UTC Synchronization and Stratum-1 Frequency Recovery Using eLoran:
The Alternate Basket for Your Eggs

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BIOGRAPHIES

Dr. Gerard Offermans is Senior Research Scientist of UrsaNav's Low Frequency (LF) Solutions business unit 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. Eurofix has been deployed at Loran installations worldwide. He has received awards for a number of his scientific papers on radio navigation systems including the Medal of Merit from the International Loran Association, and has served as a board member and chairman for the ILA's standardization working group. Dr. Offermans received his PhD, with honors, and Master's Degree in Electrical Engineering from the Delft University of Technology.

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Charles Schue is co-owner and President of UrsaNav, Inc. He champions providing Low Frequency Alternative Positioning, Navigation, Time and Frequency, and Data solutions for "sky-challenged" users. He served in the U.S. Coast Guard, where his expertise included radio navigation systems, and was the first Commanding Officer of the Coast Guard's Loran Support Unit. He holds Masters Degrees in Electrical Engineering, Engineering Management, and Business Administration. He is a former Marine Representative, DC Section Treasurer, and DC Section Chairman of the ION; and a Fellow of the Royal Institute of Navigation.

Jonathan Hirschauer is an Electronics Engineer at the U.S. Naval Observatory with a primary focus on Two-Way Satellite Time Transfer. His involvement includes operations, design, installations, calibrations, testing, and research pertaining to TWSTT. He received his BS degree in Electrical Engineering from Virginia Tech in 2006 and recently completed his MS degree in Electrical Engineering from The George Washington University.

Edward Powers is GPS and Time Transfer Operations division chief of the United States Naval Observatory (USNO) in Washington DC. Previously he worked with the Naval Research Laboratory (NRL) conducting research on various projects related to precise time keeping and GPS satellite clock development. He received both his BS and MS in Engineering from the University of Arkansas (84, 87).

ABSTRACT

Accurate timing and frequency is becoming increasingly important in many applications that influence our daily lives. Eleven out of sixteen sectors of the Critical Infrastructure and Key Resources (CIKR) identified by the Department of Homeland Security (DHS) use GPS for timing and for ten it is deemed essential. More and more systems are becoming solely dependent on GPS or other 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.

The General Lighthouse Authorities of the UK and Ireland have started the deployment of equipment for an Initial Operating Capability eLoran system along the east coast of the UK, and the Republic of Korea announced

plans to deploy a nation-wide eLoran system. Other countries are likely to follow their example.

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 UTC timing within 100 ns across large areas. LF technology, including eLoran, is a well-established solution for providing services very similar to those delivered by GNSS, with characteristics and failure modes that are complementary to GNSS.

UrsaNav has entered a Cooperative Research and Development Agreement (CRADA) with the U.S. Government, which allows using existing infrastructure to broadcast signals in the spectrum between 90-110 kHz in the U.S. UrsaNav broadcasts eLoran signals on a semi-regular basis from the former USCG Loran Support Unit in Wildwood, NJ, using a 400 kW transmitter. Monitor receivers are set up in locations in Virginia, Washington, DC, and Massachusetts to monitor the transmissions and analyze the timing performance against GPS disciplined PRS*, or better. One such monitor is installed at the U.S. Naval Observatory and is compared directly to the USNO master clock. These trials have been received with a great deal of interest in the U.S. and abroad, especially from telecommunications, power grid synchronization, and other timing application users that require alternatives or back-ups for GPS-based timing solutions.

Included in the paper is a description of the transmitter and monitor receiver set-up, as well as system improvements to increase timing accuracy, such as differential eLoran. The data shows that eLoran is easily capable of sub 100 nanosecond accuracy and that further improvements can be made. This level of accuracy can be an important component in a national resilient position, navigation, and timing infrastructure.

* - Throughout this paper "PRS" is used to refer to a cesium-based 5071A Primary Reference Standard (PRS).

INTRODUCTION

GPS and other GNSS can provide accurate frequency and Universal Coordinated Time (UTC) to within 50 ns, typically to 20 ns. An increasing number of applications and services rely on accurate timing and may become unavailable if GPS timing is interrupted. Just like any prudent navigator does not rely on a single source for position 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 precise time in the absence of GPS, having an alternative source for precise time to determine when GPS is providing incorrect or misleading data is also important. An alternate, comparable source of precise time also helps ensure GPS integrity and signal authentication.

There are numerous applications and systems that require accurate and precise time. The U.S. Department of Homeland Security (DHS) has identified sixteen Critical Infrastructure and Key Resource (CIKR) sectors that use GPS for timing. For eleven (11) of the sectors, GPS timing is deemed essential for successful operation. [1] Systems that rely on GPS for timing include:

- Telecommunications networks. Landline and mobile telephone systems, paging systems, computer networks, and the internet.
- Energy and power systems. Energy plants and substations, nuclear plants, hydro dams, and wind farms which rely on precise time for power grid phase synchronization and flow control.
- Banking and financial systems. Stock trading, inter-bank transactions, and ATM transactions.
- Transportation systems serving maritime, aviation, and land-based operations. Electronic Chart Display & Information Systems, Digital Selective Calling, Automatic Identification System, Next Generation Air Transportation System, Positive Train Control, and the Intelligent Transportation System.
- Emergency services. E-911, E-112, and the Land Mobile Radio network.
- Military and Defense operations. C5ISR systems, secure communications systems, the defense industrial base.
- Commerce and manufacturing. Plant operations, critical manufacturing, shipping, and port operations.

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). As shown in Figure 1, jamming devices (sometimes referred to as "Personal Privacy Devices) and spoofers are easily obtainable, low-cost, and very effective.

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 satellite navigation spectrum. [2]

Figure 1: Low-Cost “Personal Privacy Devices”

In the Republic of South Korea, intentional jamming has taken a completely different turn. Over the past three years, their North Korean neighbors have jammed satellite reception on numerous occasions with ever increasing intensity. Consequently the impact of their actions also increased, hampering operations of aircraft and marine vessels and disabling the mobile phone systems.

Table 1 shows the GPS disruptions reported by the Central Radio Management Office of South Korea as a result of the North Korean jamming events.

Dates	Aug 23-26, 2010 (4days)	Mar 4-14, 2011 (11 days)	Apr 28 – May 13, 2012 (16 days)
Jammer Locations	Kaesong	Kaesong, Mountain Kumgang	Kaesong
Affected Areas	Gimpo, Paju, etc.	Gimpo, Paju, Gangwon, etc.	Gimpo, Paju, etc.
GPS Disruptions	181 cell towers, 15 airplanes, 1 battle ship	145 cell towers, 106 airplanes, 10 ships	1,016 airplanes, 254 ships

Table 1: GPS disruptions of the past 3 years resulting from North-Korean jamming [3]

The South Korean government has announced their plan to install a complete eLoran system with five transmitters covering their mainland and territorial waters, protecting their interests in the Korean Economic Zone, and beyond.

Even without these threats, GPS usage 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 equipment and installation 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 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. [4]

ELORAN FOR TIME AND FREQUENCY

eLoran is a high-power, low-frequency, long range radionavigation system that provides similar Position Navigation, Time and Frequency services as GNSS, without the same failure modes as GNSS.

There are some fundamental differences between the legacy Loran-C system that was operated in the U.S. and modernized eLoran. eLoran contains a data channel to distribute UTC Messages (time of day, date, leap seconds) and integrity information. UTC Messages provide exact Time of Transmission (TOT) of eLoran Pulses.

eLoran uses pulse-shaped signals with a 100-kHz carrier. The pulses allow the receiver to distinguish between the ground wave and skywave 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 skywaves.

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

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

where:

TOR - Time of Reception
TOT - Time of Transmission
PF - Primary Factor (propagation through air)
SF - Secondary Factor (propagation over sea)
ASF - Additional Secondary Factor (propagation over land and elevated terrain)
ΔRx - Receiver and cable delays

The Primary and Secondary factors are well defined and can be calculated as a function of distance. The Additional Secondary Factor delay is mostly unknown at the time of installation. Fortunately, the ASFs remain stable over time, so a one-time calibration of ASFs and receiver and cable delays are sufficient to get UTC at the receiver close to UTC at the transmitter. The calibration is straightforward. First, an approximate antenna position is entered into the receiver to provide a coarse ASF compensation. Then a one-time calibration of ASF, receiver and cable delays is made using an external UTC source (e.g., GPS, Cesium "Hot Clock", TWSTT, etc.). The calibration is valid for each static antenna installation. Any changes in fine ASF over time may be compensated by a Differential eLoran Reference Station.

TESTING eLORAN IN THE UNITED STATES

In March 2011, UrsaNav entered into a Cooperative Research and Development Agreement (CRADA) with the Department of Homeland Security (DHS), which allows the use of former Loran-C infrastructure to test eLoran. For the purposes of this trial, the former U.S. Coast Guard Loran Support Unit site in Wildwood, NJ, was used as the broadcast site. UrsaNav installed eLoran monitor equipment at different locations to evaluate eLoran's timing performance in the field against other sources of UTC.

Shown in the following Figure 2 is the location of the transmitter site and three of the monitor locations. The monitor sites used UrsaNav's UN-152B eLoran Timing Receivers. One each was installed at the United States Naval Observatory in Washington, DC, and UrsaNav offices in Leesburg, VA, and Bedford, MA. Table 2 shows the distance between the transmitter and the monitor locations.

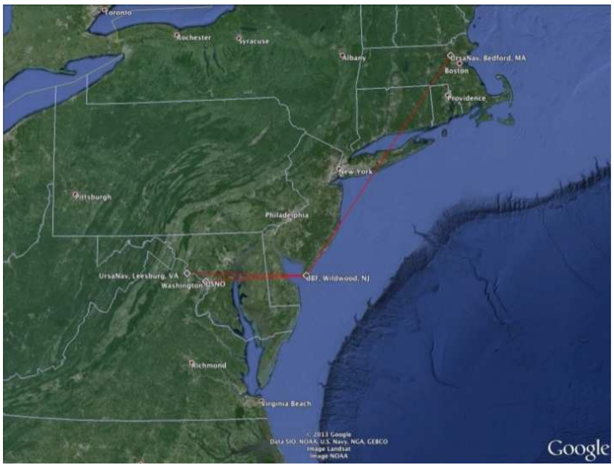

Figure 2: Locations of Test Transmitter and Monitor Receivers.

The test facility in Wildwood, NJ has multiple baseline transmitters available. Additionally, in 2011 UrsaNav installed a next generation prototype eLoran transmitter from Nautel for trials and demonstrations.

Monitor Location	Distance from Transmitter
USNO (DC)	118 miles
Leesburg, VA	143 miles
Bedford, MA	311 miles

Table 2: Distance between Transmitter and Monitor sites.

When paired with the existing 625-FT antenna, the prototype transmitter provides 60 kW of radiated power. The data of these trials were based on the use of a 400 kW legacy Loran-C transmitter, the timing of which is controlled by a GPS disciplined PRS clock.

At USNO, the 1PPS output of the UN-152 eLoran timing receiver is directly compared with USNO's Master Clock. At Leesburg and Bedford, 1PPS outputs were compared against a PRS and a Trimble GPS timing receiver, respectively. At all sites, the ASFs, receiver and cable delays were calibrated once, prior to the trials using the UTC sources present. Measurements were taken during a period of over 15 days of continuous broadcast.

Figure 3 is a plot of the time difference between the 1PPS output of the UN-152 eLoran Timing receiver and the USNO Master Clock. Measurements are taken once every minute and stored. Figure 3 shows a distinct diurnal behavior. Over the whole 15-day period the 1PPS output from eLoran remains in agreement with the USNO Master Clock. The standard deviation of the time differences is 29 ns. The offset of approximately 100 ns is caused by incomplete calibration of all cable delays from the eLoran receiver to the USNO Master Clock, and can be further improved.

In Figure 4 the time difference measurements between the 1PPS output of the UN-152 eLoran Timing receiver and a PRS in Leesburg, VA are shown. Differences between GPS or PRS and eLoran 1PPS were measured over 120-second observation interval (averaged).The measurements are taken over the same period as the measurements at USNO. The location in Leesburg is approximately 25 miles farther from the Wildwood, NJ transmitting site than USNO, and approximately along the same baseline. The measurements show the same diurnal behavior with slightly larger amplitude. The standard deviation of these measurements is 36 ns.

A comparison of the measurements of Leesburg and USNO is presented in Figure 5. It is apparent that the measurement results are highly correlated. It is clear that a user in Leesburg, or in fact the greater Washington, DC area, would benefit from differential corrections from a Reference Station collocated at USNO.

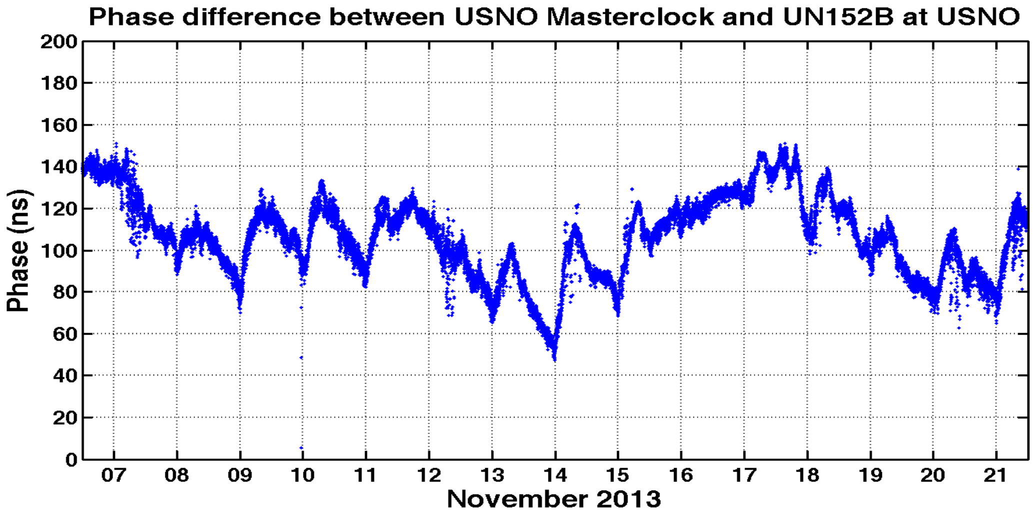

Figure 3: Measurement results of UN-152 1PPS output vs. USNO Master Clock over 15 consecutive days.

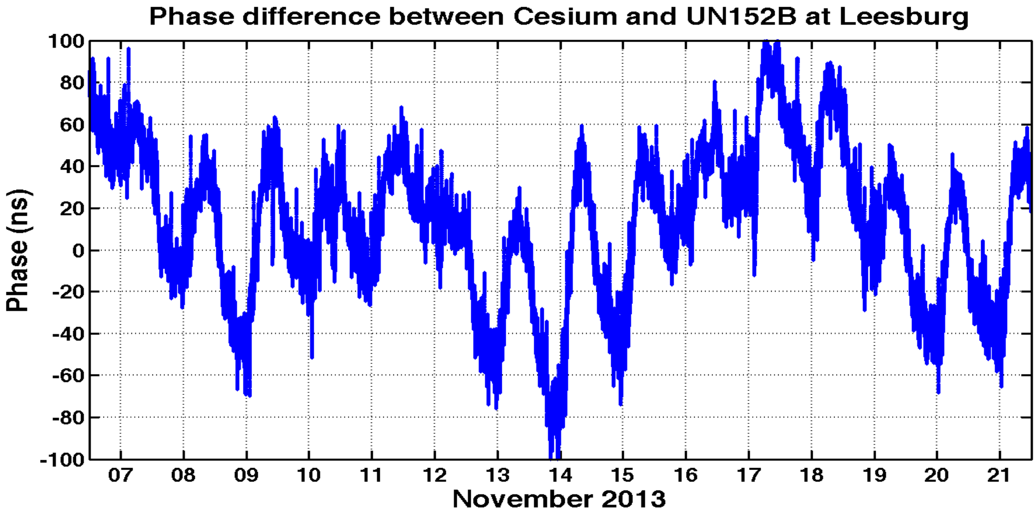

Figure 4: Measurement results of UN-152 1PPS output vs. PRS at Leesburg, VA, over 15 consecutive days.

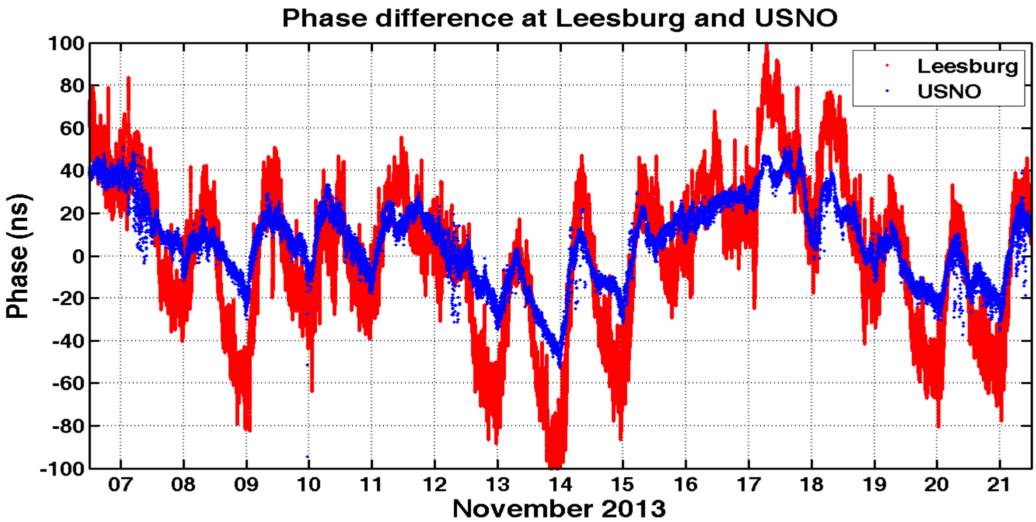

Figure 5: Comparison of measurements at Leesburg (red) and USNO (blue)

Figure 6 shows the measurement results of the UN-152 eLoran Timing receiver vs. a Trimble GPS receiver in Bedford, MA, for 5.5 days during the same period of the USNO and Leesburg data collection. Differences between GPS and eLoran 1PPS were also measured over a 120-second observation interval (averaged). Even though the monitor location is farther away from the transmitter, the plot shows less diurnal swing, and consequently a slightly lower standard deviation of 27 ns.

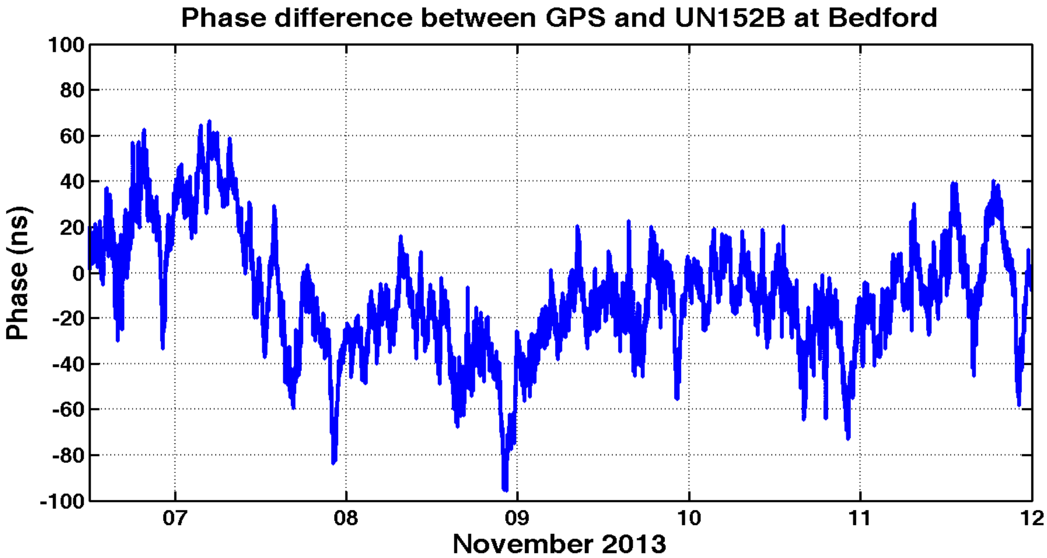

Figure 6: Measurement results of UN-152 1PPS output vs. Trimble GPS receiver at Bedford, MA, over 5.5 days

eLORAN FOR SMARTGRID APPLICATIONS

In March 2013, UrsaNav performed eLoran timing trials in cooperation with the University of Tennessee at Knoxville to investigate if eLoran could be used to time synchronize Frequency Data Recorders (FDR) for SmartGrid applications. FDRs measure the current frequency and phase of the power grid and report the measurements back to the University for analysis and correlation with other FDRs at other nodes of the grid. Frequency disturbances or phase differences are often an indication of changing grid loads or malfunctions. For its accurate measurements, the FDRs need a source of absolute (UTC) timing, for which the FDRs are equipped with an onboard GPS timing receiver. If GPS synchronization is not available the FDRs cannot output their measurements, and valuable monitor information is missing. The purpose of the trial was to show eLoran's capability to provide the same synchronization functionality for the FDRs as GPS, and provide an alternate synchronization method for SmartGrid sensors.

One FDR was unmodified and synchronized using GPS. In the other FDR, the GPS engine was replaced with a UN-152 eLoran Timing receiver providing a 1PPS signal and time messages, as shown in Figure 7. Both FDRs were connected to the internet to provide their data to the measurement server at the University of Tennessee. The lab set-up for the eLoran timing trials for SmartGrid is presented in Figure 8.

Figure 7: Modification of Frequency Data Recorder with UN-152 eLoran Timing receiver.

Presented in Figure 9 are the measurement results of the FDR units synchronized to GPS (black) and eLoran (green) respectively. The top left shows the frequency measurements; the bottom left shows a detail of the first 150 seconds. The top right shows the phase (or angle) measurements, with a detail of the first 150 seconds in the bottom right. In all plots, measurements from the FDR synchronized to GPS and from the FDR synchronized to eLoran are highly correlated. In the detailed plot of the first 150 seconds it looks like the GPS synchronized unit shows some anomalies, the cause of which is unknown. From our measurements and the feedback from colleagues at the University of Tennessee, it was concluded that eLoran can be used as a co-primary system for synchronization of equipment (such as Frequency Data Recorders) in SmartGrid systems.

Figure 8: eLoran for SmartGrid trial set-up in Bedford, MA.

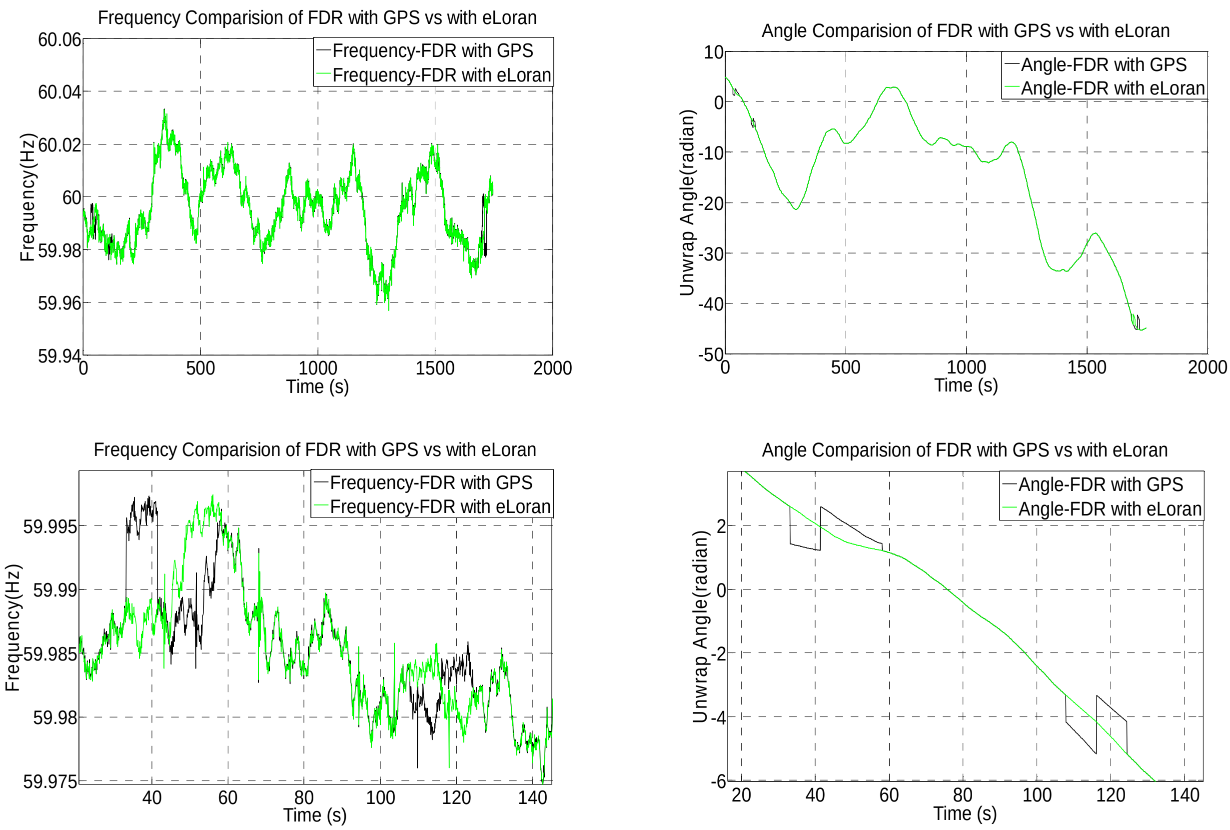

Figure 9: Frequency (Left) and Angle (Right) comparison between FDRs synchronized with GPS (black) and eLoran (green)

eLORAN IN EUROPE

In Europe, there is an existing Loran-C infrastructure with nine transmitters located in the UK, France, Germany, Denmark, and Norway. The Anthorn station in the UK has been upgraded to eLoran, with a Loran Data Channel capability providing UTC and differential corrections for navigation in UK waters.

The General Lighthouse Authorities of the UK and Ireland are installing equipment to provide an Initial Operating Capability (IOC) eLoran system at five more harbors along the Scottish and English East coast, in addition to existing installations at Harwich and Dover. The GLAs' IOC eLoran system is expected to be operational in the fall of 2014.

The measurement results of a UN-152 eLoran Timing receiver vs. a Novatel OEM3 GPS receiver in Bertem, Belgium, over six days is shown in Figure 10. Differences between GPS and eLoran 1PPS were measured over the 120-second observation interval (averaged). The eLoran receiver was synchronized to Lessay, France at a 298 mile distance from the monitor location. The measurements show similar diurnal behavior as seen in the U.S., although with a much lower amplitude. The measured standard deviation is 14 ns over the six-day period.

Figure 11 shows the Maximum Time Interval Error performance of a UN-150 eLoran Timing receiver and a TS3100 GPS Timing receiver as measured by Chronos Technology in the UK. For these measurements a PRS is used as a reference. Both the eLoran and GPS receivers meet the European Telecommunications Standardisation Institute (ETSI) mask for Primary Reference Clocks.

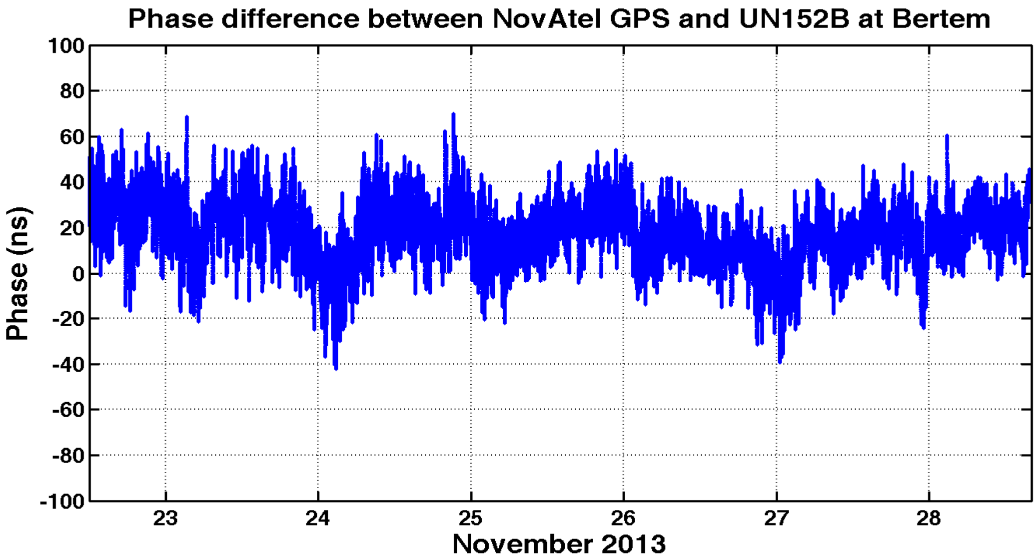

Figure 10: Measurement results of UN-152 1PPS output vs. NovAtelGPS receiver at Bertem, Belgium.

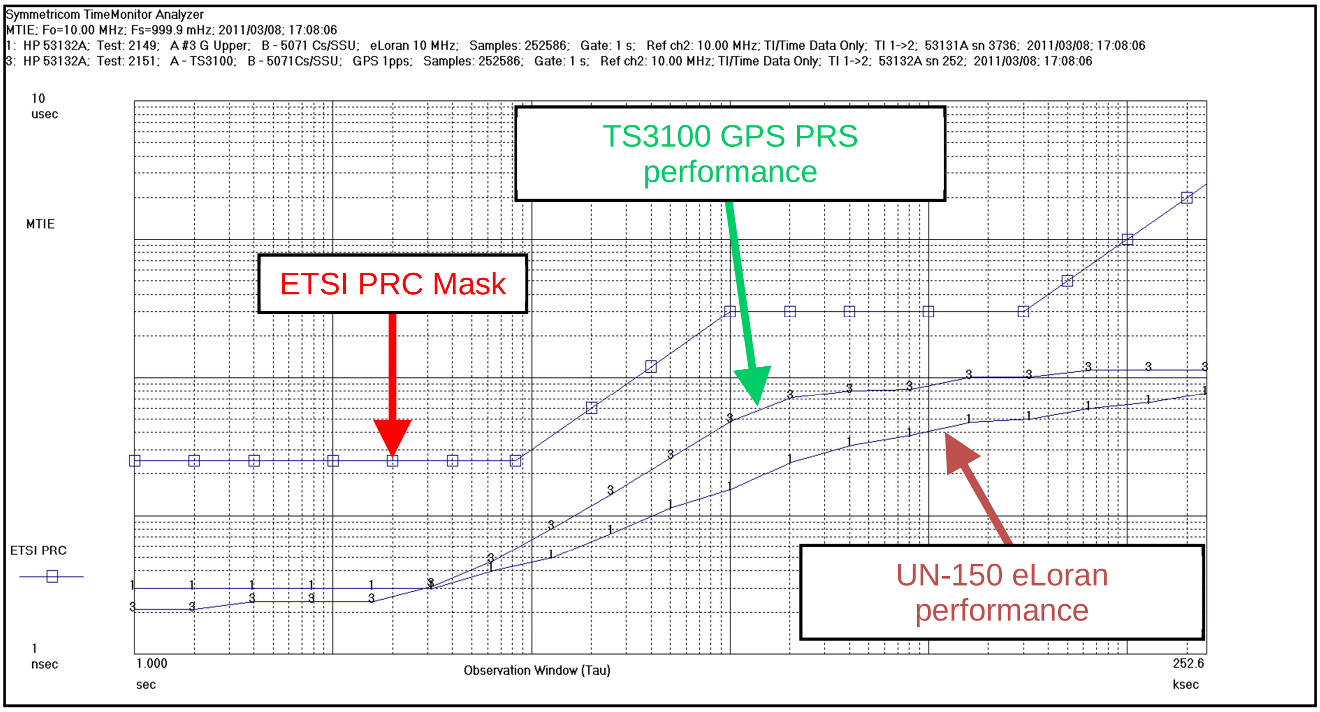

Figure 11: Maximum Time Interval Error performance of a UN-150 eLoran Timing receiver and a TS3100 GPS Timing receiver with an HP5071A Cesium as a reference at Chronos Technologies in the UK.

A POTENTIAL FOR ELORAN IN THE U.S.

It has been noted over the past years that there is a need for an alternative, or co-primary system, for many PNT applications. Even though the need for alternate systems has been identified and eLoran was identified as the prime candidate for providing these services, no plans for U.S. eLoran implementation have thus far materialized. [5]

UrsaNav has taken the initiative to propose the implementation of a Public Private Partnership (PPP), based on eLoran, that would provide co-primary timing and frequency across the CONUS.

There are a range of possible options, depending upon the level of interest and commitment by Government partner(s) that could determine the ultimate structure of such a service. One possible approach would be the loan of existing Government assets (i.e. land, buildings, antennas, site equipment) under a 20 year lease. Industry partner(s) would provide the technology and services to fulfill a service-level agreement. It is possible, with existing and proposed signal structures, to implement a tiered service with mechanism for revenue recovery to reduce or eliminate out-year costs to the Government.

The UrsaNav proposal extends beyond timing and frequency to the re-establishment of an infrastructure that could be used for positioning and navigation applications, effectively resurrecting the coverage that existed in 2008.

The approach would rapidly build out a high reliability timing network (dual coverage) in CONUS. Timing and frequency users need only acquire a single station with a data channel, and therefore a significant coverage area is developed in minimal time and at minimal cost. A candidate configuration using four transmitters for an eLoran timing service is shown in Figure 12. There is immediate benefit technically, politically, and economically, to such an approach. Assuming successful adoption by users, positioning and navigation capabilities targeting selected user communities could be added later.

There are several benefits to the U.S. Government of this approach. It fulfills backup PNT capabilities per NSPD-39, advances technology, creates employment, and defers environmental compliance and remediation costs.

CONCLUSIONS AND FURTHER WORK

The CRADA testing to date has essentially verified what was already shown in countless government, academic, and industry papers in the past: eLoran has great potential as an alternate and complementary timing source to GPS.

We showed in this paper that an eLoran system (transmitter and receiver) meets the Statum-1 frequency standard and ETSI PRC mask requirements and that an eLoran system can provide UTC synchronization over large areas. The eLoran 1PPS with respect to UTC is influenced by diurnal and seasonal variations in ASF and these fluctuations can be compensated for using differential eLoran corrections. eLoran service is capable of UTC synchronization within 100 ns (unassisted) and better than 50 ns (with differential corrections).

While the United Kingdom and Republic of South Korea are moving forward with eLoran, fulfilling requirements for resilient PNT solutions (co-primary solution to GNSS), the U.S. has been slow to move forward. An alternate way was proposed.

Further steps in research and development include continuing eLoran trials under the CRADA agreement, and implementation and demonstration of Differential eLoran for timing. This includes relocating the Two Way Satellite Time Transfer system currently synchronizing the low-power (60 KW) transmitter to enable synchronization of the high-power (400 KW) eLoran transmitter to USNO. UrsaNav also plans to continue development of eLoran provider and user equipment, including equipment and technology for the UK's IOC Differential eLoran system, and installation and test of a Nautel production eLoran transmitter.

ACKNOWLEDGMENTS

The authors would like to acknowledge the United States Naval Observatory for participating in these trials, providing access to their facilities and a timing truth reference to their Master Clock. USNO also provided the TWSTT equipment to the USCG/DHS to assist with timing studies.

The authors would further like to thank the staff and students of the University of Tennessee for their participation in the SmartGrid trials, and lending us the FDR equipment.

We thank Chronos Technology in the UK for performing timing trials in the UK and providing an independent assessment of the performance of the UN-150 and UN-151 series eLoran Timing receivers.

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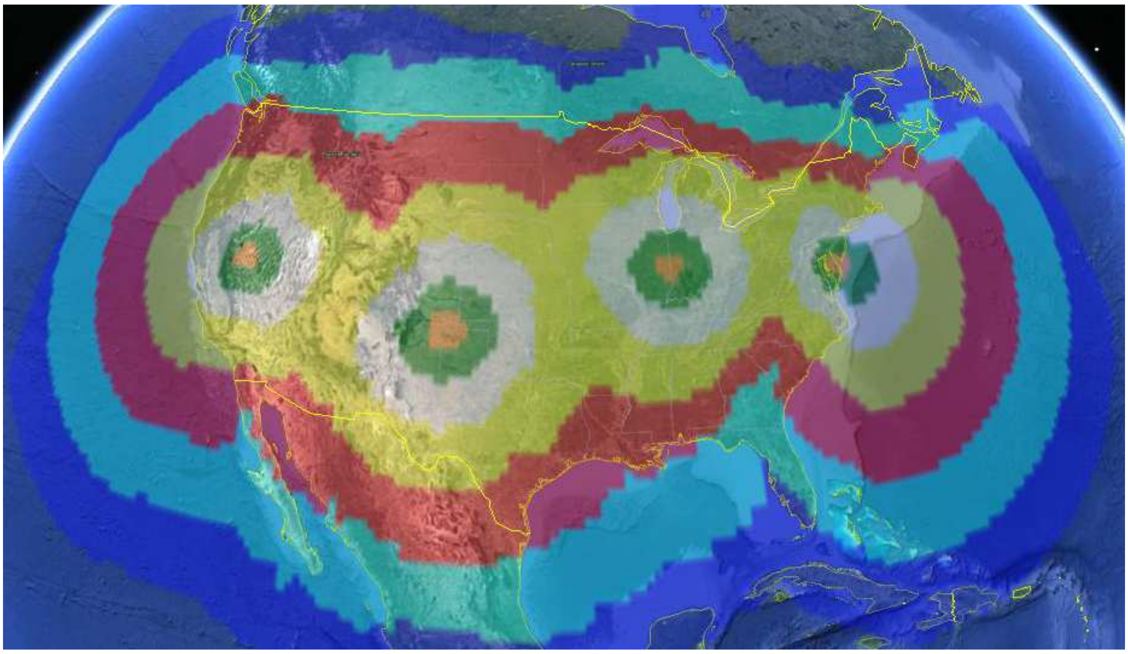

Figure 12: Potential eLoran coverage for timing with transmitters at four sites.