PTTI CAPABILITIES OF THE MODERNIZED LORAN SYSTEM

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Abstract

This paper covers the current status and future plans of the modernized LORAN system. Special focus is placed on the enhanced LORAN system in North America and Europe. These modernized systems have new capabilities that allow them to serve as sources of precise time and frequency that can meet the needs of telecommunication and power industry users. The paper discusses recent technological developments in LORAN time and frequency equipment, at both the transmission and receiving sites. It presents and discusses results from recent field tests that demonstrate the current timing capabilities of the modernized LORAN System. It also describes future changes planned for eLORAN that will further improve its accuracy and performance.

I. INTRODUCTION

LORAN, an acronym for LOng RAnge Navigation, is a radio navigation system operating at 100 kHz that was originally developed during World War II. The system is operated by the United States Coast Guard (USCG), and consists of a network of land-based radio transmitters that have traditionally allowed mariners and aviators to determine their position. Recently, there has been a growing interest in LORAN from the timing community. LORAN primarily covers the Northern Hemisphere (Figure 1), providing all-weather position, navigation, and timing (PNT) services. Although not as precise as Global Navigation Satellite Systems (GNSS), its PNT accuracies are much better than any other ground-based system.

There has been a tremendous effort since 1997, at a cost of nearly $160M USD, to modernize the LORAN system. This modernization has ensured continued service and reduced operating and manpower costs, while continuing the high level of signal availability users are accustomed to receiving. In addition, the modernization effort has enhanced the timing capabilities of LORAN. This paper predominantly covers the modernization of the North American LORAN system (known as enhanced or eLORAN), but some effort has been made to provide a more global perspective. However, non-U.S. LORAN providers were unwilling to discuss their efforts in detail, perhaps due to the fact that the U.S. government has also been unable or unwilling to provide a complete plan on the movement towards eLORAN.

Figure 1. LORAN coverage map **[1]**.

eLORAN adds a data channel to the legacy LORAN-C broadcast that improves system accuracy and integrity. Currently, two variations of this data channel exist; the LORAN Data Channel (LDC) in the United States and Eurofix in Europe. There is no current international consensus on which data channel to use; and it remains possible that another alternative with a higher data rate could be chosen. No matter which method is selected, the key concept is to separate the data channel from the navigation service in a way that allows regional LORAN providers to best meet the requirements of their users.

Although not yet fully implemented, the United States government has already designated eLORAN as a national system that will complement GNSS in the event of an outage or disruption in service, and mitigate any safety, security, or economic impacts **[2]**. To meet these goals, eLORAN must be an independent and complementary system that allows GNSS users to:

- Continue operations if the eLORAN accuracies are within the user's requirements.
- Allow users to scale back operations and take the appropriate safety measures when they are using the eLORAN system as their alternate PNT source.
- Allow users to safely cease and/or limit operations until GNSS is restored.

Recent studies and tests indicate that eLORAN meets or exceeds the accuracy, availability, integrity, continuity, and coverage requirements necessary to achieve 8- to 20-m maritime Harbor Entrance Approach (HEA) and aviation Required Navigation Performance (RNP) for non-precision approaches. It will also allow users to recover Coordinated Universal Time (UTC) to within ±50 ns RMS **[3]**.

II. MODERNIZED LORAN AS A TIMING SYSTEM

This section reviews the history and current status of LORAN timing systems in North America and Europe.

2.A. MODERNIZED LORAN IN NORTH AMERICA (ELORAN)

This section reviews the old and new methods used to control LORAN timing. Since the modernization efforts have begun, the USCG has improved the reference clocks at the individual transmitting stations, the intra-chain timing between stations, and the overall system synchronization to UTC. Each station has three cesium clocks installed, and new Time and Frequency Equipment (TFE) was installed at the stations, beginning in the spring of 2003.

Prior to the installation of the new TFE, station operators had to be careful to not allow weather and system maintenance to influence clock frequency and time adjustments. The Master Station’s #1 clock was synchronized to the UTC time scale of the United States Naval Observatory, UTC (USNO), through several far field monitoring stations located around the continental U.S. and Alaska. Weather could have a serious impact on the quality of the reported offsets. There were also several maintenance procedures that could adversely impact the system readings. Operators had to be aware of these procedures and provide feedback to the individuals performing the calculations for clock steering, but unfortunately, this did not always happen.

The C-field on the #1 clock was typically never adjusted. Instead, a phase microstepper was placed in line that provided enough resolution to make the required frequency adjustments. The #2 and #3 clocks at the Master Station were then compared to the #1 clock using a phase comparator system. The #2 and #3 clocks were manually kept in phase (within ±15 ns) of the #1 clock through a set of phase resolver dials. The operator would either advance or retard the phase of the clocks to keep them in alignment (Figure 2.A). This was eventually done automatically using a set of phase microsteppers in the #2 and #3 clock paths that introduced 10-ns steps when needed to maintain the alignment between the three clocks. The ability to adjust the #2 and #3 paths was critical to maintain the alignment, because the C-Field adjustments on the older Hewlett-Packard 5061A* cesium clocks lacked the resolution needed to adequately maintain the phase between the three clocks.

The #1 clock at the secondary stations was synchronized to the Master Station clock by determining the total number of phase corrections applied to the secondary station to maintain the Time Difference (TD) in the user area. This was divided by the number of days of data collected to get an average offset, and then used to calculate the amount of adjustment the local operators would need to add to the phase microsteppers at each secondary station. Here again, weather played a significant role. Weather fronts passing between the Master-Secondary pair would influence the amount and direction of the phase corrections during these events. Operators had to be careful to obtain an adequate amount of data before making corrections. Typically, the event would pass within 1 or 2 days, and operators would need to enter phase corrections to compensate for the event. However, if they computed corrections before the event was over and/or did not discard the data for the day the event occurred, their calculations would be incorrect. The #2 and #3 clocks at each secondary station were handled in the same way as the #2 and #3 clocks at the Master station.

Beginning around 2000, the USCG replaced the three 5061A cesium clocks at each LORAN station with three 5071A* cesium clocks (standard performance beam tube), as shown in Figure 2.B. This did not eliminate the need for the operator to determine and enter frequency corrections to the clocks, but it did provide a method of steering the #2 and #3 paths, and greatly improved the ability of the operators to align the three clocks at each station. It also eliminated the need for the phase microstepper in the #1 path, so that unit was removed.

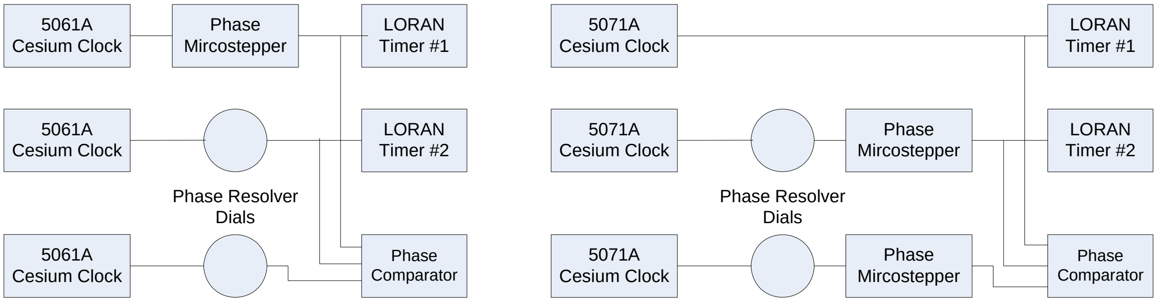

Figure 2.A and B. Typical 5-MHz distribution prior to TFE installation.

When the new TFE was installed starting in the spring of 2003, the need for operator clock management was eliminated, and a time scale was established at each station. A new requirement was instituted to keep the station time scales within ±20 ns of UTC (USNO) by using GPS as a reference, and long-term measurements have shown that most are held within ±10 ns.

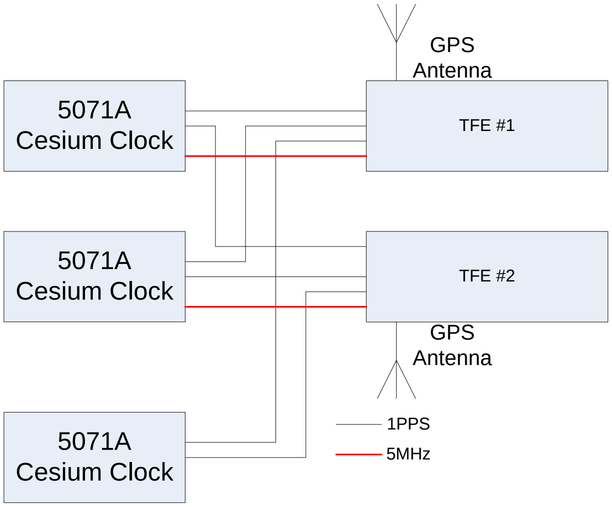

Figure 3. Time and Frequency Equipment block diagram.

The new TFE (Figure 3) replaced the 1970s' vintage equipment that applied the phase coding and coding delays to the LORAN broadcast, controlled and adjusted the timing of the broadcasts, and provided reference signals for local time interval measurements. In addition, the new TFE performed the following functions:

- UTC recovery and time scale computation using GPS
- Time-difference measurements for control and monitoring
- RF sample detection to monitor and control transmitter output
- Error detection and alarm functions
- Alarms for the operators to monitor system performance and faults

- Automatic blink function for aviation users (±500 ns w/10 s time to alarm).

The TFE uses the oscillators to compute its own local time scale, which is referenced (synchronized) to UTC (USNO) via an external reference, currently GPS. Once the time scale has been computed, the clocks are steered by TFE in order to maintain synchronization of the transmitted signals to UTC (USNO). The signals from all three oscillators are fed into both TFEs, and each TFE computes its own local time scale independently. This allows the operators to compare the values reported from each unit in the event of any undesired behavior.

As shown in Figure 4, the new TFE and a USCG initiative to improve signal monitoring reduced the amount of equipment and power required to operate the system. Routine maintenance and equipment alignment and calibration have been eliminated, and unattended operations are now possible. Removing station personnel will further reduce the costs of system operation.

(~1970 - ~2001)
Loran Station Havre, MT

(2001 – Present)
Loran Station Nantucket, MA

Figure 4. Past and present LORAN operation rooms.

Currently, all of the stations in the continental U.S. and two stations in Alaska (Kodiak & St. Paul) are operating with the new TFE. All of the clocks at the Canadian Stations and four stations in Alaska (Attu, Port Clarence, Tok, and Shoal Cove) are still being operated manually (Figure 5). All U.S. and Canadian stations are now operating with 5071A* cesium clocks.

The synchronization of the LORAN stations to UTC has been required since 1971 under an agreement between the USCG and the USNO. The initial requirement was ±25 μs and was lowered to ±2.5 μs in 1974. Originally, these requirements were met by using monitor receivers around the continental United States, Alaska, and Hawaii. As mentioned earlier, these monitors were susceptible to interference, weather, and other propagation anomalies, but were adequate for the task.

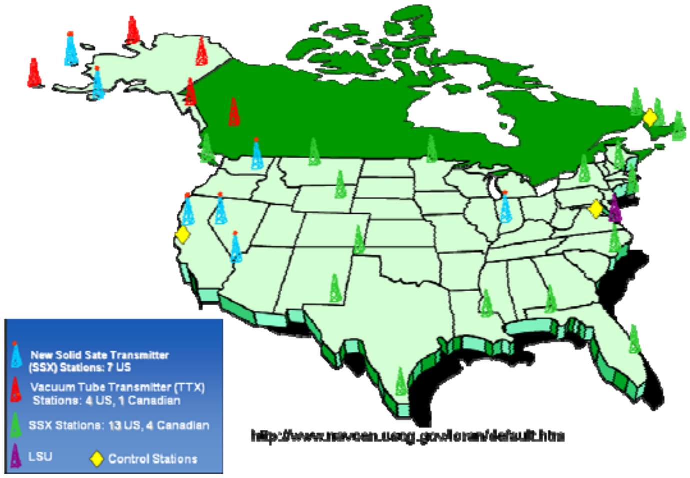

Figure 5. Loran modernization status, December 2008.

The 1987 *Airport and Airway Improvement Act* amendment (Public Law 100-223) reduced the synchronization tolerance to ±100 ns for all chains serving the National Airspace System (NAS). The USCG and USNO then established a set of administrative control procedures, and testing began on four chains (7980, 8970, 9940, and 9960) to determine whether these procedures would allow the USCG to meet this mandate. A series of frequency adjustments and chain time steps were made between February and August of 1989, and the chains were held to within ±200 ns of UTC (USNO). Although the initial report indicated that this was accomplished with about 84% confidence, the monitoring was still accomplished in the far field and was also subject to propagation issues such as weather **[4]**. Had the UTC source been available at the transmitting station rather than in the far field, the accuracy and degree of confidence could have been significantly improved.

In 1993, the USCG began studying GPS and Two-Way Satellite Time Transfer (TWSTT) methods as potential ways of improving synchronization. The results of this study showed that the TWSTT system could easily meet the requirements, but the cost of operating the system on a large scale would exceed the operating budget, so the TWSTT efforts were abandoned. Based on data obtained by the USCG, USNO, and the National Institute of Standards and Technology (NIST), it was determined the most cost-effective method available that met the requirements was GPS common view.

Between 1993 and 1996, the USCG initiated the "UTC Synchronization Project" to meet the ±100 ns requirement using one-way GPS broadcasts. Research showed that if a GPS receiver could average long enough, the impact of Selective Availability (SA) could be dramatically reduced. Thus, the USCG eventually shifted to using the Hewlett-Packard Smart Clock* to provide the source of UTC at all of the Master Stations in the U.S. and Canada. By 1997, these Time of Transmission Monitor (TOTM) systems (Figure 6) were installed, calibrated, and in operation. Under this control concept, each Master Station was synchronized to UTC (USNO). This dramatically reduced the number of clock frequency adjustments and improved the accuracy of those adjustments that were entered. The TOTM system eliminated the need for chain time steps and the need for far field monitoring, although USNO continued to provide this service for a number of years after these systems were installed. This system is still in use at three transmitting stations (Tok, Alaska; Williams Lake, British Columbia; and Comfort Cove, Newfoundland).

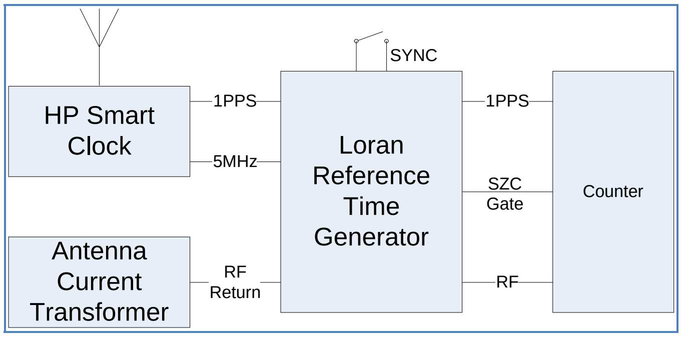

Figure 6. Time of Transmission Monitor (TOTM) System.

The use of one-way GPS broadcasts for synchronization violates the eLORAN requirement that the stations must be synchronized to a national time standard using a method independent of GNSS **[5]**. To achieve GNSS independence, the USCG and Symmetricom* have been working on a TWSTT system. The proposed concept, shown in Figure 7, includes LORAN time scales at two U.S. Loran control centers that are linked to either the USNO or NIST. The two control centers would then schedule TWSTT measurements with each station site, so that all of the station time scales are traceable to UTC. The two control centers allow the USCG to establish continuous traceability, and still maintain a flexible TWSTT measurement schedule without placing a large burden on either the USNO or NIST.

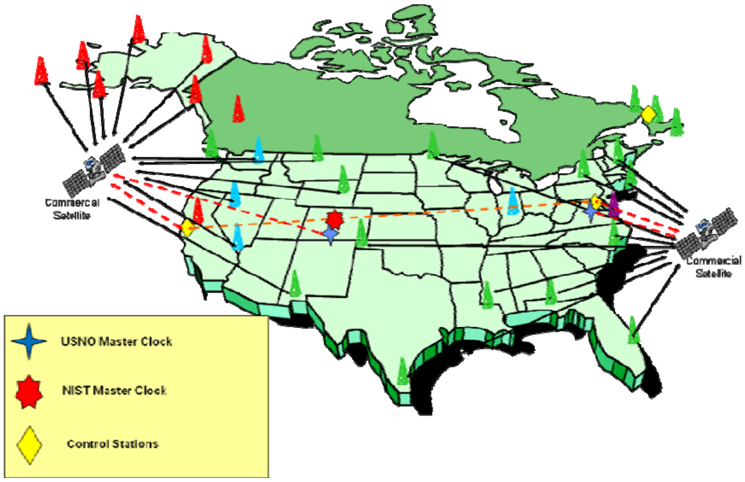

Figure 7. Proposed eLORAN TWSTT network.

Until January 2007, the USCG used System Area Monitor (SAM) control to keep the Time Differences (TDs) in the user area stable. The Monitor Sites (Figure 8) have a receiver tracking the signal and each monitor site was assigned a nominal TD value. Operators used these nominal and reported TD values to maintain the chain timing. This method, like the other far field monitoring methods, was susceptible to weather and other propagation anomalies. The phase corrections entered to maintain the intra-chain timing were the values used to compute the drift rate on the secondary station's #1 clock. This method of control provided the greatest accuracies for those users located in the vicinity of the monitor sites.

Starting in January 2007, the USCG began shifting to a new control philosophy called Time of Transmission (TOT) control. Under TOT control, all stations, including secondary stations, are synchronized to UTC via GPS. Although the basic chain structure will continue unchanged, under TOT Control timing is held constant at the transmitting station rather than in the far field. This change in control philosophy has several benefits: all of the stations in the chain are tied to a common reference (UTC), operators are no longer compensating for the weather, and it redistributes the accuracy curves in the coverage area to provide better accuracies to more of the users. It does have a negative impact for those users around the monitor sites in regards to accuracy, and the repeatable accuracy will also be degraded. Moving to TOT Control is also one of the requirements for eLORAN; all broadcasts must be tied to UTC via a traceable reference.

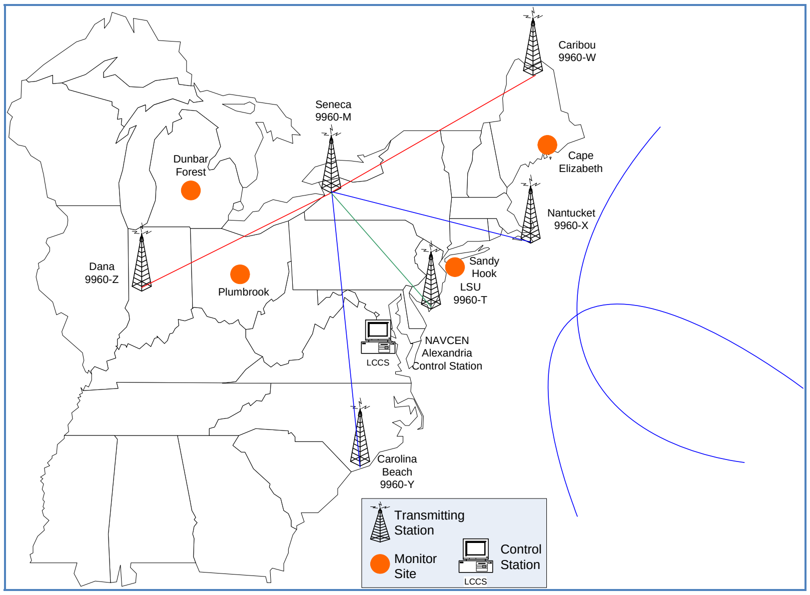

Figure 8. System area monitor control.

2.B. ELORAN IN EUROPE

The General Lighthouse Authority (GLA) for the UK and Ireland has been looking at eLoran to provide an alternate/backup source of UTC to the telecommunications industry. Its conclusion was that eLORAN can mitigate the impacts of long-term GNSS outages and by using both systems it can have a robust network infrastructure. eLORAN has the ability to work indoors, which provides a significant advantage in those areas where access to GNSS signals is limited or impractical. One of their primary concerns is the mobile phone network. All 3G base stations in the UK are to be synchronized to within ±3 us of UTC to support users moving between cell towers. eLORAN will allow these base stations to continue operating through “medium-term” GNSS outages that would otherwise take them out of service.

The UK views eLORAN as an official source of time, similar to the MSF time station that broadcasts on 60 kHz. MSF is referenced to the UTC time scale at the National Physical Laboratory (NPL), and carries a time and date code that can be received and decoded by a wide range of readily available radio-controlled clocks **[6]**. The Measurement Advisory Committee of the UK Department of Trade and Industry is currently investigating the potential of using eLORAN to replace the MSF broadcasts once the current contract with the National Physical Laboratory expires in 2017 **[7]**.

The Eurofix modulation scheme uses the last six pulses of the standard LORAN pulse group (Figure 9). These pulses are Pulse Position Modulated (PPM) by ±1 μs. There are 729 possible modulation patterns. To minimize the impacts to users, the PPM encoding uses 128 of a possible 141 balanced patterns to represent seven bits of data per Group Repetition Interval (GRI). The data rate is 70 to 175 bits per second, based on the GRI, and uses forward error correction (Reed-Solomon encoding) **[8]**. The Eurofix message length is fixed at 210 bits with consisting of 30 seven-bit words (GRIs). Seventy bits are used to represent the application data, while the remaining 140 bits are used for the forward error correction. The 70 bits of application data are structured such that four bits indicate the message type, 52 bits contain the application data, and there are 14 Cyclic Redundancy Check (CRC) bits. There are 16 possible message types that can be broadcast using Eurofix with Message Type 6 providing the UTC data **[9]**.

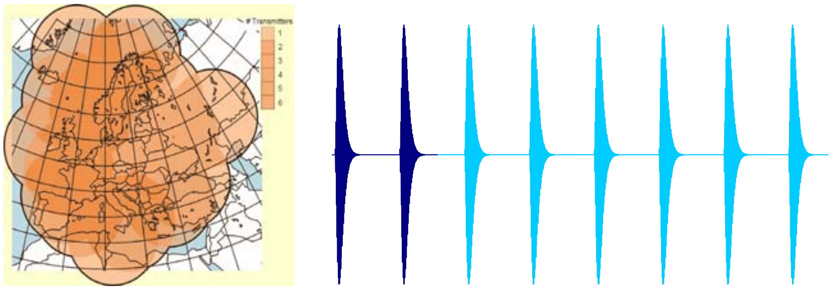

Figure 9. Projected Eurofix coverage and signal format.

III. NORTH AMERICAN ELORAN SIGNAL FORMAT

The major difference between legacy LORAN-C and eLORAN is the LDC. The LDC, provided as part of the transmitted signal, conveys user application-specific corrections, warnings, and signal integrity information. One LDC message will provide real-time differential corrections. The data transmitted will not be needed for all applications, but will include at a minimum:

- The identity of the station; an almanac of LORAN transmitting and differential monitor sites
- Absolute time based on the Coordinated Universal Time (UTC) scale; leap-second offsets between eLORAN system time and UTC
- Warnings of anomalous radio propagation conditions including early skywaves; warnings of signal failures, aimed at maximizing the integrity of the system
- Messages that allow users to authenticate the eLORAN transmissions; official-use-only messages
- Differential LORAN corrections to maximize accuracy for maritime and timing users
- Differential GNSS corrections **[5]**.

3.A. NINTH PULSE COMMUNICATIONS

This modulation scheme (Figure 10) was designed to have a minimal impact on the current operational signal so as not to violate the existing signal specification or interfere with the legacy LORAN-C user community. Under this scheme, a pulse (red) is inserted between the eighth and ninth pulses on the Master Station (1000 μs after the eighth pulse) and 1000 μs after the eighth pulse on secondary stations **[10]**.

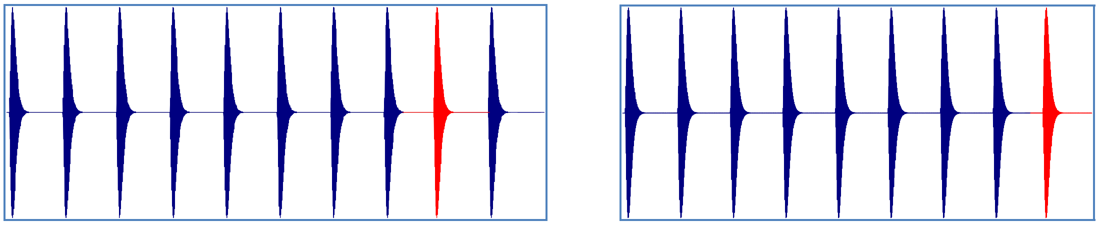

Figure 10. Ninth pulse communications.

The scheme uses 32-state pulse-position modulation to encode the data and has a data rate of five bits per Group Repetition Interval (GRI). The phase coding of the LDC pulse is the same as the previous navigation pulse, and the zero-symbol offset is 1000 µs after the eighth navigation pulse. The remaining 31 symbols are positioned a specific number of microseconds later in relationship to the zero symbol, based on the ideal formula:

$$D_x = 1.25 \text{ mod}[x, 8] + 50.625 \text{ floor}(x / 8)$$

However, the actual symbol delays are the ideal values shifted to coincide with the 5-MHz system clock (cesium reference clock). Table 1 lists the symbol *x* and corresponding time delay D_x with respect to the zero symbol.

Table 1. Symbol delays for eLORAN modulation.

x= [0, 7]		**x = [8, 15]**		**x = [16, 23]**		**x = [24, 31]**	
0	0.0	8	50.6	16	101.2	24	151.8
1	1.2	9	51.8	17	102.6	25	153.2
2	2.6	10	53.2	18	103.8	26	154.4
3	3.8	11	54.4	19	105.0	27	155.6
4	5.0	12	55.6	20	106.2	28	156.8
5	6.2	13	56.8	21	107.6	29	158.2
6	7.4	14	58.2	22	108.8	30	159.4
7	8.6	15	59.4	23	110.0	31	160.6

All messages are 120 bits long and have three parts: 1) four-bit message type flag, 2) a 41-bit payload, and 3) 75-bit parity component. The messages are transmitted at a rate of five bits per GRI. The time length of the messages is 24 GRI (maximum of approximately 2.4 s) and can be calculated for each GRI based on:

$$\text{GRI } (\mu\text{s}) * 24 = \text{Message Repetition Interval (MRI)}$$

Based on the current GRI's available in North America, the message interval can be between 1.4323 s and 2.3976 s for the Canadian East Chain (59300 µs) and the North Pacific Chain (99900 µs), respectively. There are 16 possible message types, and as of December 2008 only four have been identified:

- Reference Site Phase Corrections

- Almanac Messages
- Government Use Only
- Station ID and Time of Day.

The Time of Day (Message Type 15) contains the absolute time, expressed as the number of seconds since 000000Z 01 JAN 1958, the epoch used to calculate the Time of Coincidence (TOC) for all LORAN chains. The number of seconds *T* from 000000Z 01 Jan 1958 to the Time of Transmission of the first pulse of the first GRI of this message calculated using:

$$\mathrm{T} = 24(GRI) * (MEC) + ED$$

where *MEC* is the current message epoch count, and *ED* is the published emission delay of the station sending this message. Forward error correction is provided by the 75-bit parity payload using Reed Solomon encoding.

Message Type 1, subtype 5, contains the proposed description of the transmitting station. It includes a “UTC source” field that identifies the national timing laboratory, for example, the USNO or NIST; that serves as the reference for the transmitted time. The link back to a national timing laboratory also allows the station to establish metrological traceability.

It is not beneficial to describe the system further at this point, because the current signal format is primarily of interest only to those individuals involved in the evolution of the system, and for manufacturers developing eLORAN receivers. The modulation scheme, message type, and message payloads can change as needed, as progress is made on the transition to eLORAN. Users desiring to have the latest information regarding the Ninth Pulse Modulation scheme and current coverage diagrams are encouraged to visit the USCG Navigation Center’s Web site for the most recent description of the modulation scheme:

http://www.navcen.uscg.gov/eloran/9th-pulse-modulation-ldc.html

IV. ELORAN ANNOUNCEMENTS

Several major announcements regarding eLORAN were made in 2008, as summarized in this section.

4.A. DEPARTMENT OF HOMELAND SECURITY (DHS) ANNOUNCEMENT

On February 7, 2008 the Department of Homeland Security released the following statement regarding LORAN-C and eLORAN:

> *“Today the U.S. Department of Homeland Security will begin implementing an independent national positioning, navigation, and timing system that complements the Global Positioning System (GPS) in the event of an outage or disruption in service. The enhanced Loran, or eLoran, system will be a land-based, independent system and will mitigate any safety, security, or economic effects of a GPS outage or disruption. GPS is a satellite-based system widely used for positioning, navigation, and timing. The eLoran system will be an enhanced and modernized version of Loran-C, long used by mariners and aviators and originally developed for civil marine use in coastal areas. In addition to providing backup coverage, the signal strength and penetration capability of eLoran will provide support to first responders and other operators in environments that GPS cannot support, such as under heavy foliage, in some*

> *underground areas, and in dense high-rise structures. The system will use modernized transmitting stations and an upgraded network."* **[2]**

4.B. GENERAL LIGHTHOUSE AUTHORITY (GLA) ANNOUNCEMENT

The General Lighthouse Authority (GLA) for the U.K. and Ireland welcomed the U.S. decision on eLORAN on 21 February 2008, with this announcement:

> *"The General Lighthouse Authorities of the United Kingdom and Ireland (GLAs) today applaud the US decision to implement Enhanced Loran (eLoran) in the US as a complement to the Global Positioning System (GPS), particularly in the event of an outage or disruption in service. Robust, reliable and high-performance positioning, navigation and timing (PNT) is the lifeblood of modern society's critical infrastructure: power systems, telecommunications, transport and finance. GPS has revolutionised PNT but it has known vulnerabilities. Galileo will have a positive impact on GPS system-level vulnerability although all satellite navigation systems share common vulnerabilities at signal and user levels. Loran is a terrestrial radionavigation system, one that is fully independent of GPS and delivers complementary levels of performance. It allows GPS users to retain the safety, security and economic benefits of GPS even when their satellite services are disrupted. The US decision establishes eLoran's role as a key component of the future US PNT mix: the world's premier satellite navigation service provider knows its own vulnerabilities, has done extensive analysis and has settled on eLoran as the solution. Other satellite navigation service providers have a similar PNT mix: the Russian Federation operates its Glonass satellite navigation system and its version of eLoran, Chayka; and the People's Republic of China is developing its Compass satellite navigation system and has deployed Loran in the Far East. Now Europe needs a similar eLoran back up to complement its eagerly awaited Galileo system. As responsible and prudent service providers, the GLAs have long identified the need for eLoran to mitigate satellite navigation vulnerabilities. This is why the GLAs have deployed their new eLoran station in Cumbria. Together with stations in Norway, France, Germany and the Faeroe Islands, we are now providing a trial eLoran service in Northern Europe. In determining its long-term PNT mix Europe needs a mature and rational debate about GNSS vulnerability that recognises both the benefits of having two satellite navigation systems, Galileo and GPS, as well as the benefits of system diversity based on eLoran. Now is the time for governments, service providers and users to demand a European Radio Navigation Plan based on Galileo, GPS and eLoran. Only in this way can we establish a robust, reliable and high-performance PNT mix in Europe that will protect our critical infrastructure and allow our European users to retain the safety, security and economic benefits of GPS that they enjoy, even when their satellite services are disrupted."* **[11]**

4.C. ITU STUDY

The International Telecommunications Union (ITU) has a draft question **[12]** regarding eLORAN considering:

- That eLORAN is the primary Position Navigation and Timing (PNT) backup to the Global Positioning System for some countries,
- that LORAN is available in many areas of the world,
- that eLORAN will be a source for precise time and frequency information, and
- that user equipment specific to time and frequency users may soon be widely available.

The group is recommending that the following questions should be studied:

- What is the geographical coverage for time and frequency use of eLORAN?
- Can eLORAN provide similar backup to users of other GNSS services?
- What is the time and frequency performance of eLORAN?

- Will time and frequency information from eLORAN be traceable to National Metrology Institutes and to UTC?

The results of the above studies should be included in one or more recommendations and/or reports and that the above studies should be completed by 2011.

V. PROTOTYPE ELORAN RECEIVER

A prototype Enhanced Loran Research Receiver (ELRR) has been developed and beta units are now being tested at several facilities, including NIST. The ELRR is capable of operating with an E-field or H-field antenna and sets the receiver analog gain and bandwidth prior to digitizing the received signals. The high-speed digital processing of the LORAN signals is done by digitizing the analog inputs by two 18-bit analog to digital converters. A field programmable gate array (FPGA) and digital signal processor handle the signal processing, and a second FPGA controls the PCI interface to the embedded single-board computer. The computer runs the ELRR application software and hosts the Ethernet and console interface. The internal timing is derived from a rubidium oscillator, which, in turn, is steered to UTC by the LORAN signal (Figure 11).

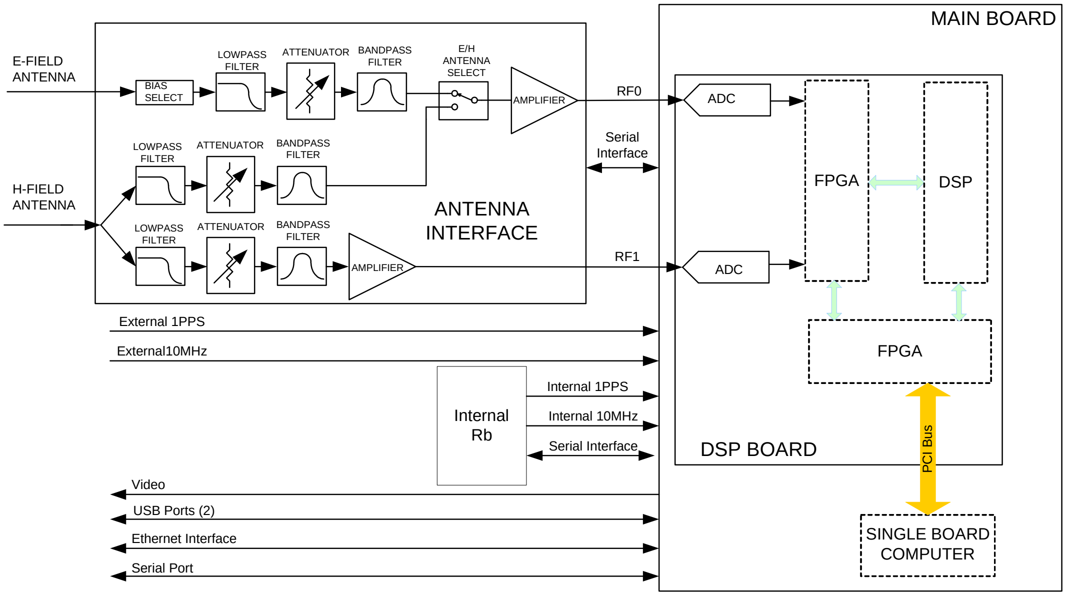

Figure 11. ELRR block diagram.

LORAN chains are acquired by averaging the raw envelope 50 kHz baseband data over each chain's PCI (1 PCI = 2 GRI). Over time, this averaging builds up the signal pulses and beats down any noise and other stations not repeating over the GRI/PCI. This is done for all chains as set up by the operator. When enough averaging is done, the Master Station is found via matched filter of the coded pulses in GRI A and B. After the start of the master sequence is found, the other secondary stations are located within the GRI, based on tier coding delays. While tracking, a composite pulse is formed for each station, which consists of an average of all station pulses within the GRI. This average pulse is used to track Doppler shifts and to find the necessary track point for each station. The track points are also used to find the Time of Arrival (TOA) measurements from each station, which are in turn used to compute the navigation solution via the least-squares method. Each chain also goes through a cross-rate canceling algorithm, which minimizes the noise caused by all of the other LORAN chains. This improves tracking and reduces the measurement errors normally caused by cross-rate interference. UTC measurements and ASF corrections are recovered over the LDC and applied to the receiver as necessary.

Testing of the ELRR's performance began in November 2007 during the GPS JAMFEST exercise conducted on White Sands Missile Range (Figure 12). The ELRR was set up using an H-Field antenna and was demodulating the LDC broadcast provided by the USCG Loran Station in Las Cruces, New Mexico. Performance over the 5-day test period was excellent; the ELRR was able to produce accurate time and frequency signals at all times and the receiver met and/or exceeded the Stratum-1 specification **[13,14]** throughout the test. The timing performance of the ELRR was also acceptable for a GPS alternative, with a standard deviation of 33 ns over the entire period. One point to clarify is that differential correction messages were not broadcast during the testing. Had differential corrections been broadcast, the receiver would have further compensated for small variations in the received signal due to propagation changes caused by temperature and weather, and the overall performance of the ELRR would have improved.

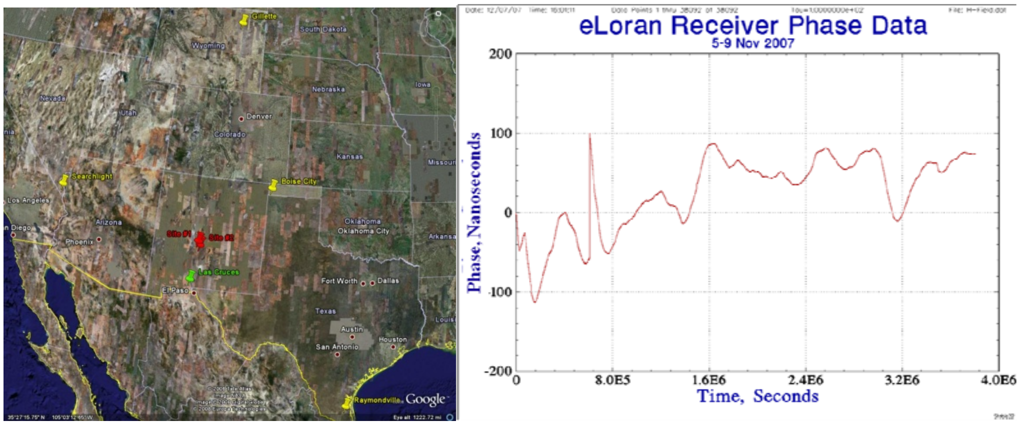

Figure 12. November 2007 test results.

Testing conducted in Stafford, Virginia, during the summer of 2008 consists of a series of data collections using H-Field antennas both indoors and outdoors (Figure 13). The amount of testing has been limited, because only eight of the 29 stations in North America have the equipment installed that is required to broadcast the LDC. The USCG has also placed operational limitations on the stations, and only three of the eight continually broadcast the LDC. The remaining five stations only broadcast the LDC during normal working hours.

The LDC broadcasts originating from Seneca, New York (495 km) and Jupiter, Florida (1295 km) were demodulated from Stafford, Virginia. Measurements show similar results over several days during this period. The measurements from Jupiter were limited to the daylight hours because of the skywave reception at night. As with the JAMFEST results, there are no differential corrections available or applied for these data sets. The performance noted in Figure 14 is simply the ELRR recovering UTC from the selected station (either Jupiter or Seneca), and then steering the internal rubidium clock to UTC.

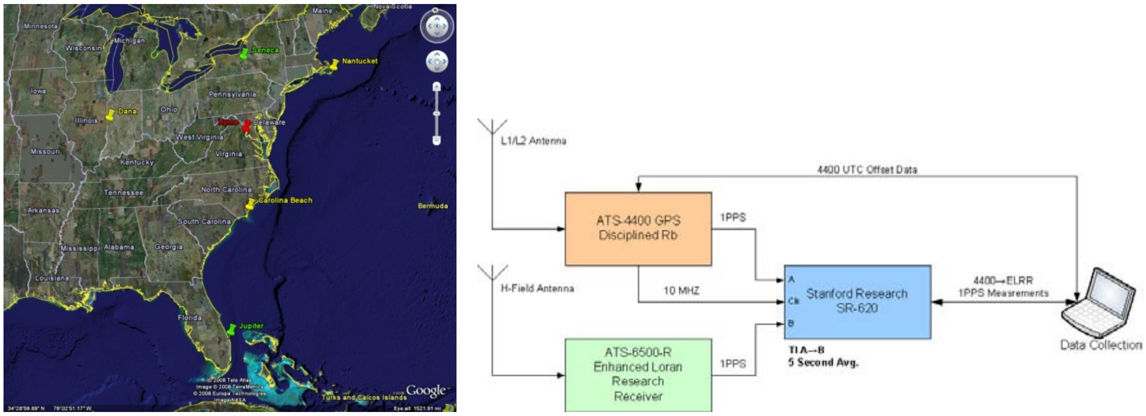

Figure 13. Test locations and measurement setup.

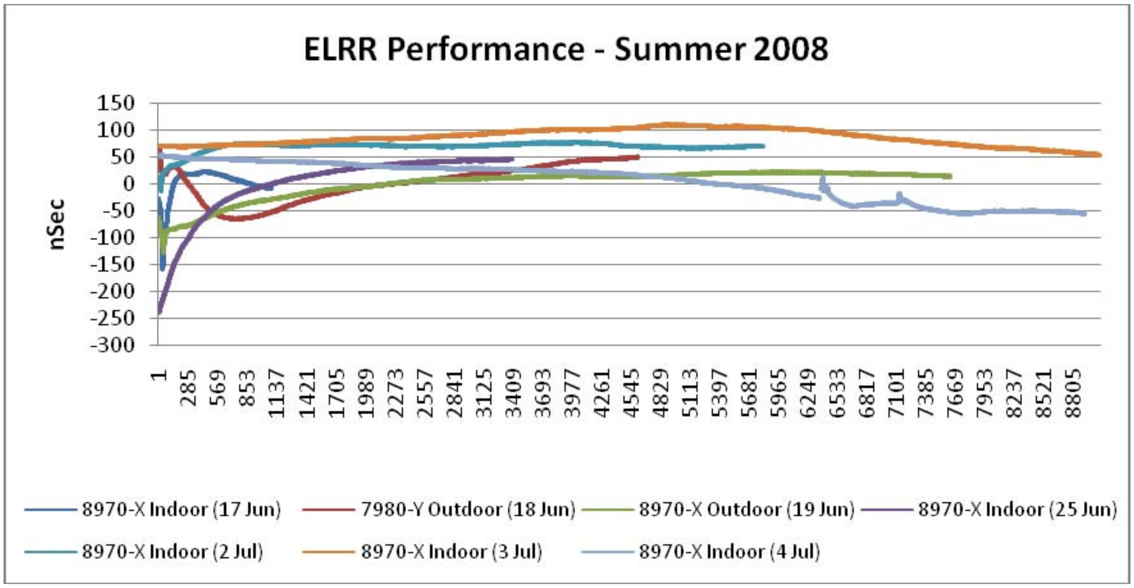

Figure 14. ELRR performance – summer 2008.

VI. ELORAN’S ABILITY TO MEET INDUSTRIAL TIMING REQUIREMENTS

The most stringent industrial timing requirements generally relate to telecommunication networks and the electric power grid, two critical elements of the nation’s infrastructure. The telecommunications and electric power industries meet their requirements by maintaining many thousands of GPS timing receivers, making them vulnerable to a GPS signal outage. Several comprehensive studies have examined the problem of GPS vulnerability, and the use of LORAN as a backup or alternative to GPS for PNT applications **[3,15,16]**. Much of the current interest in eLORAN is tied directly to timing **[17,18]**, and its capability as a timing system is perhaps the key to its long-term survival.

This section discusses the requirements of the telecommunications industry, including the frequency requirements for primary reference sources used in telecommunication network and the timing requirements for base stations used for Code Division Multiple Access (CDMA) wireless telephone. It also discusses the timing requirements for the phasor measurement units (PMUs) operated by the electric power industry. It briefly looks at how GPS serves these applications and discusses eLORAN's ability to serve as a redundant timing source.

6.A. TELECOMMUNICATION NETWORKS

The Stratum-1 (ST1) frequency accuracy requirement used by the telecommunications industry is 1×10^{-11} **[13,14]**. This number is sometimes misinterpreted in the literature, but it refers to the fractional offset of the frequency being used with respect to its nominal value. If the nominal frequency is 10 MHz, then a ST1 source must remain within ±100 μHz of 10 MHz at all times (10^7 Hz $\times 10^{-11} = 10^{-4}$ Hz = 100 μHz).

The ST1 requirement seems relatively easy to achieve, but only a few types of devices can meet ST1 requirements without periodic adjustment. One such device is a cesium oscillator. The others are disciplined oscillators, where the periodic adjustment is done automatically by use of a reference signal received by radio. Rubidium oscillators are sometimes erroneously called ST1 sources because they have the necessary stability, but they can miss the accuracy requirement by one or two orders of magnitude unless they are periodically adjusted.

Because cesium oscillators are too expensive to use for widespread deployment, GPS-disciplined oscillators (GPSDOs) are normally used as ST1 sources. If GPS is unavailable for any reason, eLORAN (or legacy LORAN)-disciplined oscillators (LDOs) are the best available choice for meeting the ST1 requirements, because they would potentially cost much less than a cesium, and because the LORAN coverage area is large enough to service the telecommunication networks of North America **[19]**. In fact, LDOs have been used for many years as ST1 sources.

Because LORAN signals are traceable to UTC, LDOs are also capable of serving as the primary reference source for a network. The synchronization reference for a network is called the primary reference source (PRS) by the American National Standards Institute (ANSI) standard **[13]**, or alternately, a primary reference clock (PRC) by the International Telecommunications Union (ITU) standard **[14]**. The ANSI *T1.101* standard defines a PRS as:

> *Equipment that provides a timing signal whose long-term accuracy is maintained at 1×10^{-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* **[13]**.

The definition tells us that a PRS must meet two requirements: a frequency accuracy requirement of 1×10^{-11} (equivalent to ST1) and a requirement of being verifiably traceable to UTC. It also tells us that other clocks in the network will rely on the PRS for their synchronization reference, which implies that 1×10^{-11} accuracy must be maintained at all times. Like a GPSDO, an LDO is capable of meeting both requirements.

Some wireless telephone networks have synchronization requirements, and these are technically harder to meet than the syntonization requirements of ST1. For example, code division multiple access (CDMA) networks require all base stations except repeaters to be synchronized to within ±3 μs, and base stations that support multiple simultaneous CDMA channels to be within ±1 μs. The time requirement is ±10 μs, even if the external source of CDMA system time is disconnected for up to 8 hours **[20]**. To meet these requirements, CDMA system time is nearly always obtained from GPS (more than 100,000 CDMA base stations are GPS equipped in North America), and it is important to realize that the CDMA system was designed around GPS capability.

Legacy LORAN could easily meet the ST1 frequency requirements, but was unable to recover time automatically so that it could both syntonize and synchronize a network clock to UTC. A cesium oscillator also lacks synchronization capability; it cannot recover time unless its 1 pps output is synchronized to the UTC second with GPS or another timing system. In contrast, a GPSDO can synchronize to UTC by itself. For these reasons, the use of GPSDOs has historically been *the only practical way* for industry to meet a ±1 μs time accuracy requirement. However, eLORAN, with the addition of the time information contained in the LDC, can now automatically recover time and potentially serve as a CDMA base station reference.

6.B. ELECTRIC POWER GRID

The electric power industry has many systems that require precise time and frequency, but perhaps their most demanding application is to synchronize and align phasor measurements made at power substations. This allows the state of power system to be monitored in real time. A synchronized phasor, or synchrophasor, is a phasor calculated from data samples using a UTC signal as the reference for the measurement (Figure 15). Because they are referenced to an absolute point in time, synchrophasors collected from remote sites have a common phase relationship **[21]**.

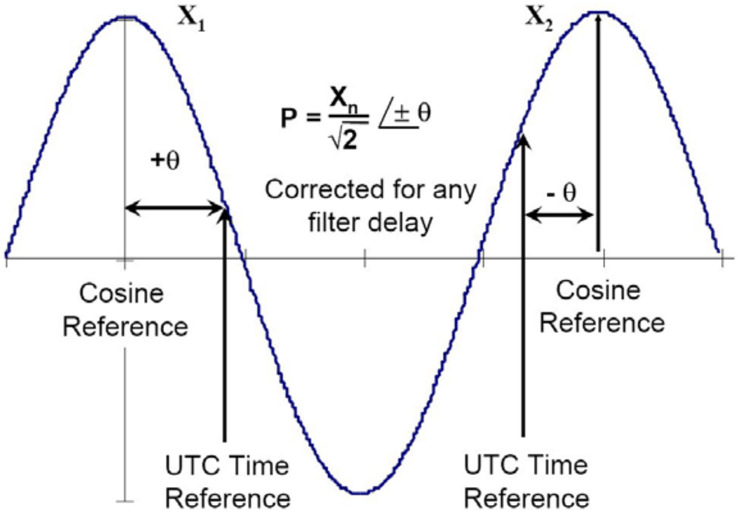

Figure 15. Synchrophasor definition.

The electric power industry deploys phasor measurement units (PMUs) to perform the synchrophasor measurements. PMU units measure positive sequence voltages and currents at power system substations and time stamp each measurement with time obtained from GPS. As was the case with CDMA, GPS was an enabling technology for synchrophasor measurements.

The *IEEE C37.118-2005* standard **[21]** defines the requirements and data formats for synchrophasor measurements. Time tagging of measurements is done with a three-bit "fraction of second" field that potentially allows referencing to UTC with a resolution of about 60 nanoseconds. The maximum allowable time error for the lowest level of compliance with the standard is ±26 μs (Section 4.4).

However, the desired accuracy level is ±1 µs, which corresponds to a phase error of 0.022° for a 60-Hz system. The UTC time source thus needs ±1-µs accuracy, the same timing requirement as CDMA.

The synchrophasor standard does not specifically state that GPS must be the time reference for PMU devices. In fact, it voices concerns (Annex E.2) about the use of satellite signals, noting that "the principal problem with satellite broadcasts has been availability." The standard goes on to state (Annex E.3) that "synchronizing signals may also be broadcast from a terrestrial location." However,

> *Synchronizing signals may also be broadcast from a terrestrial location. The accuracy of U.S. government provided AM broadcasts, WWV, WWVB, and WWVH, is typically around 1 ms, which is not accurate enough for this application. The LOng RAnge Navigation system (Loran C) can provide 1 µs accuracy, but requires careful monitoring and external raw time input. It is not available in many continental areas* **[21]**.

In short, the standard is acknowledging that there is no current backup for synchrophasor measurements, but modernized LORAN can provide a redundant timing source for the power grid. LORAN no longer requires an external time input and can now recover UTC with the necessary ±1-µs accuracy from the reception of just one station.

VII. SUMMARY AND CONCLUSIONS

The LORAN system has undergone some major changes in recent years that have made it a more valuable part of the nation's timing infrastructure. eLORAN is both dissimilar and complementary to GNSS, and can provide a redundant source of frequency and time for critical systems such as telecommunication networks and the electric power grid. While eLORAN may not meet the needs of every PTTI user, it can meet the needs of the majority of users and satisfy all existing industrial timing requirements, even without the use of differential corrections.

** Commercial products are identified for technical completeness only. This does not imply endorsement by NIST.*

VIII. ACKNOWLEDGMENTS

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