resilient Timing and UTC Service Using eLoran in the United States

Gerard Offermans, Steve Bartlett, Charles Schue, *UrsaNav, Inc.*

BIOGRAPHIES

Dr. Gerard Offermans is Senior Research Scientist at UrsaNav engaged in various R&D project work and product development. He supports customers and operations in the European, Middle East, and Africa (EMEA) region from UrsaNav's office in Belgium. Dr. Offermans is one of the co-developers of the Eurofix data channel concept deployed at Loran installations worldwide. Dr. Offermans received his PhD, with honors, and Master's Degree in Electrical Engineering from the Delft University of Technology.

Steve Bartlett joined UrsaNav in 2013 as Vice President of Operations. He's responsible for all aspects of business operations including manufacturing, engineering, quality control, program management, & project delivery. Steve brings more than 20 years of engineering and manufacturing business industry expertise to UrsaNav. Prior to joining UrsaNav, Steve led worldwide teams at both Autodesk & PTC focused on helping clients gain the most value from their technology investments in product lifecycle management & engineering solution software.

Charles Schue is founder and President of UrsaNav, Inc. He champions providing Low Frequency Alternative Positioning, Navigation, Time and Frequency, and Data solutions for "sky-challenged" users. He holds Masters Degrees in Electrical Engineering, Engineering Management, and Business Administration. He is a Fellow of the Royal Institute of Navigation.

ABSTRACT

Accurate timing and frequency is becoming increasingly important in many applications that influence our daily life. Fifteen out of sixteen sectors of the Critical Infrastructure and Key Resources (CIKR) identified by the Department of Homeland Security Department of Homeland Security (DHS) Science and Technology Directorate (S&T) use GPS for timing and for eleven it is deemed essential. More and more systems are becoming solely dependent on GPS or other Global Navigation Satellite System (GNSS) for their precise position, timing, and frequency information, especially as additional multi-constellation GNSS, i.e. Galileo, Compass, and GLONASS, and Regional Navigation Satellite Systems (RNSS) become fully operational and "fill the world's skies." Along with the explosive growth of systems and applications comes an increasing awareness of GNSS vulnerabilities. Interference, jamming and spoofing reduce availability and reliability of all GNSS.

National Security Presidential Directive-39 (NSPD-39) of 2004 established implementation actions for the development of a back-up system to GPS for positioning and timing. In July 2015, a Congressional Hearing was held to discuss the Federal Radionavigation Plan. Chairman Duncan Hunter (R, CA) opened the hearing by saying that the government had been studying the issue of a backup for GPS for 11 years and that it was time for action. Congressman Garamendi (D, CA) added that there was "real time", like what GPS and eLoran provide, and "federal time" which is the model of comparison Congress uses when trying to get a decision or something done. Both Congressmen made it clear, quoting Dr. Brad Parkinson, that there is a need for a back-up to GPS and that eLoran is the prime candidate to do so. In June 2015, Congressman LoBiondo (R, NJ) turned on the eLoran transmitter at the former US Coast Guard Loran Support Unit site in Wildwood, NJ, thereby initiating a Cooperative Research and Development Agreement (CRADA) between the DHS S&T, the Coast Guard, Exelis, and UrsaNav to demonstrate eLoran's capability to provide accurate time and frequency over a wide area.

eLoran is a high power, Low Frequency (LF), ground wave radio broadcast system, capable of providing 10-meter positioning accuracy, Stratum-1 frequency distribution, and Universal Time Coordinated (UTC) timing well within one microsecond (μs) across very large areas (1,000 miles). Application of differential corrections for timing further improve the accuracy to better than 100 nanoseconds (ns). eLoran is proven technology, well-established for providing services very similar to those delivered by GNSS, with characteristics and failure modes that are complementary to GNSS.

This paper discusses the general concept of eLoran timing and UTC distribution, and the current prototype service. It further highlights plans to provide an initial four-station CONUS-wide timing service, which can gradually be expanded to provide increased coverage and redundancy and deeper penetration into buildings. Additional stations also enable positioning and navigation services.

INTRODUCTION

It is widely recognized that GPS, or more generally GNSS, has become the primary means of obtaining Positioning, Navigation, and Timing (PNT). GPS and other GNSS can provide accurate frequency, and UTC to within 100 ns. An increasing number of applications and services rely on accurate timing and may become unavailable if GPS reception is interrupted. Just like any prudent navigator does not rely on a single source for positioning and navigation information, relying on GPS as the sole means of obtaining precise time for critical systems, without having an alternative system or backup in place, is not prudent or responsible, and can have severe operational and economic impacts.

Besides the ability to obtain accurate time in the absence of GPS, having an alternative source for accurate time to determine when GPS is providing incorrect or misleading data is also important. An alternate, comparable source of accurate time also helps ensure GPS integrity and signal authentication, and provides resilience for the timing user.

There are numerous applications and systems that require accurate and precise time. The DHS S&T has identified fifteen (15) Critical Infrastructure and Key Resource sectors that use GPS for timing. For eleven (11) of the sectors, GPS timing is deemed essential for successful operation. [1] In recent years, it was assumed that any GNSS outage would be extremely unlikely and, in any event, of very short duration. This led to a strategy of implementing holdover technology based on oscillators. The predicted performance of this approach is summarized in Table 1. Additionally, as seen in Table 2, the 2014 US Federal Radionavigation Plan lists the timing user accuracy requirements for the financial, energy transmission, and telecommunications sectors as 1 µs.

Despite the overwhelming success of GPS as the leading global PNT system, it has vulnerabilities. GPS performance is degraded, or even interrupted, by natural phenomena, such as solar flares, or unintentional or intentional interference (e.g., jamming or spoofing devices) [2,3]. These manmade interference events have grown more frequent and more sophisticated as well. In recent years, GPS has had to compete for spectrum with emerging GNSS from other countries whose systems broadcast in the same frequency bands. These systems also contribute to the overall noise level at GPS frequencies. Communications systems are also capable of competing with GPS for spectrum, and communications technologies continue to encroach on PNT satellite spectrum. [4].

Even without these threats, using GPS has other challenges. In many cases, timing is needed inside buildings or in areas with many sources of local interference. GPS signals can be blocked or become partially unavailable. Installing GPS antennas on the roof of a building to get a clear view of the sky can add to operational costs, and often incur leasing fees.

Alternatives to GPS for precise timing are limited. Other GNSS systems suffer the same sort of vulnerability problems as GPS, and current low frequency time distribution systems such as WWVB, DCF77, and MSF only provide several tens of microseconds to millisecond timing accuracy. Systems that claim GPS "independence" often actually contain a link to GPS signals at some point in their architecture. LF systems, such as the Long Range Navigation (Loran-C) and Enhanced Loran (eLoran), are the only homogeneous, multi-modal, independent alternative to GPS for providing very wide-area precise time synchronization. [5]

In 2010, the General Lighthouse Authorities of the UK and Ireland (GLA) followed the UK Treasury methods to produce the GLA's eLoran Business Case [6,7]. This comprehensive document presented and analysed various options for providing 'Resilient PNT' in UK and Irish waters. It was clear that if the GLA chose to implement eLoran, it could rationalize its physical Aids to Navigation (AtoN) infrastructure, removing some lights and other physical aids, and on balance actually reduce costs by implementing eLoran. Indeed, compared to other possible resilient PNT options, such as GNSS hardening, radar absolute positioning, or increasing physical AtoN provision, eLoran would have saved the GLA over £4M per year over a nominal system lifespan of 10 years from the introduction of e-Navigation services in 2018 to 2028. So, the GLA opted to provide differential Loran services in selected ports on the East coast of the UK, in what they elected to call its Initial Operational Capability (IOC) [8].

The existing Loran-C services in North-West Europe (i.e., France, Germany, Norway, and Denmark) were phased out at the end of 2015. Without this infrastructure, it was not possible to provide eLoran Navigational coverage in the UK waters in the short term. Instead of shutting down the eLoran transmitter in Anthorn, Cumbria, the UK government has decided to keep it in operation, as a single eLoran transmitter, independently synchronized to UTC, providing accurate UTC timing and data services to UK users. Similar to the decision in the US in 2009, terminating Loran-C service provides the foundation for repurposing the infrastructure into an eLoran service. With the UK leading the way, it is hoped that other European countries will also upgrade their systems to eLoran. Discussions are currently ongoing between government and industry to determine the best method of moving ahead with eLoran in Europe.

In the United States, UrsaNav entered into its second CRADA with the DHS S&T and the USCG, this time also including Exelis (nka Harris Corporation), to test eLoran for time and frequency distribution, in anticipation of a decision by the government to implement a non-GNSS alternative to GPS for time and frequency users. This paper provides test results of timing trials using the eLoran transmission site technology located in Wildwood, NJ.

GPS Timing Essential CIKR Sector	Timing Accuracy Requirements*	Oscillators Used**			Least Robust Oscillator	Osc. Holdover Time (Hours)
		TCXO	OCXO	Rb		
Communications Sector	~ Nanoseconds (SONET, CDMA)		X	X	OCXO (HS)	24 +
Emergency Services Sector	~ Nanoseconds (CDMA E911, LMRs)		X		OCXO (HS)	24 +
Information Technology Sector	20 to 100 Nanoseconds (PTP)*		X		OCXO (MS)	1
Banking and Finance Sector	Millisecond- Microsecond (HFT)^	X	X	X	TCXO	< .24 -1.7
Energy/Electric Power Subsector	1-4.6 Microsecond (Synchro-Phasors; Fault Loc.)		X		OCXO (MS)	1
Energy/Oil and Natural Gas Sector Subsector	Microsecond (exploration, SCADA)		X	X	OCXO (MS)	1
Nuclear Sector	1 Microsecond (Synchro-Phasors)		X		OCXO (MS)	1
Dams Sector	1 Microsecond (Synchro-Phasors)		X		OCXO (MS)	1
Chemical Sector	Sub Microsecond-Microsecond		X		OCXO (MS)	1
Critical Manufacturing Sector	Millisecond	X	X		TCXO	1.7
Defense Industrial Base Sector	Millisecond	X	X		TCXO	1.7
Transportation Sector	~ Nanoseconds (Wireless modal comms)		X	X	OCXO (HS)	24 +

Table 1. CIKR Sector Oscillators and Holdover Times [1]

Table 4-14 Timing User Requirements

REQUIREMENTS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS					
	ACCURACY (Time with respect to UTC)	AVAILABILITY	CONTINUITY	INTEGRITY	TIME TO ALERT	COVERAGE
Financial transaction timestamp	1 s	TBD	TBD	TBD	TBD	Worldwide
Electric power transmission	1 μs	TBD	TBD	TBD	TBD	North America
Cellular telephony	1 μs	Outages not to exceed 8 hr	TBD	TBD	TBD	North America
Inter-carrier telephone and data networks	1 μs	TBD	TBD	TBD	TBD	North America
Scientific community	nanoseconds	TBD	TBD	TBD	TBD	Worldwide
Traffic Signal Timing	TBD	TBD	TBD	TBD	TBD	Nation Wide/Intersections

Table 2. 2014 Federal Radionavigation Plan Timing User Requirements

ELORAN FOR TIME AND FREQUENCY

eLoran is a high-power, low-frequency, long range radionavigation system that provides similar Positioning, Navigation, Time and Frequency services as GNSS, without the same failure modes as GNSS. It uses pulsed signals at a center frequency of 100 kHz. The pulses are designed to allow the receiver to distinguish between the ground wave and sky wave components in the received composite signal. This way, the eLoran signals can be used over very long ranges without fading or uncertainty in the time of arrival measurement related to sky waves. eLoran, like its predecessor Loran-C, is the only Stratum-1 service alternative to GPS in the US.

The main differences between eLoran and Loran-C are improved technology, additional functionality, and better operational practices. These small improvements on the DOD-developed Loran-C system that turn it into eLoran yield incredible improvements in PNT accuracy. eLoran makes use of 21^{st} century technology, thereby taking advantage of significantly improved timing and signal tolerances, while also reducing size, weight, input power, and cooling. Each eLoran transmission is individually synchronized to UTC, as opposed to System Area Monitor control for Loran-C. Our typical design for UTC synchronization at transmitting sites includes a combination of Local and Remote Time Scales. The Local Time Scale consists of a disciplined ensemble of three cesium-based 5071A Primary Reference Standards (PRS). The Remote Time Scale consists of one or more of the following inputs: Two-Way Satellite Time Transfer, Two-Way Low-Frequency Time Transfer, microwave, dedicated fiber, “hot clock”, or GNSS. The application of Additional Secondary Factor (ASF) data bases and differential corrections enable the highest possible positioning accuracy: less than 10 m for maritime applications, and better than 100 ns timing, with respect to UTC. eLoran includes one or more low data rate, long range, and robust data channels. Data from these Loran Data Channels (LDC) are broadcast as part of the transmitted eLoran signal, and include navigation or timing related data (i.e., differential corrections and UTC messages), system specific data (i.e., station ID and health), user-defined data (e.g., as part of a “third-party” data channel service), and an almanac with system configuration information.

An eLoran receiver measures the Time of Arrival (TOA) of the eLoran signal:

$$TOA = T_{TOR} - T_{TOT} = PF + SF + ASF + \Delta Rx \qquad (1)$$

where:

TOR - Time of Reception,
TOT - Time of Transmission,
PF - Primary Factor,
SF - Secondary Factor,
ASF - Additional Secondary Factor, and
ΔRx - Receiver and cable delays.

The PF accounts for propagation through air, SF for propagation over sea water, and ASFs for propagation over land and elevated terrain. The Primary and Secondary Factors are well defined delays and can be calculated as a function of distance. The Additional Secondary Factor delay is typically unknown at the time of installation, but may be modeled and/or measured.

ASF is the incremental TOA delay of the 100 kHz signal resulting from propagation over heterogeneous signal paths. Depending upon path length and conductivity, ASF delay can be significant. There is both a spatial and a temporal component to ASF. The RTCM Minimum Performance Standards for eLoran specifies that ASF can be considered to have two components: the nominal ASF, and the local or grid ASF.

Nominal ASF is a coarse value for a region that is tens or hundreds of square miles in area. The ASF values significantly increase the absolute accuracy of eLoran receivers by removing the majority of the spatial component of ASF. When supporting the highest accuracy applications, such as Harbor Entrance and Approach, finer values are required with higher grid density. The fine ASF grid is a grid of the local variations of ASF relative to the nominal value and the grid spacing may be on the order of hundreds of feet, depending upon the amount of ASF variation.

In addition to very local ASF variations, there is a temporal component resulting from such factors as weather (i.e., temperature and dew point), seasonal conductivity changes, and diurnal influences. These temporal components are removed through the use of differential Loran (dLoran) corrections. The dLoran corrections can also compensate for other slowly varying or common errors from minor inaccuracies in PF and SF models, as well as systemic errors.

In a timing application, only one TOA is necessary to derive a UTC aligned 1PPS, assuming the position of the timing receiver is known. It is interesting to know what variation can be expected from a single TOA as the signal path changes as a function of location. Figure 2 shows such a published ASF map for the Lessay transmitter in France as seen at the Humber River approach to Immingham and Hull in the UK, a distance of 315 miles. As can be seen by the scale to the right, the different propagation paths to the receiver locations result in ASFs changing 400 ns between locations that are 60 km apart. Clearly, not compensating for the ASFs results in a large timing and/or position error; the type of error that contributed to the 20^{th} century Loran-C system’s published accuracy of a quarter nautical mile.

UrsaNav conducted earlier timing trials in the US in 2013 under a similar CRADA agreement with DHS S&T, and in Europe in 2014, the results of which were presented in previous PTTI papers [9,10]. These trials showed clear correlation between time interval measurements of eLoran derived UTC and an external UTC reference (e.g., GPS, 5071A PRS, USNO Master Clock), measured at different locations separated several tens of miles. This gave rise to the implementation of a differential UTC service providing corrections from an eLoran Reference Station to users in the vicinity.

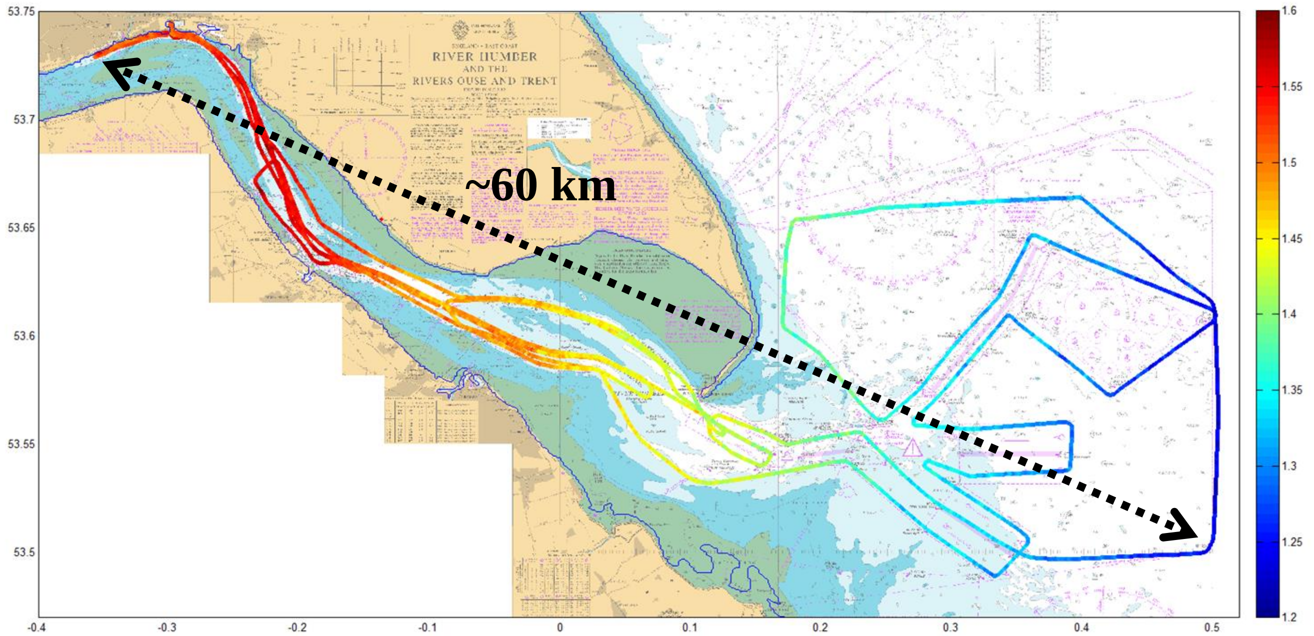

Figure 1. Variation of Lessay (FR) ASF at Humber (UK)

eLORAN TIMING AND UTC SERVICE IN THE US

Based on the experiences of the earlier CRADA trials, as well as the differential UTC trials in Europe, UrsaNav implemented a prototype differential UTC service. Under the CRADA, UrsaNav ran the Wildwood Loran transmitter, outfitted with a LDC using the 9th pulse transmission format [11]. The LDC carries UTC timing messages as well as differential UTC corrections from reference sites in the coverage area of the transmitted signal. The dark blue inner line on Figure 2 shows the estimated coverage area of the current 360 kW Wildwood transmitter. The green outer line shows the estimated coverage area if the Wildwood transmissions were at one (1) MW. Transmitting sites are represented by: ⊗.

Similar to GPS, eLoran can provide two levels of service: BeTS and PeTS. BeTS and PeTS are internal naming schemes developed primarily for us to easily distinguish between the two levels of service.

- Basic eLoran Timing Service (BeTS). We define BeTS as timing service of better than one (1) µs synchronization with respect to UTC throughout the coverage area of the transmitter.

The BeTS uses the accurate Time of Transmission of the eLoran pulses and the UTC messages on the Loran Data Channel that are providing Time, Date, and Leap Second information. A user receiver requires a one-time calibration of its internal delays (e.g., antenna, cable length, etc.) and ASFs during installation. After this one-time calibration, the receiver is able to synchronize to within 1 µs of UTC. Earlier publications, and our own initial measurements, have shown that diurnal and seasonal variations of ASFs stay well within the 1 µs accuracy boundaries. Reference [12], in particular, demonstrates the stability of ASFs over time frames measured in multiple years. Figure 3 shows the BeTS coverage area over the entire CONUS, if four 1 MW transmitters were installed at former Loran-C sites at Wildwood, NJ; Dana, IN; Boise City, OK; and Fallon, NV.

- Precision eLoran Timing Service (PeTS). We define PeTS as timing service better than 100 ns synchronization with respect to UTC in the vicinity of a Differential eLoran Reference Station.

For even more accurate timing performance, the temporal variations in propagation, such as diurnal and seasonal variations of ASFs, can be compensated by differential techniques. Just like with Differential GPS installations, a

Differential eLoran receiver installed at a fixed and known location will be able to measure the current offset of its ASF with respect to the nominal or published ASF value. This difference can then be broadcast to users in the vicinity of the Differential eLoran Reference Station using the LDC. The user receiver applies the differential correction to compensate for the ASF fluctuation and arrives at a timing accuracy of better than 100 ns. Based on recent tests, we expect the coverage range of a differential site for timing to be over 35 miles, similar to, but not necessarily the same as the coverage range of differential eLoran sites for navigation. Figure 4 depicts a representative laydown that would provide BeTS coverage, as well as PeTS coverage for more discerning timing users. In this example, we have selected 71 Differential eLoran Reference Station sites for improved timing accuracy. Differential sites are represented by: ♦. These 71 locations would cover the 50 major metropolitan areas, 50 major airports, and 50 major ports/harbors in CONUS. Each transmitting site would be equipped with one or more LDCs, with each data channel capable of broadcasting correction information gathered from at least 40 Differential eLoran Reference Stations.

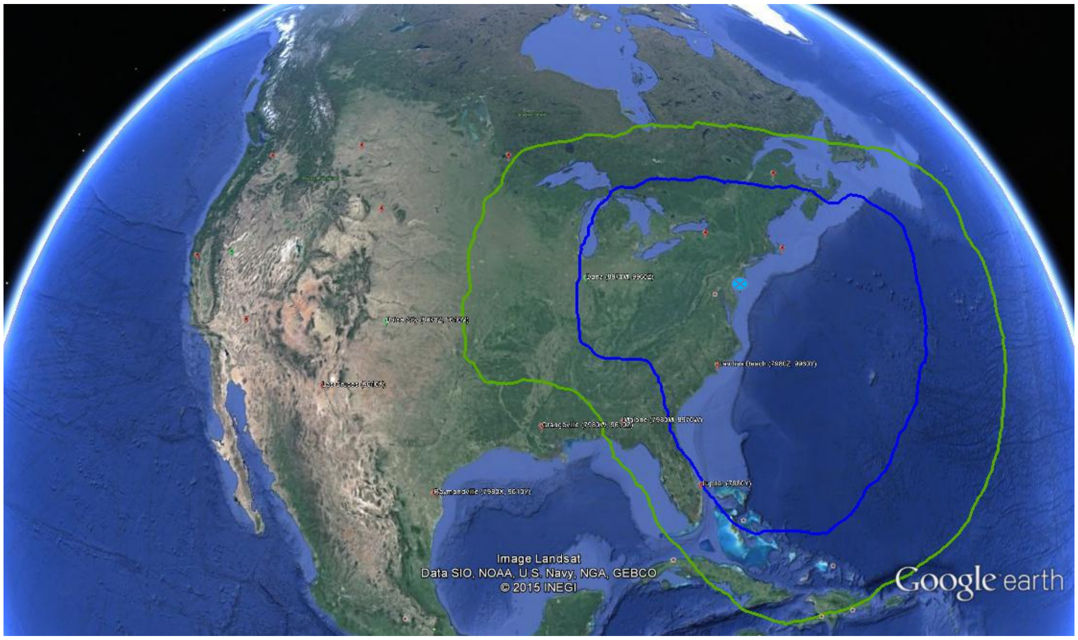

Figure 2. BeTS coverage areas using eLoran signals from the transmitter in Wildwood, NJ.

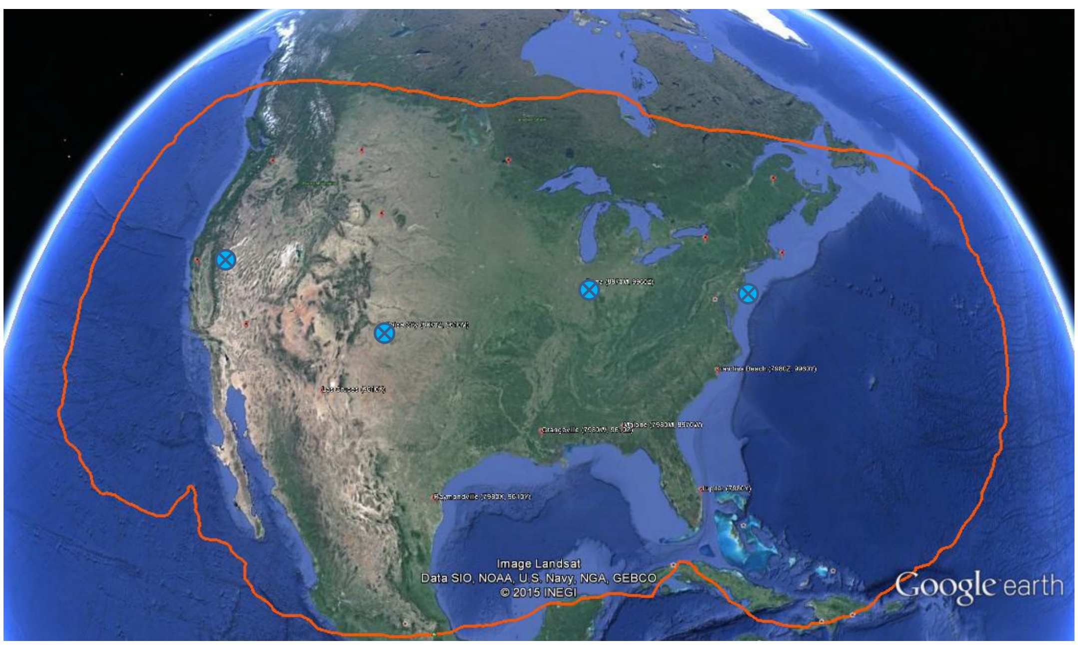

Figure 3. BeTS coverage area using eLoran signals from four 1 MW transmitters.

Figure 4. Representative higher accuracy (i.e., PeTS) locations within CONUS.

The data channels at each site will have sufficient spare bandwidth available for additional services such as Daylight Savings Time information or one way emergency communications services.

TESTING eLORAN TIMING SERVICES

As mentioned before, our CRADA with the DHS S&T allows us to use decommissioned Loran-C infrastructure to test eLoran. In June 2015, Congressman Frank LoBiondo, who is the local congressional representative for Southern NJ, officially turned on the eLoran signal at Wildwood for test purposes. We installed additional equipment to enable remote monitoring and control, and to provide LDC capability for the broadcast of differential corrections.

Figure 5. UN-155 Resilient PNT Receiver

We installed eLoran receivers at our Leesburg, VA, office; at the US Naval Observatory (USNO) in Washington, DC, where eLoran' s timing output could be directly compared with USNO's Master Clock; at our North Billerica, MA, office; at Franklin, MA, and at Bangor, ME. These sites range in distance from 120 to 500 miles from the Wildwood, NJ eLoran transmitter. The receivers were all UrsaNav UN-152, stand-alone eLoran timing receivers, or UN-155, Resilient PNT receivers (Figure 5). The UN-155 houses eLoran, GPS, and radiobeacon DGPS and has the capability to take in external positioning inputs. To make comparisons, all receivers need to have access to another source of UTC. For simplicity, we chose either a standalone GPS, a GPS-disciplined 5071A PRS, or the USNO Master Clock for that purpose.

Figure 6 shows a block diagram of the test set-up we used testing our differential UTC service. At our Differential eLoran Reference Station sites in Billerica, MA, and Leesburg, VA, we installed an eLoran timing receiver and compared its 1PPS output against a PRS. The 1PPS Time Interval Counter (TIC) measurements are collected for 10 minutes and a UTC correction is calculated, which is sent over the internet to the eLoran transmitter in Wildwood, NJ, where the correction is formatted and sent over the LDC to the user receivers. At the same location, we installed a second eLoran receiver that applies the received UTC correction and adjusts its 1PPS output accordingly. Its 1PPS output is then compared against the same PRS to provide a zero-baseline (ZBL) reference output. All other receiver sites had Rover Receiver set-ups, with either a GPS, a PRS, or USNO's Master Clock as its reference. The PRS references were regularly compared to, or disciplined by, GPS measurements to synchronize them to UTC and remove any long-term drift.

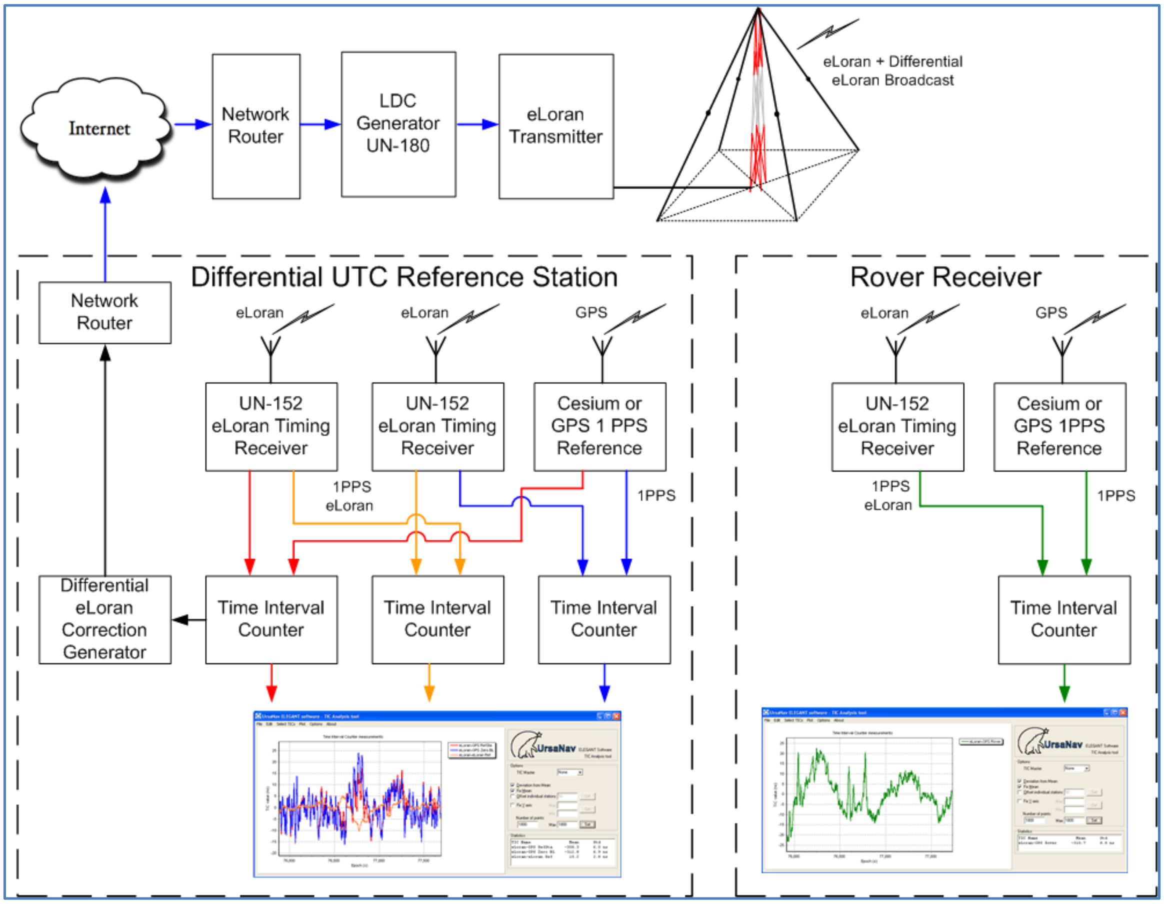

Figure 6. eLoran Timing Test Block Diagram

BASIC eLORAN TIMING SERVICE PERFORMANCE

The plot shown in Figure 7 is the Time Interval Counter output of our eLoran timing receiver using the BeTS in Bangor, ME, at more than 500 miles from the Wildwood transmitter, and as compared against GPS. On the x-axis is the time of the measurements, represented as dates in December 2015. The major graduations are at 12:00 hours UTC, corresponding to 07:00 AM EST. There is a clear diurnal behavior present, which peaks at about 07:00 AM EST, sunrise at Bangor. The mean offset from the UTC reference, after the one-time installation calibration, is 49.7 ns, with a standard deviation of 68.6 ns. The maximum and minimum deviation of 216 and -91 ns, respectively, stayed well within the target accuracy of 1 µs for the BeTS over the ten-day observation period.

The plot shown in Figure 8 is the Time Interval Counter output of the eLoran timing receiver at USNO in Washington, DC, at 120 miles from the Wildwood transmitter. Here, the eLoran output is compared against USNO’s Master Clock. The mean offset from UTC, after the one-time installation calibration, is 22.9 ns, with a standard deviation of 26.1 ns. The maximum and minimum deviation of 147 and -90 ns, respectively, stayed well within the target accuracy of 1 µs for the BeTS over the twelve-day observation period. These measurements do not show a distinct diurnal behavior, most probably because the propagation path from transmitter to receiver is short, thereby minimizing any ASF movement related to the diurnal changes.

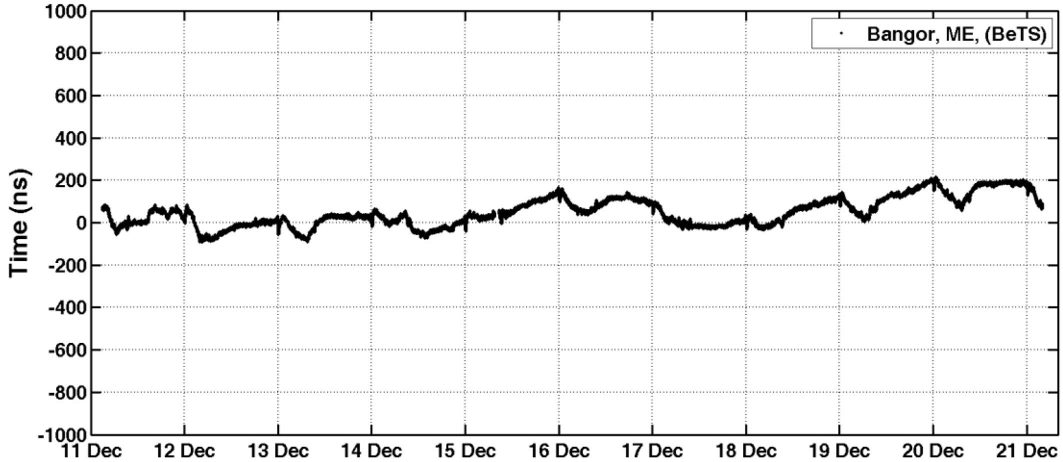

Figure 7. BeTS performance at Bangor, ME as compared to GPS.

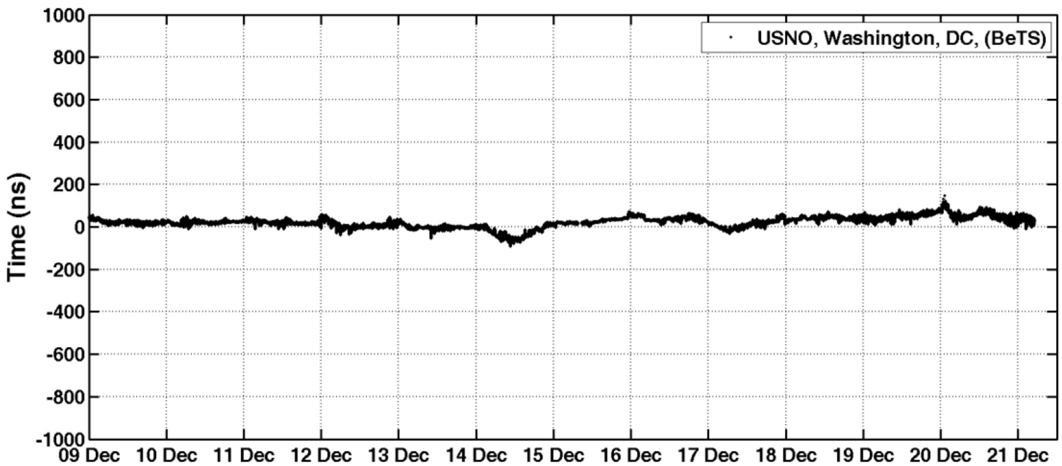

Figure 8. BeTS performance at USNO, as compared to the USNO Master Clock.

PRECISE eLORAN TIMING SERVICE PERFORMANCE

Figure 9 shows the timing performance of two eLoran receivers compared against a GPS disciplined PRS in Billerica, MA, 310 miles from the Wildwood transmitter. The black line is from the receiver that is acting as the Differential eLoran Reference Station. It measures the timing difference between eLoran and the PRS and calculates a differential correction based on a 10-minute average. These measurements show the BeTS performance. The mean offset is 166.7 ns, with a standard deviation of 53.6 ns. The maximum and minimum of 299 and 56 ns, respectively, confirm the achievable target accuracy of the BeTS service.

The blue line is for a receiver collocated at the same site as the Differential eLoran Reference Station receiver, and also compared against the same GPS disciplined PRS. In this case, the receiver acts as a user receiver, applying the differential corrections as received through the LDC. Because the Reference and User are at the same location, this measurement is called a zero-baseline (ZBL) measurement. Clearly, the application of differential corrections completely removes any temporal changes in propagation delay. The remaining mean offset is 5.0 ns, with a standard deviation of 4.4 ns, and maximum and minimum of 36 and -31 ns, respectively.

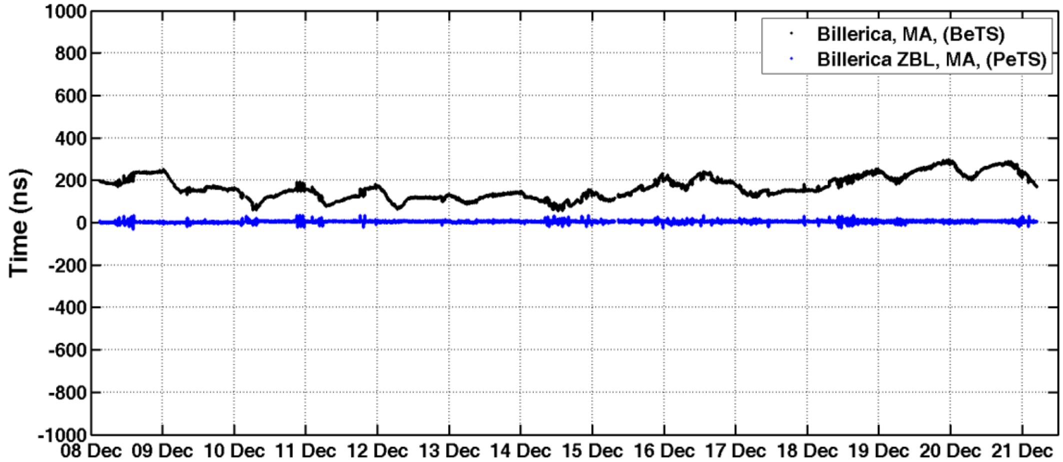

Figure 9. BeTS (black) and PeTS (blue) performance at Billerica, MA, as compared to a GPS disciplined PRS.

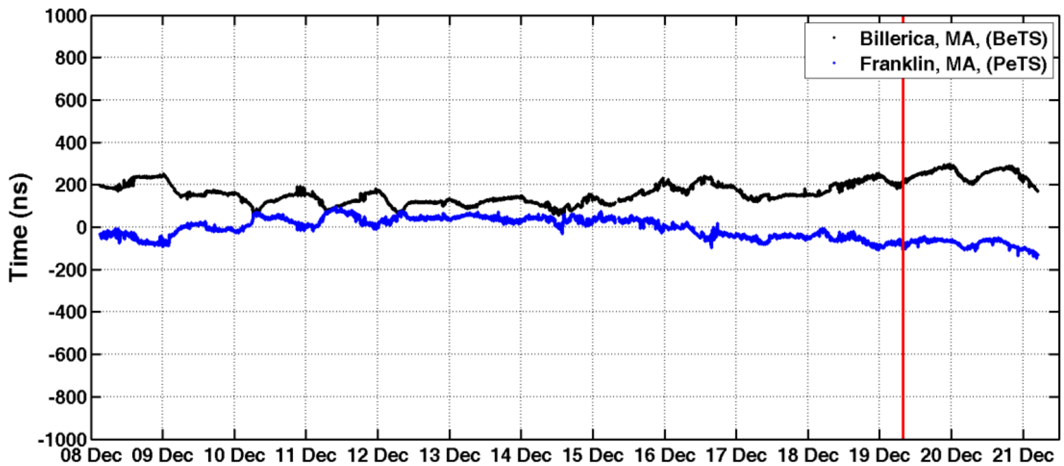

Figure 10. PeTS (blue) performance at Franklin, MA, as compared to a PRS.

Figure 10 shows in blue the performance of a receiver in Franklin, MA, 280 miles away from Wildwood. For reference, the black line showing the BeTS performance of the Billerica Reference station is shown too. The Franklin receiver is configured as a user receiver applying differential corrections originating from the Billerica Reference Station, some 35 miles away. As expected, the corrections become de-correlated with distance moving away from the Reference Station, because of the differences in propagation path for the signal from transmitter to Reference and User receivers. The magnitude of any differences depends largely upon the terrain differences between the Reference Station and the user receiver. Nevertheless, application of corrections will improve the timing output, largely through compensating for the mean seasonal, as well as part of the diurnal, behavior

Application of corrections results in a mean offset of 1.2 ns and a standard deviation of 45.2 ns. The maximum and minimum of 96 and -106 ns, respectively, are close to the target accuracy for the PeTS of 1 µs. At 20:00 hours UTC on December 19^{th} (see the red line), we configured the receiver to no longer update the differential corrections. Instead of the blue line being the mirror image of the black in the first days, hinting towards overcompensation, the blue line more or less follows the same trend as the black, be it with a smaller amplitude. Further comparison and correlation of data collected at the two sites will be done in future trials to determine if we can confirm the relationship between longer propagation path and larger diurnal swing.

CONCLUSIONS AND FURTHER WORK

This testing confirms that eLoran easily meets the requirements for a one microsecond timing service as outlined in the 2014 version of the US Federal Radionavigation Plan.

The tests described in this paper are a continuation of tests we performed in 2013 and 2014. The results confirm what was already shown in many government, academic, and industry papers in the past: eLoran has great potential as an alternative and complementary timing source to GPS.

We implemented a Differential eLoran service for timing applications. The application of differential corrections for eLoran timing receivers removes diurnal variation (zero-baseline). Differential corrections are applicable over larger distances, but de-correlate with distance between reference and rover sites because of different propagation paths to both.

These results were collected using eLoran E-field antennas. We know from previous measurements and publications that H-field antennas will generally provide better signal reception in built-up areas, and can work inside buildings. We plan to conduct side-by-side H- and E-field antenna trials to assess the different performance.

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