The Potential Role of Enhanced LORAN-C in the National Time and Frequency Infrastructure

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Abstract - *The United States LORAN-C network has been significantly upgraded in recent years so that it might better serve as a backup to the Global Positioning System (GPS) both for navigation and timing applications. This paper examines the potential role of the enhanced LORAN-C network by comparing it not only to GPS, but to the other network and wireless distribution systems that anchor the time and frequency infrastructure for the United States. It then ranks enhanced LORAN-C amongst these systems as a reference source for time-of-day, precise time synchronization, and frequency. The rankings are primarily based on the estimated accuracy and stability that can be obtained with each system; but other factors are discussed including availability, coverage area, acquisition time, reliability, redundancy, and traceability to national and international standards.*

I. Introduction

The public and private sectors, the national economy, and nearly all facets of everyday life in the United States depend heavily upon the many millions of clocks and oscillators that collectively form the nation's time and frequency infrastructure. This infrastructure is anchored by a number of providers whose broadcast signals serve as references or standards. These signals are continuously distributed through either networked or wireless mediums, and are routinely used to synchronize clocks to the correct time or syntonize oscillators to the correct frequency.

The dominant distribution source for time and frequency in the United States and throughout the world is the Global Positioning System (GPS) [1]. Although it is primarily a radionavigation system, GPS is a superb source of time accurate to less than 100 ns and frequency accurate to about 1×10^{-13} after 1 day of averaging. Many applications and technologies depend exclusively on GPS as their time and frequency source, and this exclusivity has been the cause for concern. It is generally agreed that backups and alternatives are needed to protect the national time and frequency infrastructure from the consequences of a GPS outage. Several studies have examined the vulnerability of GPS, the possible consequences of an outage, and the use of LORAN-C as a backup system to GPS [2, 3, 4]. Not surprisingly, these studies have been very broad in scope, discussing timing issues only briefly, and focusing primarily on the transportation and navigation infrastructure. As a result, they have not clearly identified and compared all of the sources that can potentially supplant and/or support GPS for time and frequency applications.

This paper was written to complement existing studies by defining and describing the available broadcast sources of time and frequency in the United States (Section II), with special emphasis placed on the potential role that the enhanced LORAN-C network (eLORAN) can play in the national time and frequency infrastructure. It compares eLORAN not only to GPS, but to other broadcast sources of time and frequency, limiting the comparison to the three topics we consider to be the most important: the time-of-day synchronization of clocks to the nearest second (Section III), the precise time synchronization of clocks to an uncertainty of 1 ms or less (Section IV), and the frequency control of oscillators (Section V).

Before beginning our discussion, it is important to note that broadcast sources can be trusted only if they are traceable to national standards of time and frequency and the international Coordinated Universal Time (UTC) time scale. Traceability is normally easy to establish if the signal source is either controlled or monitored by one of the two major national timing laboratories in the United States, the National Institute of Standards and Technology (NIST) or the United States Naval Observatory (USNO). Both maintain time scales, called UTC(NIST) and UTC(USNO) respectively, that serve as national standards for time-of-day, time interval, and frequency, and can be considered equivalent to each other and to UTC for nearly all applications. Thus, the uncertainties listed in this paper can be used with respect to either UTC(NIST), UTC(USNO), or UTC.

The reference for all of the broadcast sources listed in Section II can be traced back, directly or indirectly, to either UTC(NIST) or UTC(USNO). However, in cases where the signals are not controlled or monitored by NIST or USNO, the traceability chain can be tenuous and hard to document, making these signals less desirable as reference sources.

II. Definition and Description of Time and Frequency Signal Providers

This section defines and briefly describes the various broadcast signals (both networked and wireless) that anchor the time and frequency infrastructure in the United States. We intentionally exclude providers whose signals originate from outside the United States, even if these signals are easy to receive. Some examples of excluded providers are the Russian GLONASS satellite constellation, the forthcoming European GALILEO satellite constellation, the Canadian broadcast station CHU, and Network Time Protocol (NTP) servers located outside of the United States. We also exclude certain providers that originate in the United States and are considered to be part of the infrastructure, but whose signals do not contain a digital time code and were not designed to be machine readable, or whose signals lack the resolution and accuracy of the other signals discussed here. Some examples are the NIST and USNO audio announcements of time by telephone, local telephone time-of-day services, television time displays (such as those displayed by program selection menus, *CNN*, and *The Weather Channel*), GSM (Global System for Mobile Communications) and other mobile phone signals not referenced to GPS, and Internet time displays (such as http://time.gov). Although millions of users obtain time from these systems, their output is generally difficult to integrate into other systems, their accuracy is difficult to verify, and they are seldom used for critical applications.

The time and frequency signal providers that we include in the comparison are listed alphabetically and described briefly below. References are cited for each provider, and Table I provides a summary.

- **ACTS** refers to the Automated Computer Time Service [5] operated by NIST and a similar computer time service operated by the USNO [6]. These services are designed to synchronize computer and standalone clocks that can interface to analog telephone lines via dial-up modems.

- **CDMA** refers to signals from Code Division Multiple Access base stations that transport mobile telephone calls. There are numerous types of CDMA systems, but most are backward compatible with the *TIA/EIA 95-B* standard [7] and have the same specifications for time and frequency. The standard defines CDMA time as equivalent to GPS time and each base station contains a GPS receiver. The primary CDMA frequencies used in the United States are in the 800 and 1900 MHz regions, although frequencies near 900, 1700, and 1800 MHz are sometimes used. Note that CDMA will fail if there is a prolonged GPS outage, so it cannot be considered as a GPS backup system.

- **eLORAN** refers to the modernized version of the preexisting LORAN-C network, now referred to as legacy LORAN-C. eLORAN features improved time and frequency control at each transmitter, with each site maintaining an ensemble of cesium oscillators. eLORAN also features pulse position modulation with a ninth pulse added nominally 1 ms after the 8^{th} pulse on secondary stations, and between the existing 8^{th} and 9^{th} pulses on master stations. The 9^{th} pulse is used to send a 120 bit message that includes a time code. The message is sent at a rate of five bits per Group Repetition Interval (GRI), thus requiring 24 GRIs, or a maximum of 2.38 s to transmit based on the currently used GRIs. All 29 North American transmitters are expected to have eLORAN capability, all broadcasting at 100 kHz, at power levels ranging from about 400 kW to more than 1000 kW [8, 9].

- **FLEX** refers to the one-way paging protocol introduced by Motorola in 1993 and subsequent two-way paging systems such as ReFLEX now deployed around the world. The FLEX paging protocol is a synchronous time-slot protocol that uses GPS as its time base, and has been used as the synchronization source for radio controlled wristwatches. The FLEX time code is modulated on to a forward link frequency near 931 MHz [10]. As is the case with CDMA, FLEX is dependent upon GPS and cannot be considered as a GPS backup system.

- **GPS** refers to the Global Positioning Satellite system operated by the U.S. Department of Defense. GPS is a radionavigation system that includes a constellation of least 24 satellites in semi-synchronous orbit. All satellites carry atomic oscillators and receive continuous clock corrections from ground-based control stations. The satellites broadcast spread spectrum signals on the L1 (1575.42 MHz) and L2 (1227.60 MHz) carrier frequencies. As mentioned in the introduction, GPS is the world's dominant distribution source for high accuracy time and frequency [1, 11].

- **NTP** refers to the Network Time Protocol, the most widely used mechanism for time distribution via the Internet, defined by the RFC-1305 standard [12]. NTP servers continually listen for a timing request on port 123, and respond by sending a data packet that includes a 64-bit time code containing the time in UTC seconds since January 1, 1900. NTP servers are operated by a number of organizations using GPS, WWVB, or other sources as a reference [13]. NIST [14] and the USNO [15] each operate multiple servers that combine to handle more than 2 billion timing requests per day.

- **RDS** refers to the time information broadcast by the Radio Data System, a service carried by many commercial FM (87.8 to 108 MHz) radio stations on a 57 kHz subcarrier [16]. It is estimated that well over 1000 FM radio stations in the United States utilize RDS as of 2005, and its time code is used to synchronize clocks on car radios, clock radios, and other receivers with FM capability.

- **SDARS** refers to signals from the Satellite Digital Audio Radio Service providers who broadcast in the 2320 to 2345 MHz frequency band. Two commercial providers transmit signals from a total of five satellites, three of which have orbital periods of slightly longer than one day, and two of which are geostationary [17, 18]. Time information is used to set clocks in satellite radios intended for automobile, home, and portable use.

- **SPOT** refers to the Smart Personal Objects Technology developed jointly by Microsoft and SCA Data Systems [19, 20]. SPOT is similar to RDS, but uses a different FM subcarrier (67 kHz), and sends data at a faster rate. As of 2005, the signals are available from more than 200 FM stations in all 50 states, and are used to synchronize wristwatches and small electronic devices.

- **WAAS** refers to the GPS Wide Area Augmentation System developed by the Federal Aviation Administration (FAA) to make GPS work better for aviation navigation and precision flight approaches. The WAAS system consists of about 25 ground reference stations that monitor GPS satellite data and forward the data to two master stations, one on each coast, that create a GPS correction message. The correction message is uplinked to two geostationary satellites. The corrected differential message is then broadcast through the geostationary satellites as an overlay on the GPS L1 frequency at 1575.42 MHz [21]. Since the WAAS signal uses the GPS L1 frequency and GPS-type modulation, WAAS capability can be integrated into GPS receivers. Note that WAAS was designed to augment or improve the performance of GPS, and is not really a standalone alternative or backup, because if GPS is unusable for a given application, WAAS will probably also be unusable. However, receivers exist that allow using WAAS for time and frequency without using GPS [22].

Table I. General information about time and frequency signal providers (listed alphabetically).

Signal	**Carrier**	**Delivery System and Estimated Coverage Area**	**Time Scale Reference**
ACTS	Analog telephone lines	NIST operates 24 telephone lines from Boulder, Colorado and four lines from Hawaii. The USNO operates lines from Washington, DC and Colorado Springs, Colorado.	UTC(NIST) UTC(USNO)
CDMA	800, 900, 1700, 1800, and 1900 MHz regions	The forward link signal containing the time code is typically usable within about 50 km of a CDMA base station, and signals reach nearly all populated areas of the United States.	GPS
eLORAN	100 kHz	A network of ground based transmitters (24 in the U. S. and five in Canada) that transmit a ground-wave signal at 100 kHz. A three clock cesium ensemble is maintained at each site. UTC(USNO) is recovered via GPS (current) or two-way time transfer (future).	UTC(USNO)
FLEX	930 to 931 MHz	Similar to CDMA (above).	GPS
GPS	1575.42 MHz (L1) 1227.60 MHz (L2)	A constellation of at least 24 satellites in semi synchronous orbit. Each satellite carries one or more atomic oscillators.	UTC(USNO)
NTP	Internet	As of September 2005 [13], there are 74 primary NTP servers available to the public (open or restricted access) in the United States. A total of 19 are maintained by the USNO and 16 by NIST. Of the remaining 39 servers, 28 are referenced to GPS, five to CDMA, four to WWVB, and two to WWV.	UTC(NIST) UTC(USNO) ACTS, GPS, WWVB, WWV, CDMA
RDS	87.8 to 108 MHz via 57 kHz FM subcarrier	Signals are broadcast by more than 1,000 commercial FM broadcast stations.	Various
SDARS	2320 to 2345 MHz	Signals are broadcast from two commercial providers via five satellites.	Unknown
SPOT	87.8 to 108 MHz via 67 kHz FM subcarrier	Signals are broadcast by more than 200 commercial FM broadcast stations.	NTP
WAAS	Overlay on GPS L1 frequency (1575 MHz)	Signals are broadcast from two geostationary satellites. Coverage reaches all 50 states, but excludes parts of Alaska.	UTC(USNO)
WWV	2.5, 5, 10, and 15 MHz from WWV and WWVH, 20 MHz from WWV only	Two shortwave stations, located in Colorado and Hawaii respectively, continuously broadcast from nine transmitters. At least one frequency should be usable in the United States at all times.	UTC(NIST)
WWVB	60 kHz	A single transmitter in Fort Collins, Colorado that can be received in all 50 states during the nighttime hours, although reception in Alaska and Hawaii is tenuous.	UTC(NIST)
XDS	Analog television (VHF and UHF), cable and satellite television systems	The XDS time code is estimated to reach more than 90% of the United States population through various television outlets (available wherever PBS programming is available).	ACTS NTP GPS

- **WWV** refers to the shortwave radio station operated by NIST from Fort Collins, Colorado, and its sister station, WWVH, located on the island of Kauai in Hawaii [23, 24]. Both stations broadcast on 2.5, 5, 10, and 15 MHz, and WWV is also available on 20 MHz. These signals predate all of the other signals described in this paper and are widely recognized as a time and frequency reference, and are used for many new and legacy time and frequency applications [24].

- **WWVB** refers to the 60 kHz radio station operated by NIST from Fort Collins, Colorado [23, 24]. WWVB provides the synchronization source for nearly all of the consumer-oriented radio controlled clocks sold to the general public through United States retail outlets [25]. Millions of WWVB clocks and wristwatches are sold each year in the United States, and the market is continuing to expand as of 2005.

- **XDS** refers to the television time code sent by the Public Broadcasting System (PBS). The time code is contained in the vertical blanking interval (VBI), or the horizontal lines in the video field that are not part of the visible picture. Television broadcasters use line 21 of the VBI to send text messages for closed captioning, a service required for all television sets with displays of 33 cm (13 inches) and larger sold in the United States since 1993. Field 2 of line 21 is also used for the Extended Data Service (XDS), which includes a time code containing UTC, the date, daylight saving time information, and a time zone offset [26, 27]. Digital television (DTV) systems also provide the time code, either on line 21 as before, or on a separate data stream defined by the DTV captioning standard [28]. The XDS time code can be obtained from a variety of sources, including terrestrial television signals in the VHF and UHF part of the spectrum, from cable television systems, and from the geostationary direct broadcast satellite that provide television signals at frequencies in the 12.2 to 12.7 GHz region.

III. Broadcast Sources for Time-of-Day Information

Time-of-day information is usually provided in the form of a digital time code that is machine readable and that can be displayed or stored in a variety of formats. All time codes provide enough information to obtain the time-of-day in hours, minutes, and seconds, and generally include other information such as the date (month, day, and year), daylight saving time (DST) and leap second notification, and diagnostic indicators. Time codes often have a resolution of just 1 s, which is sufficient for most applications, where synchronizing a clock to the nearest second (±0.5 s) is all that is required. Time codes are typically used to synchronize clock displays, and to time tag or time stamp data stored by computer systems.

A. Time-of-day capabilities of eLORAN

The enhanced LORAN-C service includes a new pulse that is modulated in position to send data to LORAN-C receivers. This modulated pulse, called the LORAN Data Channel (LDC), was added to enable all-in-view processing (rather than chain processing used in legacy LORAN) and to communicate differential corrections to LORAN-C receivers [8]. LDC messages have been defined that communicate time-of-day, leap second information, differential corrections and LORAN-C network health and status information to users [8]. Time-of-day is calculated by propagating a count of LORAN message repetition intervals (MRI) that have occurred since the LORAN-C epoch (January 1, 1958) and applying the leap second information. The MRI count and the leap second information are provided in the time message via the LDC.

To recover time-of-day, an eLORAN receiver is only required to be within the coverage area of one station, and to track and demodulate that station’s signal. Figure 1 shows the locations of the existing LORAN-C transmitters in North America and a conservative estimate of the reliable time code coverage based on a 1000 km signal radius from each station. The use of a high power, 100 kHz ground wave from 24 U.S. stations gives eLORAN some advantages over existing time-of-day providers. For example, one challenge of using GPS for time-of-day recovery is the necessity of an outdoor antenna. In contrast, eLORAN will work indoors using an H field antenna [29]. While the indoor reception of LORAN-C would not be sufficient for navigation applications, it is adequate for the recovery of time-of-day. WWVB also works well indoors, but eLORAN has the advantage of potentially having 24 U.S. transmitters (versus one for WWVB), making reception much more reliable.

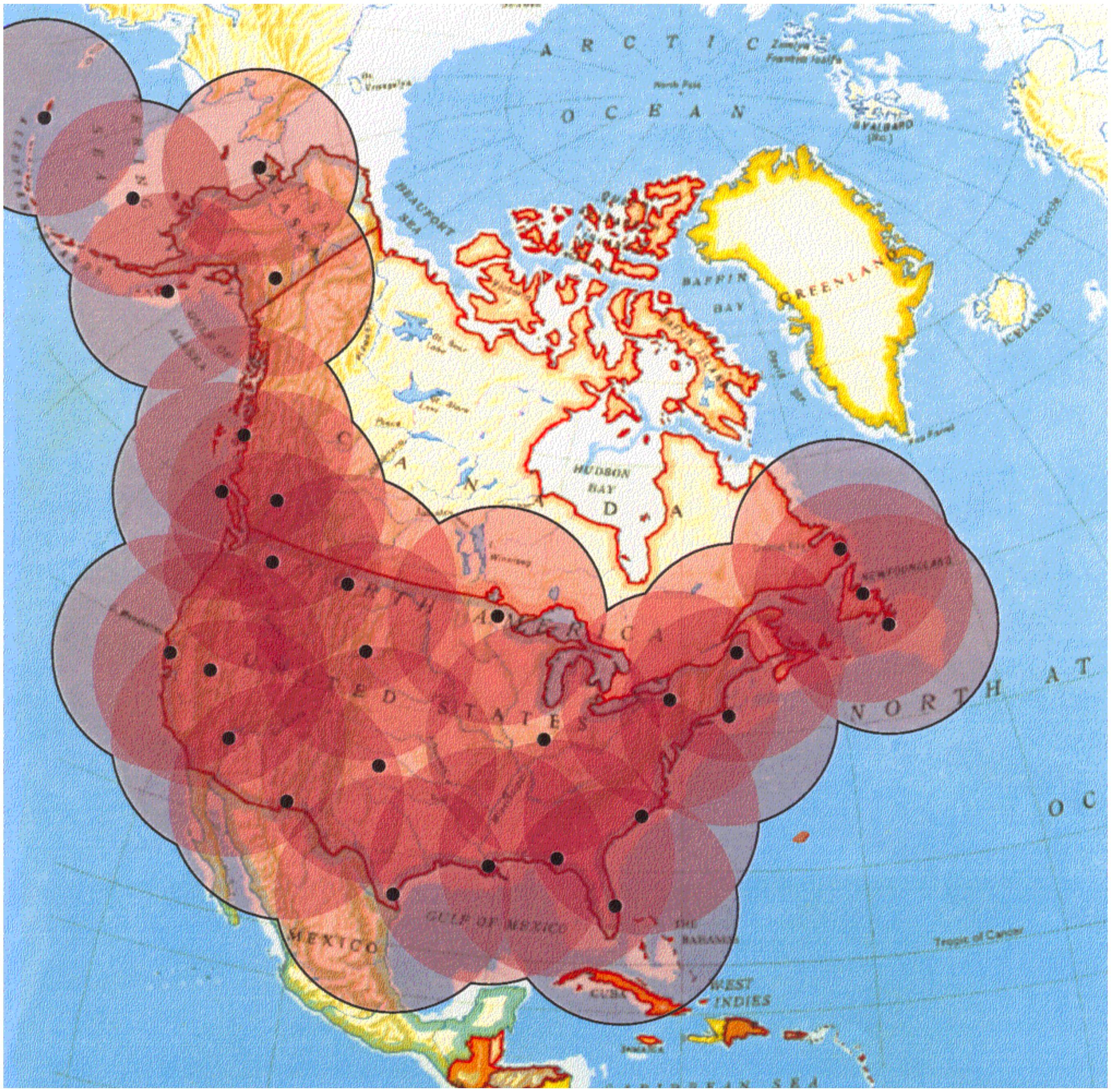

Figure 1. Conservative estimate of reliable eLORAN time-of-day coverage.

B. Time-of-day capabilities of all providers

Table II lists the time-of-day providers alphabetically. It also lists whether the signals work indoors, the interval required to receive the time code, and the information contained in the time code.

C. The Potential Role of eLORAN as a Time-of-Day Reference Source

The national time-of-day infrastructure depends upon providers that send time both directly and indirectly to end users. To illustrate this, consider that GPS may well be the provider that synchronizes the most clocks in the United States, but the majority of these synchronizations are indirect. While the number of standalone GPS clocks is relatively small, GPS is indirectly responsible for the synchronization of many millions of cell phone clocks (through CDMA), of pager clocks (through FLEX), and of computer clocks (through NTP). In contrast, WWVB time normally goes directly to end users as the synchronization source for millions of low-cost radio controlled clocks and wristwatches [25]. It seems likely that sources such as WWVB, CDMA, XDS (responsible for synchronizing millions of clocks embedded in television systems), NTP, and perhaps even RDS directly synchronize more clocks than GPS. Figure 2 provides a flow chart of the time-of-day infrastructure. All of the 13 providers listed in Figure 2 provide time-of-day directly to end user clocks, but not all of them are used to synchronize other providers of time-of-day.

Table II. Time-of-day signal providers and time code formats (listed alphabetically).

Signal	Works without outdoor antenna?	Interval required to receive time code	Information contained in Time Code	Types of clocks synchronized	Time Code Format Ref.
ACTS	-----	< 1 s	NIST sends hour, minute, second, month, day, year, Modified Julian Date (MJD), DST and leap second indicators, UT1 correction, and server time advance. USNO sends hours, minutes, seconds, MJD, and day of year.	Computer clocks	[5, 6]
CDMA	Yes	< 1 s	GPS time, the current UTC leap second offset to GPS time, and a local time offset to UTC that includes DST information.	Cell phones, NTP servers	[7]
eLORAN	Yes	2.38 s or less	The time in LORAN message repetition intervals since Jan 1, 1958, a leap second correction, a station identification, and correction factors with 2 ns resolution.	See text for potential applications	[8]
FLEX	Yes	1.875 s	Date, local time, and time zone offset from UTC.	Pagers, wristwatches	[10]
GPS	No	6 s for GPS time, 750 s for UTC(USNO)	Week number, second within the week, and offset between GPS time and UTC.	General purpose use	[11]
NTP	-----	< 1 s	The time in UTC seconds since January 1, 1900 with a resolution of 200 ps.	Computer clocks	[12]
RDS	Yes	60 s	MJD, UTC hour and minute, and the local time zone offset. The time refers to the arrival time of the next time message. A new message is sent each minute.	Car radios, clock radios, other radios with FM band	[16]
SDARS	Yes	< 1 s	XM radio format includes 7 byte UTC field, but exact format is believed to be proprietary.	Satellite radios	[17, 18]
SPOT	Yes	< 1 s	Contains time and date, but exact format is believed to be proprietary.	Wristwatches	[19]
WAAS	No	300 s or less	Broadcasts WAAS Network Time (WNT), which is steered to agree with GPS time, and the time offset between WNT and UTC(USNO).	General purpose use with outdoor antenna	[21]
WWV	Yes	60 s	Frame includes minute, hour, day of year, year, UT1 correction, DST and leap second indicators. Seconds are determined by counting frame pulses.	General purpose use with outdoor antenna	[23]
WWVB	Yes	60 s	Frame includes minute, hour, day of year, year, UT1 correction, DST, leap year, and leap second indicators. Seconds are obtained by counting frame pulses.	Wall, desk, and alarm clocks, wristwatches, appliances, NTP servers	[24]
XDS	Yes	60 s	Hour, minute second, month, day, year, day of week, DST, and time zone information.	Television receivers and equipment	[26, 28]

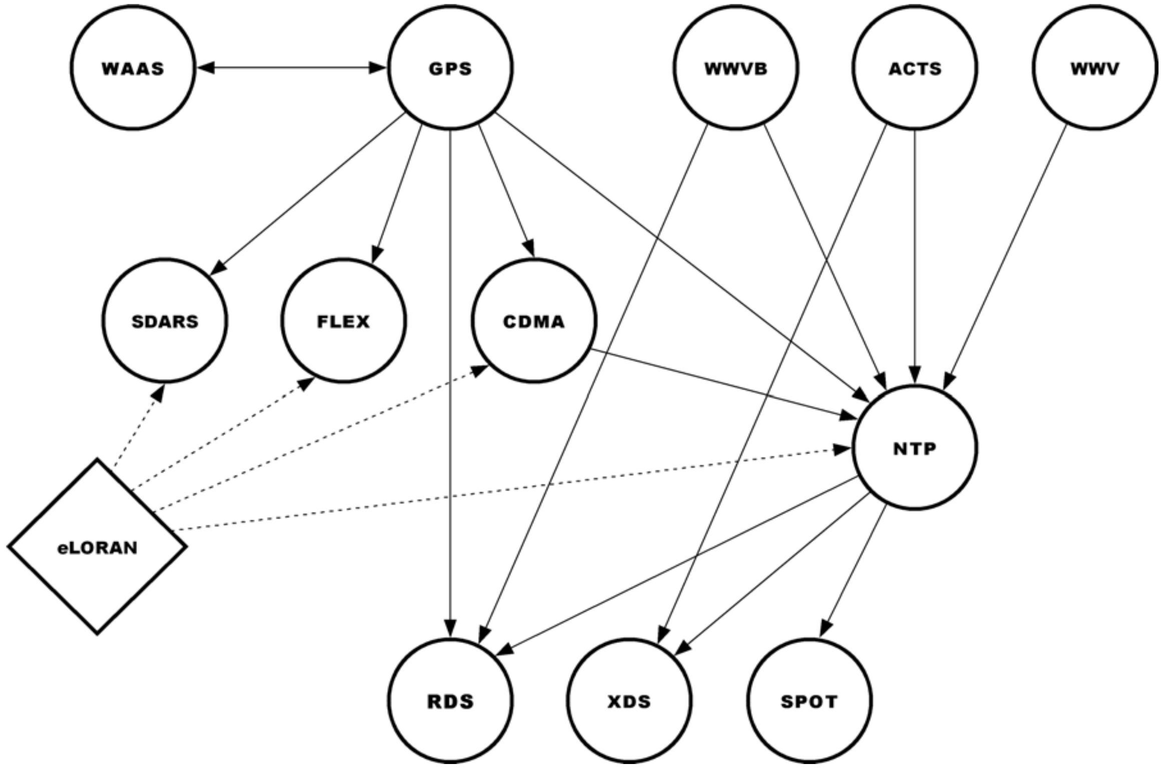

Figure 2. Flow chart of the time-of-day infrastructure service providers.

Where does that leave eLORAN? Legacy LORAN-C did not broadcast a time code, and thus eLORAN does not have a history as a time-of-day provider. It is not expected that eLORAN will make immediate inroads in a source of time-of-day for end users, because time-of-day receivers for eLORAN will not be immediately available, and other systems are well established and have considerable momentum. However, it seems obvious that its large coverage area, multiple transmitters, and the ability to work indoors make it an attractive choice as a time-of-day reference for future applications. In addition, the governmental control and monitoring of its signals makes it easy to establish traceability through eLORAN, and its time code will certainly be more trustworthy than systems such as XDS, RDS, and NTP. Based on the trust factor alone, it seems clear that eLORAN will immediately complement the existing infrastructure as a backup or alternative to GPS for the synchronization of providers such as SDARS, FLEX, CDMA, and NTP (as shown by the dashed lines in Figure 2). In addition, eLORAN can potentially be used to directly synchronize low-cost consumer electronic products as an alternative to WWVB, XDS, and RDS, if and when low-cost eLORAN receiving equipment becomes available. In summary, we think that eLORAN can quickly become an important contributor to the national time-of-day infrastructure, and that its importance will increase in future years as more receiving products become commercially available.

IV. Broadcast Sources for Precise Time Synchronization

We define precise time synchronization as synchronization accurate to 1 ms or less with respect to UTC. This requires a time code that is associated with an on-time marker (OTM) that can be measured with much higher resolution than the time code itself. The OTM is normally used to generate a 1 pulse per second (pps) signal that coincides as closely as possible with the UTC second. The 1 pps signals serve as a standard both for synchronization and for time interval measurements.

As will be seen in Section V, some providers have the inherent accuracy (1×10^{-11}) to qualify as stratum-1 frequency sources (see Section V). This allows relative time to be kept to within 1 µs per day, and keeping absolute time to within 1 µs of UTC is possible if all delays are known and removed. However, in many “real world” applications only a coarse knowledge of the delays is available, and a stratum-1 frequency source will be unable to provide absolute time to within 1 µs. Thus, we contend that 1 ms accuracy is a reasonable definition for precise time synchronization.

A. Precise Time Synchronization Capabilities of eLORAN

Precise time recovery via legacy LORAN-C was enabled by the requirement to maintain time at the transmitting stations to within 100 ns of UTC(USNO). With legacy LORAN-C, signals were transmitted within 100 ns of UTC(USNO) and time could be recovered to within 1 to 5 µs [9]. The primary limitation in time recovery via legacy LORAN-C was the unmeasured (and uncompensated) change in propagation delay between the transmitter and receiver. This change is caused by a change in ground conductivity during seasonal, diurnal and weather-based changes in temperature and precipitation. Another limiting factor was the inability to calibrate legacy LORAN receivers and compensate for delay biases.

eLORAN includes improvements at the transmitter and distribution of differential corrections via LDC that enable significantly better timing recovery performance. New time and frequency equipment at the LORAN-C transmitting stations provides time (via an ensemble of three cesium clocks) that is synchronized to less than 20 ns with respect to UTC(USNO) [30]. Differential corrections are computed based on the collection of the LORAN-C signal by a network of far-field monitors operated by the United States Coast Guard (USCG) as part of the LORAN-C system. The monitor information is processed and distributed as corrections via the LDC, and receivers can demodulate and decode the LDC message and apply the appropriate correction to remove the temporal variations. By calibrating the receiver (done at installation) and applying differential corrections, 50 ns RMS time recovery is possible [31].

Figure 3 shows the results of a comparison between the time scale at the Nantucket station (9960X) and a time scale located in Wildwood, New Jersey. The green line shows the performance of legacy LORAN-C. Due to propagation delay changes across the signal path, there is a peak-to-peak variation exceeding 300 ns over an interval of about three months. The blue line shows the improvement to the data when temporal corrections are applied from a monitor receiver located at the USNO in Washington, DC, about 190 km away from Wildwood. Note that the blue line has a peak-to-peak variation of about 100 ns, with an RMS of about 20 ns. As a reference, the pink line is provided by common-view GPS for the last 40 days of the comparison. These results show that a monitor providing temporal corrections makes eLORAN a viable backup or alternative to GPS for precise time. Previous experiments have shown that the use of local monitors (< 20 km from the receiving site) can result in timing performance that rivals GPS [32].

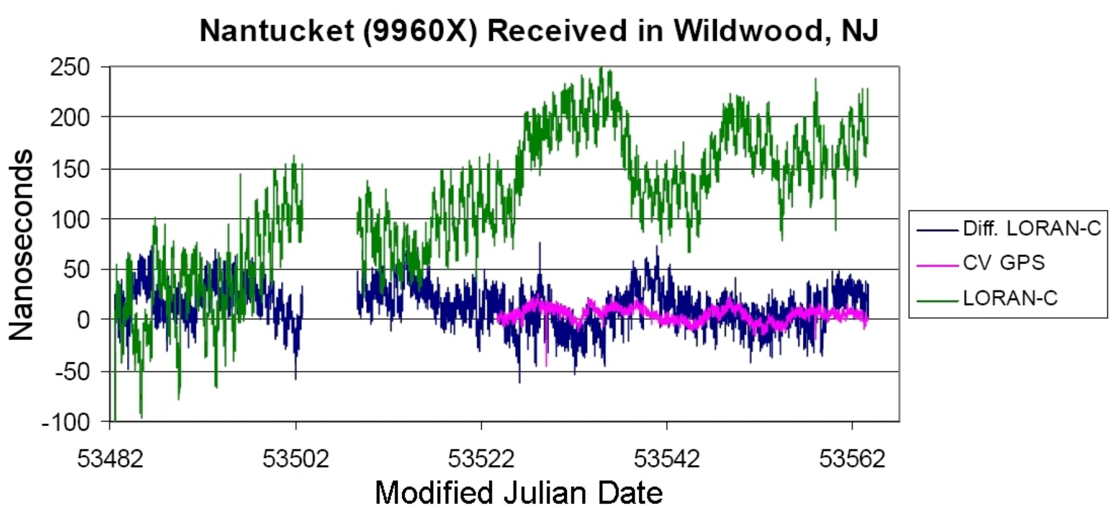

Figure 3. Comparison of Legacy LORAN-C and Differential LORAN-C for Time Recovery.

B. Precise Time Synchronization Capabilities of all providers

Table III ranks the providers according to the received time uncertainty of their signals. It also lists the providers that have been used by national laboratories for common-view time comparisons. Note that seven of the 13 providers are capable of meeting the 1 ms precise time synchronization requirement.

C. The Potential Role of eLORAN as a Precise Time Synchronization Reference

As listed in Table III, only five providers other than GPS can be considered a stratum-1 time synchronization source (1 µs per day). Three of these (WAAS, CDMA, and FLEX), rely on GPS for their accuracy and would not be available as a backup source in the event of a GPS failure. This leaves eLORAN and WWVB as the remaining backup sources. WWVB is completely independent of GPS, but is a less accurate timing source than eLORAN even if its users correct for path delay. It seems clear that eLORAN would be the only available candidate as a backup source for a critical application such as synchronizing the CDMA network. In addition, eLORAN is the only source not reliant on GPS that has proved usable for the common-view time comparisons [32] performed by national laboratories. Thus, we identify eLORAN as the best available backup source to GPS for precise time synchronization in the United States.

Table III. Precise time synchronization providers (ranked by received time uncertainty).

Signal	**Received Time Uncertainty (microseconds)**	**Usable for Common-View Time Comparisons**	**Notes**
GPS	< 0.1	Yes	An uncertainty of 100 ns is typical if the antenna cable is calibrated and a delay constant is entered into the receiver, but lower uncertainties are often realized.
WAAS	< 0.1	Yes	An uncertainty of 100 ns is typical if the antenna cable is calibrated and a delay constant is entered into the receiver, but lower uncertainties are often realized.
eLORAN	0.1	Yes	An uncertainty of 100 ns requires the application of monitor corrections from the LDC and calibration of the receiver and antenna.
CDMA	100	No	An uncertainty of 100 µs assumes that a base station is located within 30 km of the receiver. In areas with a high density of base stations the uncertainty is often < 10 µs.
FLEX	100	No	The actual uncertainty depends upon the distance from the paging station, similar to CDMA (above).
WWVB	100	No	The user must estimate and remove path delay to obtain 100 µs uncertainty.
WWV	1000	No	The user must estimate and remove path delay to obtain 1 ms uncertainty.
ACTS	5000	No	The uncertainty is limited by the stability of the computer's modem and operating system.
NTP	10000	No	An uncertainty of 1 ms is possible with some operating systems and client software.
RDS	10000	No	Station clocks can be synchronized by various means, so the actual uncertainty is unknown, but 10 ms is probably typical.
SPOT	10000	No	Short and stable signal path, but the uncertainty is limited by the system clock, which is typically synchronized via NTP.
XDS	16667	No	Generally accurate to at least one half the video frame rate, or about 1/60 of a second, but frame "buffering" can reduce this accuracy.
SDARS	Unknown	No	The method of synchronization is not known to the authors, but is likely to be GPS.

V. Broadcast Sources for Frequency

Frequency is usually provided in the form of a sine wave or square wave that is generated by a quartz or atomic oscillator. The network signals currently available are seldom used to distribute frequency; instead a frequency reference is normally obtained from either the carrier frequency of a radio signal, or from information modulated on to the carrier. For example, a radio signal can be used to phase lock or frequency lock the output of a local 10 MHz oscillator so that it never needs to be calibrated or adjusted as long as the radio signal is continuously received. Devices that provide a continuously controlled frequency are known as disciplined oscillators and are essential to many applications.

A. Frequency Control Capabilities of eLORAN

Legacy LORAN-C has been successfully used for many years as frequency reference, and the slow changes in propagation delay don't affect the frequency applications as much as the time applications. The use of common-view processing for LORAN-C will probably not improve its short-term frequency stability, but is expected to improve frequency stability at averaging times of 1 day or longer. Figure 4 shows a modified Allan deviation plot of the legacy LORAN-C data collected in Wildwood, New Jersey from the Nantucket transmitter. Figure 5 shows the modified Allan deviation plot of the same LORAN-C data set corrected with monitor data from the USNO. The performance is comparable for averaging times less than a day but is beginning to show the benefit of the common-view correction at averaging times longer than 1 day. More data are required before any conclusions can be reached, but we expect the common-view correction to improve frequency performance at long averaging times by removing the long-term phase changes caused by seasonal propagation effects.

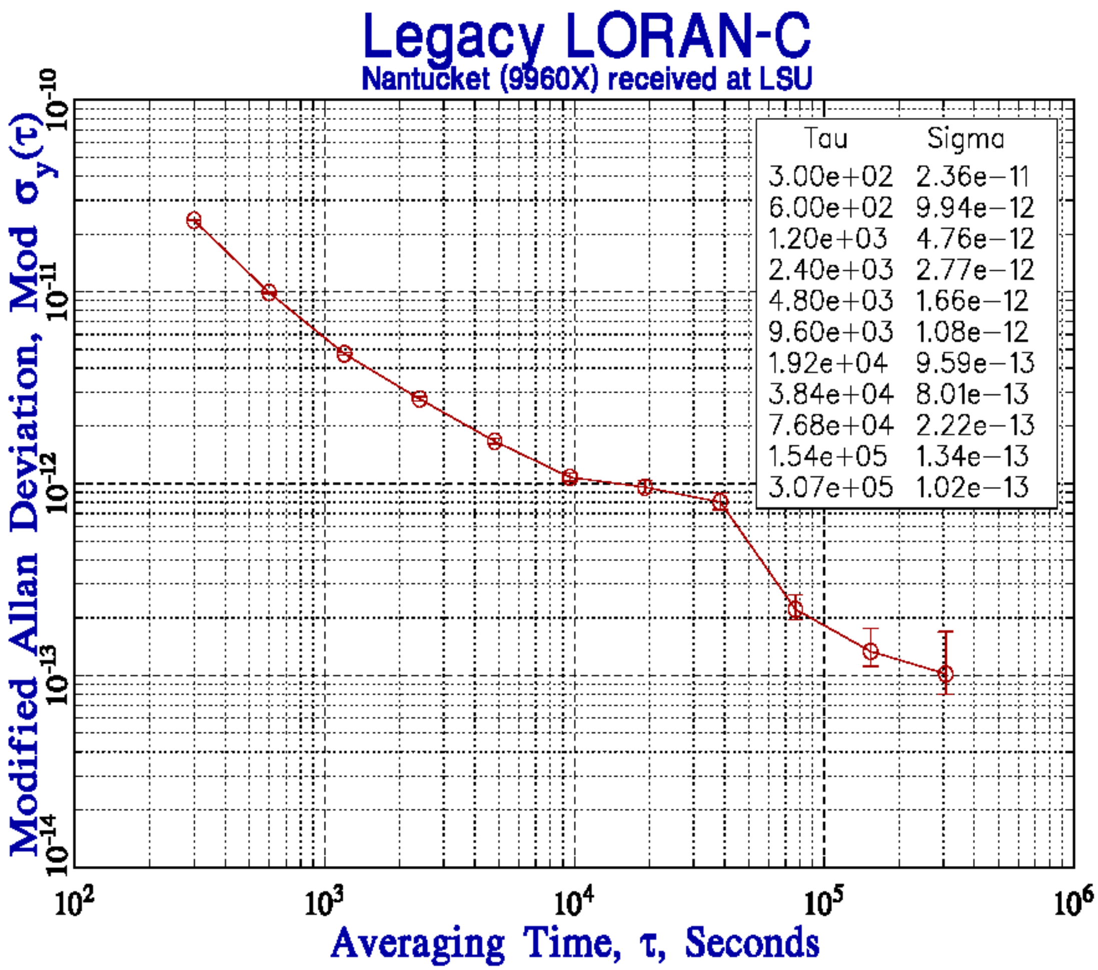

Figure 4. Frequency stability of legacy LORAN-C.

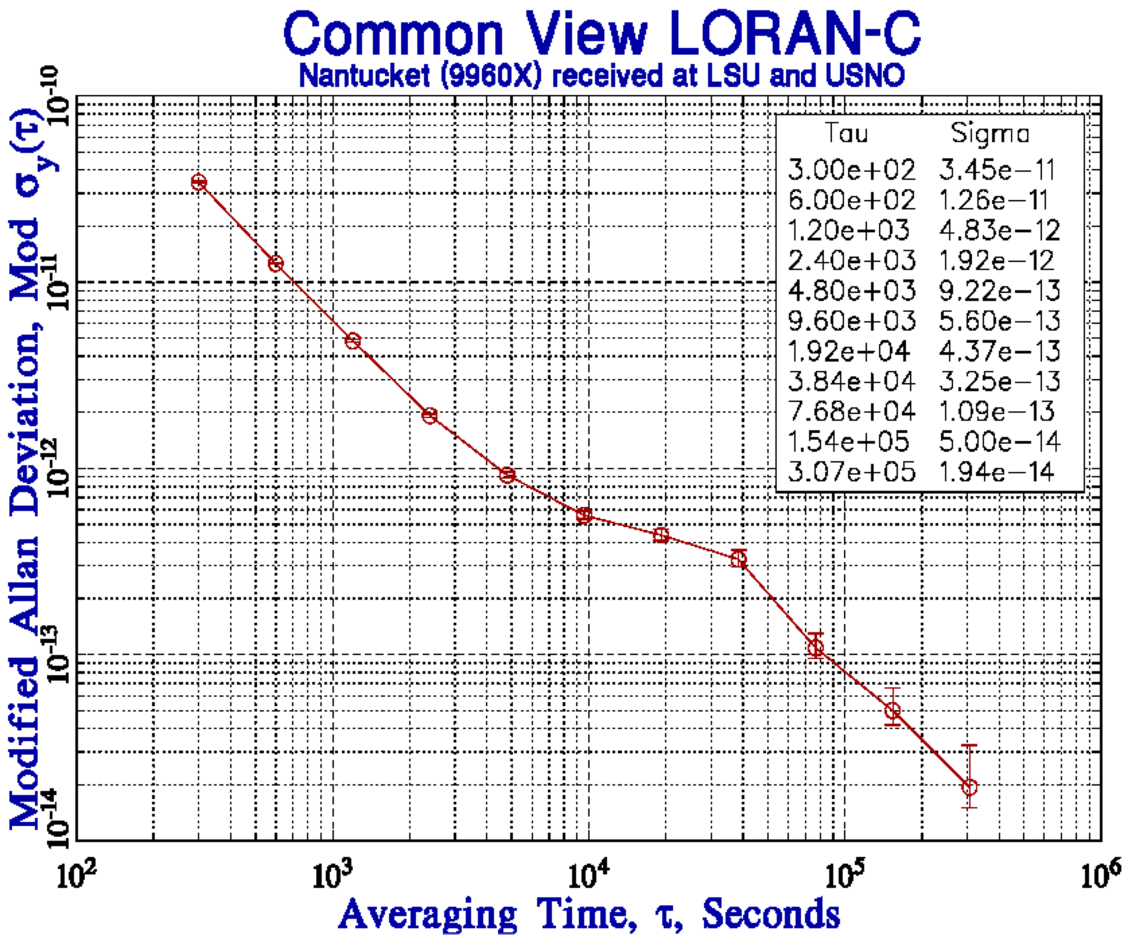

Figure 5. Frequency stability of LORAN-C with corrections applied from monitor sites..

B. Frequency Control Capabilities of all providers

Table IV ranks the providers according to the received frequency uncertainty of their signals. It identifies the providers that meet stratum-1 (1×10^{-11}) and stratum-2 (1×10^{-8}) requirements for frequency.

C. The Potential Role of eLORAN as a Frequency Control Source

As identified in Table IV, only four providers other than GPS can currently meet the requirements of a stratum-1 source for frequency control (WAAS, eLORAN, CDMA, and WWVB). Two of these (WAAS and CDMA) rely on GPS and cannot be regarded as a GPS backup system. This leaves only eLORAN and WWVB as potential backup systems. eLORAN has several advantages over WWVB that lead to better performance, including multiple stations that provide much stronger signals in nearly all geographic regions, and a pulse envelope that largely eliminates the problem that WWVB has with cycle ambiguity. Thus, it is clear to us that eLORAN is the best available backup source to GPS for frequency control in the United States.

VI. Summary and Conclusion

We have thoroughly reviewed all of the available broadcast signals that anchor the time and frequency infrastructure in the United States. As a result of this review, we have identified eLORAN as potentially the best available backup provider to GPS as a reference source for precise time synchronization and frequency control. With its large coverage area, its high level of redundancy due to multiple transmitters, and its ability to be received indoors, eLORAN also has the potential to become one of the leading providers of time-of-day information in the United States, a role that legacy LORAN-C was not able to fulfill.

Table IV. Frequency providers (ranked by received frequency uncertainty).

Signal	Received Frequency Uncertainty	Stratum-1 source	Stratum-2 source	Notes
GPS	1×10^{-13}	Yes	Yes	The dominant system for frequency control, with GPS disciplined oscillators commercially available from a number of vendors.
WAAS	1×10^{-13}	Yes	Yes	Excellent performance, but normally used as an adjunct to GPS, and not as a standalone frequency source.
eLORAN	2×10^{-13}	Yes	Yes	Stable ground wave signals and modulation that reduces the problem of cycle ambiguity.
CDMA	5×10^{-13}	Yes	Yes	Very good performance, essentially an "indirect" version of GPS that works indoors, with a smaller coverage area and some degradation in accuracy. However, the required frequency tolerance for the CDMA carrier is just 5×10^{-8}, so only this type of frequency accuracy can be "guaranteed."
WWVB	5×10^{-12}	Yes	Yes	The LF signal path is similar to that of eLORAN and the frequency uncertainty could potentially be equivalent. However, WWVB's form of modulation makes cycle identification more difficult than it is with eLORAN.
WWV	1×10^{-9}	No	Yes	The frequency uncertainty is limited by the sky wave propagation of HF radio signals.
XDS	3×10^{-6}	No	No	The frequency uncertainty of television signals is normally limited by the frequency specification for the color burst oscillator, which is ±10 Hz at a nominal frequency near 3.58 MHz. This uncertainty can potentially be 5 or 6 orders of magnitude smaller if the television station uses an atomic oscillator.
SPOT	NA	No	No	FM radio signals have a stable line of sight path and could potentially be a stratum-1 frequency source, but there is no current mechanism in place to achieve this.
SDARS	NA	No	No	Could potentially be useful as a frequency source, but no information is currently available.
RDS	NA	No	No	FM radio signals have a stable line of sight path and could potentially be a stratum-1 frequency source, but there is no current mechanism in place to achieve this.
NTP	NA	No	No	Not usable as a continuous frequency source.
FLEX	NA	No	No	It is possible to extract a good frequency reference from the code, but the carrier frequency is not required to be locked to GPS and might be unusable as a frequency reference.
ACTS	NA	No	No	Not usable as a continuous frequency source.

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