Comparing LORAN Timing Capability to Industrial Requirements

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Abstract - *The telecommunications and electric power industries both operate systems that depend upon precise time synchronization or frequency control. These systems typically use signals from the Global Positioning System (GPS) satellites as their timing source, making them vulnerable to an extended GPS signal outage. This vulnerability has generated interest in LORAN as a redundant timing source. This paper discusses and interprets the stringent time and frequency requirements of three industrial applications: the frequency requirements for primary reference sources used in telecommunication networks, the timing requirements for base stations used for Code Division Multiple Access (CDMA) wireless telephones, and the timing requirements for the phasor measurement units (PMUs) operated by the electric power industry. It briefly looks at what GPS is required to do for these applications and discusses the holdover capability of GPS disciplined oscillators. The paper then compares the current and future timing capability of LORAN to the previously described industrial requirements.*

1. Introduction

Numerous industrial applications rely on precise time synchronization and frequency control, but the most stringent requirements relate to telecommunication networks and the electric power grid [1], 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 position, navigation, and timing [2, 3, 4]. More recent studies have focused entirely on timing issues and have favorably compared LORAN to all other available radio time signals both for general usage [5] and for telecommunications usage [6]. However, it seems that questions remain about how to identify and interpret industrial timing requirements, and about how long critical infrastructure elements can function without the reception of GPS signals. This paper attempts to answer these questions, and compares the current and future timing capability of LORAN to the existing timing requirements of United States industry.

2. Interpreting industrial requirements for frequency and time accuracy

Most of the time and frequency literature is about state-of-the-art measurements. Progress is made each year, and increasingly better results are continuously published. Of course, the best results are achieved under optimal laboratory conditions using instruments operated by subject matter experts who have many years of experience. These results are often not easy to duplicate elsewhere. Some twenty years ago, a colleague of mine described this seemingly endless process as "stalking the elusive picosecond."

Industrial timing requirements are very different. Industry requires timing instruments that work right out of the box, continuously producing the required signals over long periods with little or no attention. Non-experts usually install these instruments, and they expect them to run continuously without maintenance or adjustment in much harsher environments than those found in a laboratory. If an instrument fails, another functionally equivalent instrument is installed in its place. The goal is not to "stalk the elusive picosecond", but rather to capture and tame the microsecond. The accuracy requirements are currently limited to $\pm 1 \times 10^{-11}$ for frequency and ± 1 µs for time, but these requirements must be simultaneously met at many thousands of sites deployed across the entire United States, a challenging problem for industry. Some requirements were defined based on GPS capability, and meeting them without GPS is difficult. In the rest of this section, we'll explore what these requirements mean. In sections 3 through 5, we'll examine three specific industrial applications that must meet them.

2.1. Frequency Accuracy

Frequency accuracy is usually stated as a unitless value. For example, the Stratum-1 (ST1) frequency accuracy requirement used by the telecommunications industry is 1×10^{-11} [7, 8]. This number 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 × 10^{-11} = 10^{-4} Hz = 100 µHz). To put this in perspective, a frequency counter with 12 digits of resolution is needed to show a frequency offset of 1×10^{-11} at 10 MHz without averaging. With a common 10-digit counter, an ST1 frequency would appear to be "perfect".

Only a few types of devices meet ST1 requirements without periodic adjustment [5]. One, of course, is a cesium oscillator, which is a primary standard of frequency. The others are disciplined oscillators, where the periodic adjustment is done automatically by use of a radio time signal. The oscillator being disciplined is usually a quartz crystal oscillator, with the better quality devices temperature controlled (TCXO) or ovenized (OCXO); or a rubidium, presently the least expensive type of atomic oscillator. The oscillator is usually disciplined by GPS signals (GPSDO), or by LORAN signals (LDO).

When operating normally, a cesium oscillator, a GPSDO, and an LDO should all maintain ST1 accuracy indefinitely, but a few caveats should be noted. Cesium oscillators are too expensive for industry to purchase in large quantities, and have a relatively short lifetime. They typically cost $30,000 or more, and their cesium beam tubes are subject to failure, often after five to ten years. The cost of replacing a beam tube can be more than half of the purchase price of a new cesium oscillator. GPSDO and LDOs cost much less and have a longer lifetime, but they will eventually fail to meet ST1 requirements if the radio time signal they are tracking becomes unavailable.

A common mistake when discussing requirements is to confuse stability with accuracy. This happens because oscillator performance is often stated in terms of the Allan deviation (ADEV), a statistic that estimates frequency stability [9]. ADEV numbers for given averaging times are commonly found on oscillator data sheets, and can be confused with accuracy numbers. For example, rubidium oscillators are often called ST1 sources, because some models have ADEV numbers that drop below 1×10^{-11} after a few seconds of averaging, and stay there for averaging periods of more than a day. This indicates that they are stable enough to serve as ST1 sources *if they are periodically adjusted*. However, their "out of the box" turn-on accuracy is nearly always worse than 1×10^{-11}, and unadjusted rubidium oscillators can miss the ST1 requirement by one or two orders of magnitude.

2.2. Time Accuracy

Time accuracy refers to the time difference between a industrial time source and Coordinated Universal Time (UTC). The official UTC is kept by the International Bureau of Weights and Measures (BIPM) in France, by averaging clocks located at nearly 60 laboratories around the world. However, the official UTC is a paper time scale that does not generate or distribute signals, and is of little use to industry. Fortunately, two national timing laboratories in the United States, the National Institute of Standards and Technology (NIST) and the United States Naval Observatory (USNO), maintain real-time UTC time scales for use as measurement references. These time scales, called UTC(NIST) and UTC(USNO) respectively, can be considered equivalent to each other and to UTC when ±1 µs is the time accuracy requirement. From January 2000 until this writing (October 2006), the difference between UTC(NIST) and UTC has never exceeded 0.046 µs, and has remained within 0.1 µs since July 6, 1994. UTC(NIST) and UTC(USNO) have never differed by more than 0.043 µs since January 2000 [10].

Note that a cesium oscillator is a frequency standard that cannot recover UTC unless its 1 pps output is synchronized to the UTC second. This synchronization cannot be done without GPS or another UTC time source. In contrast, a GPSDO can synchronize to UTC(USNO) by itself. For these reasons, the use of GPSDOs has historically been *the only practical way* for industry to meet its ±1 µs time accuracy requirement.

3. Industrial timing requirements for telephone networks

The telecommunications infrastructure of the United States continues to evolve toward becoming a high-speed fully digital environment, with all network elements requiring synchronization [11]. Synchronization is needed to support fast bit rates, to preserve data, and to maximize the use of available bandwidth so that networks can operate at full capacity. Synchronization failures can cause data to be lost, can cause networks to be unreliable or to operate at reduced capacity, and can even cause networks to fail. In a study completed in 2002, the Network Reliability Steering Committee (NRSC) reported that 9.4% of all telecommunications outages were caused by timing outages [12].

Because the costs of an outage can be severe, both financially and otherwise, telecommunication providers should have redundant timing sources within their networks to prevent a single point of failure.

The synchronization reference for a network is called the primary reference source (PRS) by the American National Standards Institute (ANSI) standard [7], or alternately, a primary reference clock (PRC) by the International Telecommunications Union (ITU) standard [8]. Since the AT&T divestiture of 1984, telephone carriers have had to interconnect and exchange data with each other, forcing each carrier to maintain its own timing references. The PRS maintained by one carrier must appear to be synchronized with the PRS units maintained by all of the other carriers with which it interacts, even though there are no synchronization paths and no master-slave timing relationship between carriers (Figure 1). This is called plesiochronous operation, which simply means that it “looks synchronous”. It works with a minimal amount of data loss if all carriers maintain PRS sources that stay within narrow frequency tolerances defined with respect to Coordinated Universal Time (UTC).

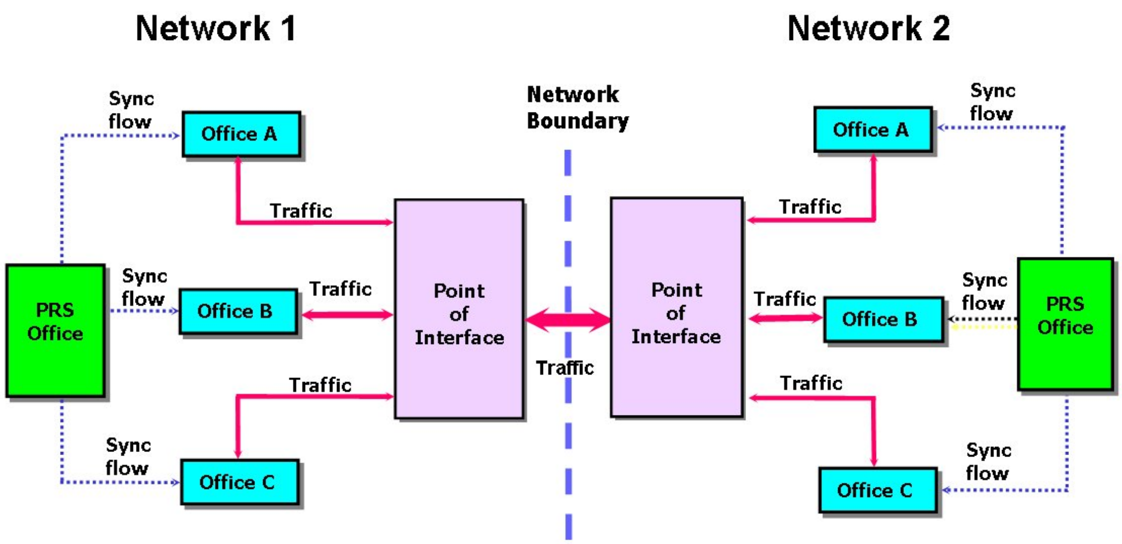

Figure 1. A plesiochronous connection between two networks. Each network maintains its own PRS.

To illustrate this, consider the traffic exchanged in Figure 1 to be a T1 connection between two telephone carriers. The North American DS1/T1 standard for telecommunications consists of a digital data stream clocked at a frequency of 1.544 MHz. This data stream is divided into 24 voice channels, each with 64 kHz of bandwidth. Each voice channel is sampled 8000 times per second. When the time difference between the two PRS units exceeds the period of the sampling rate, a cycle or frame slip occurs. This results in loss of data, noise on the line, or in some cases, a dropped call. The slip rate, *SR*, can be calculated as

$$SR = \frac{\mathrm{T}_{samp}}{\mathrm{F}_{diff}} \quad ,$$

where T_{samp} is the period of the sampling rate (a constant for T1 of 125 μs), and F_{diff} is the frequency difference between PRS A and PRS B. If PRS A is high in frequency with respect to UTC by $+1 \times 10^{-11}$ and PRS B is low in frequency by -1×10^{-11}, then the interval between slips is

$$SR = \frac{125 \times 10^{-6} s}{2 \times 10^{-11}} = 6250000\ s = 72.3 \text{ days}.$$

One slip every 72 days is considered acceptable network performance because it limits the number of problems to a manageable level. Thus, the ANSI T1.101 [7] 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.

The definition tells us that a PRS must meet two requirements: a frequency accuracy requirement of 1×10^{-11}, 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 the 1×10^{-11} accuracy must be maintained at all times. The accuracy requirement is equivalent to Stratum 1 (ST1) as defined by both ANSI and ITU [7, 8].

4. Industrial timing requirements for the wireless CDMA telephone network

Code division multiple access (CDMA) systems have the most stringent synchronization requirements (Table 1) of the various types of wireless telephone networks. CDMA standards [13, 14] require all base stations except repeaters to be synchronized to within ±3 µs, and for all 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. 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.

Table 1. CDMA timing requirements.

Specification	Section in CDMA standard [14]	Requirement
Timing Reference Source	4.2.1.1	Each base station *shall* use a time base reference from which all time-critical CDMA transmissions, including pilot PN sequences, frames, and Walsh functions, shall be derived. The time base reference shall be time-aligned to CDMA System Time. Reliable external means *should* be provided at each base station to synchronize each base station time base reference to CDMA System Time. Each base station should use a frequency reference with sufficient accuracy to maintain time alignment to CDMA System Time.
Timing Reference Tolerance	4.2.1.1.3	For all base stations except repeaters, the pilot time alignment error *should* be less than 3 µs and *shall* be less than 10 µs. In the case of base station repeaters, the difference in the pilot time alignment error between the output of the remote base station and the output of the base station repeater *shall* be less than 5 µs. For base stations supporting multiple simultaneous CDMA Channels, the pilot time tolerance of all CDMA channels radiated by a base station *shall* be within ±1 µs of each other.
Holdover	4.2.1.1	With the external source of CDMA System Time disconnected, the base station *shall* maintain transmit timing within ±10 µs of CDMA System Time for a period of not less than 8 hours.

CDMA base stations identify themselves via a time offset. By synchronizing to a common time reference, they can perform a nearly seamless handover of a mobile phone from one base station to another. The base stations operate in the same RF channel and are identified by a spread spectrum pseudo random noise (PRN) code. This works because each base station offsets the start of the code by a different time interval with respect to their common time reference. When the time alignment of base stations exceeds ±10 µs the ability to support soft-handoff will fail, the carrier-to-noise ratio will suffer, and poor pilot assignments will occur. In short, mobile phone performance is much worse when synchronization is lost. Base station failures might not occur at exactly the 10 μs limit, as a larger time error can sometimes be tolerated. For example, if the required time difference between two base stations is 64 μs, then an error of half this difference; or 32 μs can be tolerated before the stations "collide" and coverage is lost [6].

5. Industrial requirements for synchrophasor measurements

As the electric power grid continues to expand and as transmission lines are pushed to their operating limits, it has become more important to dynamically control the power system in real time to prevent wide scale cascading outages. For decades, control centers have estimated the "state" of the power system (the positive sequence voltage and angle at each network node) from measurements of the power flows through the power grid. In recent years, the power industry has begun to synchronize and align phasor measurements made at power substations to monitor the state of the power system in real time [15]. A synchronized phasor, or synchrophasor, is a phasor calculated from data samples using a UTC signal as the reference for the measurement (Figure 2). Because they are referenced to an absolute point in time, synchrophasors collected from remote sites have a common phase relationship [16].

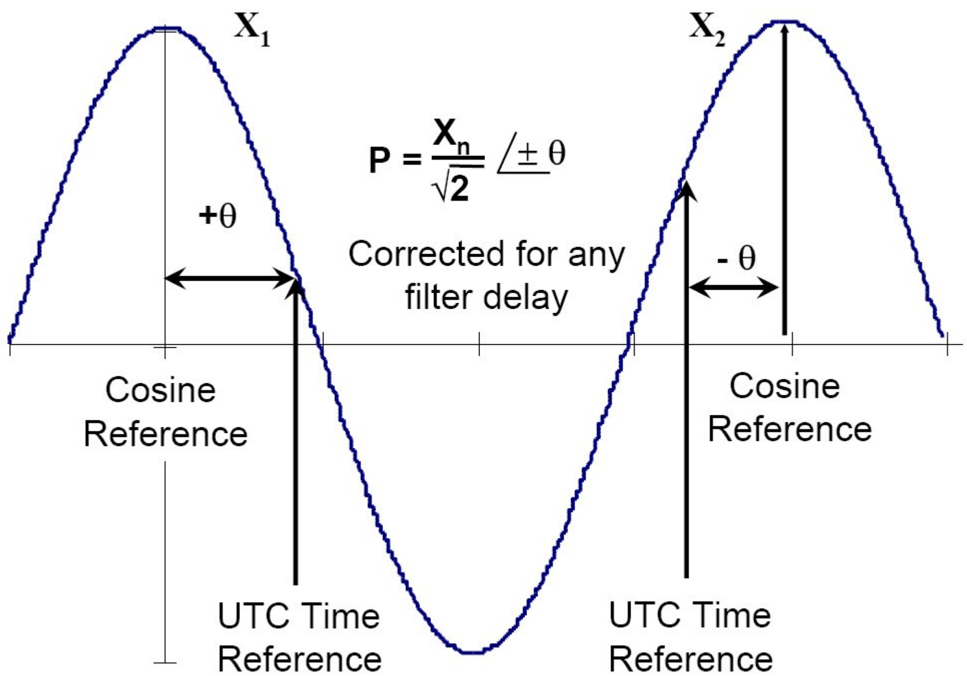

Figure 2. Synchrophasor definition.

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. Although the concept of a PMU had been explored long before the GPS satellites were launched, GPS was necessary to provide the necessary timing accuracy. The first prototype PMU was assembled in 1988 with a GPS clock [17], and today commercial units are available from a number of vendors [18]. PMU units send their measurements over a network connection to a central site, where the time stamps of the measurements are aligned, the measurements are processed, and real time decisions are made about how to distribute power within the grid (Figure 3).

The *IEEE C37.118-2005* standard [16] 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) [16]. However, the desired accuracy level is ±1 μs, which corresponds to a phase error of 0.022° for a 60 Hz system [16, 17]. The UTC time source thus needs ±1 μs accuracy.

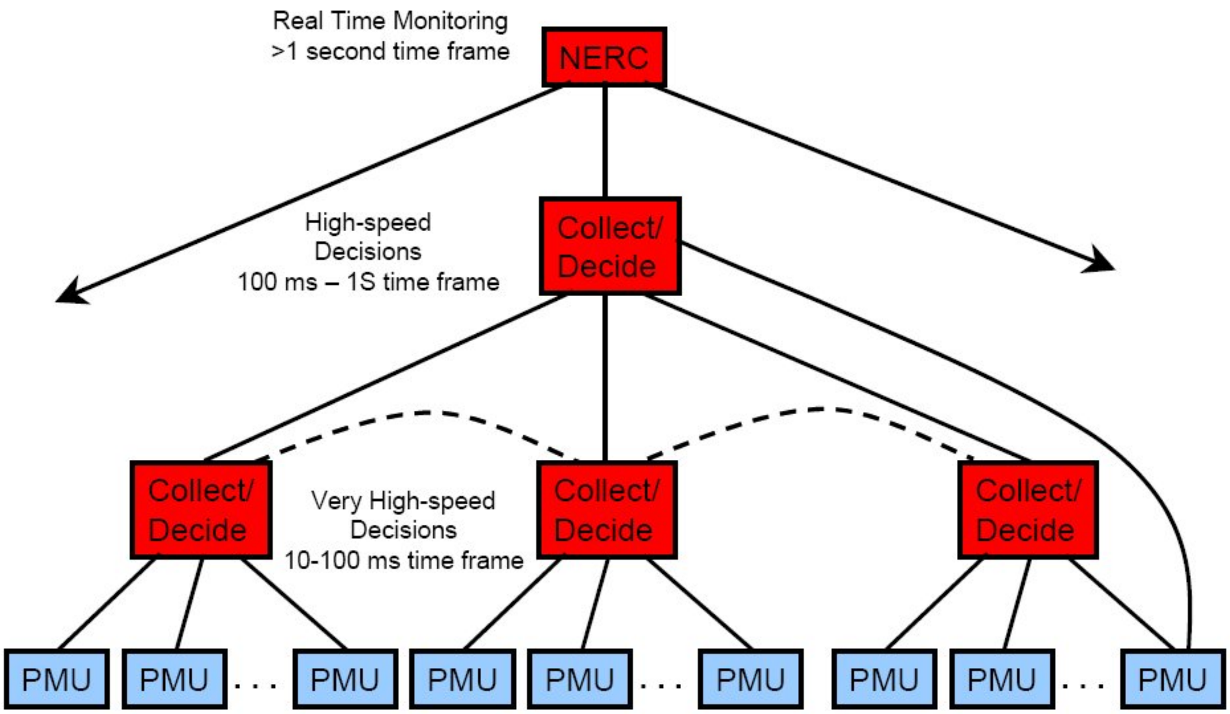

Figure 3. PMU data collection topology.

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:

> *The principal problem with satellite broadcasts has been availability. All satellite broadcast systems have been put up for purposes other than time dissemination. During crises the primary purposes take priority and timing function users have occasionally lost access. Satellite systems are expensive to put up and maintain, so in the longer term the time function user is also at the mercy of funding provided for the primary function* [16].

The standard also notes (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* [16].

In short, there is no current backup for synchrophasor measurements, and the accuracy of the time tags quickly degrades when GPS reception is lost. However, the modernized LORAN network can provide a redundant timing source for the power grid. LORAN no longer requires an external time input and can recover UTC with the necessary ±1 µs accuracy from the reception of just one station (Section 8).

6. The performance of GPSDOs during normal operation and during signal failures

All three applications described in Sections 3 through 5 rely heavily on GPS disciplined oscillators (GPSDOs) to meet their requirements. The requirements discussed in Sections 3 through 5 suggest that the "magic numbers" for industry are accuracies of $\pm 1 \times 10^{-11}$ for frequency, and ±1 µs for time, both with respect to UTC. Actual GPSDO performance is usually much better than the requirements [19]. Any GPSDO that remains locked to the signal should exceed the frequency accuracy requirement. The time accuracy requirement is met by nearly all GPSDOs right out of the box, even without calibration of the receiver or antenna cable. Most GPSDOs have internal receiver delays of much less than 0.5 μs, and even if a 100 meter long antenna cable were used (unlikely), it would introduce an additional delay of less than 0.5 μs. Other factors that limit GPS accuracy, such as antenna coordinate errors, multipath errors, ionospheric delay errors, and so on, can usually be ignored and the ±1 μs time accuracy requirement will still be met. To illustrate this, Figure 4 shows a GPS antenna at a CDMA site that is located near the side of a metal grain elevator. To GPS timing experts, this would appear to be a horrific multipath environment. One side of the sky view is completely obstructed and there is a large reflective metal surface very close to the antenna, but the CDMA time requirements are still met. It seems clear that concerns about using GPS have nothing to do with its performance or ease of use, and everything to do with its vulnerabilities to certain types of failures.

Figure 4. A GPS antenna at a CDMA base station with an obstructed view of the sky.

GPS can and does fail, particularly in local areas. There are many possible failure modes that are discussed in detail elsewhere [2, 3, 4, 6], but the most likely cause of failure is probably RF interference and jamming (either intentional or unintentional). One published account described how GPS was unintentionally jammed for more than two months in a California harbor area by commercially available television antennas located on private boats [20]. The main reason that GPS is so susceptible to interference is the low power of the signal. A receiver can lose lock on a satellite due to an interfering signal that is only a few orders of magnitude more powerful than the minimum received GPS signal strength, which is –160 dBW on earth for the L1 carrier, equivalent to 10^{-16} W [21].

When the GPS signal is unavailable, a GPSDO begins relying on its holdover capability to maintain synchronization. The holdover capability is provided by either by a free running local oscillator, or a local oscillator that is steered with software that retains knowledge of its past performance. There is no exact answer as to how long GPSDOs can continue to meet timing requirements in the absence of GPS. It depends entirely on the specific model of GPSDO in use. Manufacturers often do not provide holdover specification for their GPSDOs, and even if they do, actual tests could produce different results. For CDMA, the requirement of ±10 μs in eight hours is equivalent to a frequency accuracy of $\pm 2.8 \times 10^{-10}$.

A real world test of GPS holdover took place during the GPS JAMFEST held at Holloman Air Force Base and White Sands Missile Range in New Mexico in late 2005 [22]. GPS was intentionally jammed while four timing receivers produced by the same manufacturer were compared to a cesium oscillator. One device received LORAN signals; the other three were GPSDOs (one with a quartz local oscillator and two with a rubidium). During four jamming periods lasting for 30 to 40 minutes, all three GPSDOs came unlocked, while the LORAN receiver remained locked as expected. The rubidium based GPSDOs had no significant time error, but the quartz based GPSDO accumulated a time error of about 8 µs during three of the four jamming periods, nearly exceeding the CDMA requirement in much less than 1 hour. More importantly, the local CDMA telephone provider reported problems with its base stations in the vicinity, which apparently were out of tolerance. The complaint from the phone company put an end to the jamming exercise, so a five hour outage was simulated by disconnecting the GPS antennas. During this outage, the rubidium units stayed well within CDMA tolerance, but the time error of the quartz GPSDO was nearly 30 µs, much worse than the requirement.

A similar experiment was conducted at the NIST laboratories in Boulder, Colorado in October 2006. This test consisted of removing the antennas from four GPSDOs that had been continuously running for weeks or months, and leaving them off for a week. The frequency accuracy of each device was measured during the "outage", as well as the length of time before the ±10 µs CDMA requirement was exceeded. The results are summarized in Table 2. Note that only one device maintained ST1 frequency accuracy requirements during the simulated week long outage.

Table 2. Holdover performance of GPSDOs.

GPSDO	Type	Frequency Accuracy during one week of holdover	Time Offset after one week of holdover	Meet ST1 requirement during holdover?	Time until CDMA specification failure
A	Rubidium	8×10^{-11}	42 µs	No	50 hours
B	Rubidium	3×10^{-12}	< 3 µs	Yes	> 1 week
C	Rubidium	1×10^{-9}	637 µs	No	20 hours
D	OCXO	3×10^{-10}	82 µs	No	37 hours

The NIST test was certainly not representative of the entire GPSDO marketplace. It was limited to four devices that we had on hand, and only one device (D) is known to have been used by a CDMA provider. The other three units were rubidium based, and CDMA providers normally deploy less expensive TCXO or OCXO devices. All other things being equal, a rubidium GPSDO should have better holdover capability; but device D outperformed C, and a cleverly devised steering algorithm that compensates for oscillator aging and drift can allow some quartz units to outperform some rubidium units. In fact, one published algorithm claims holdover capability of 1.5 µs per day for an OCXO based device [23].

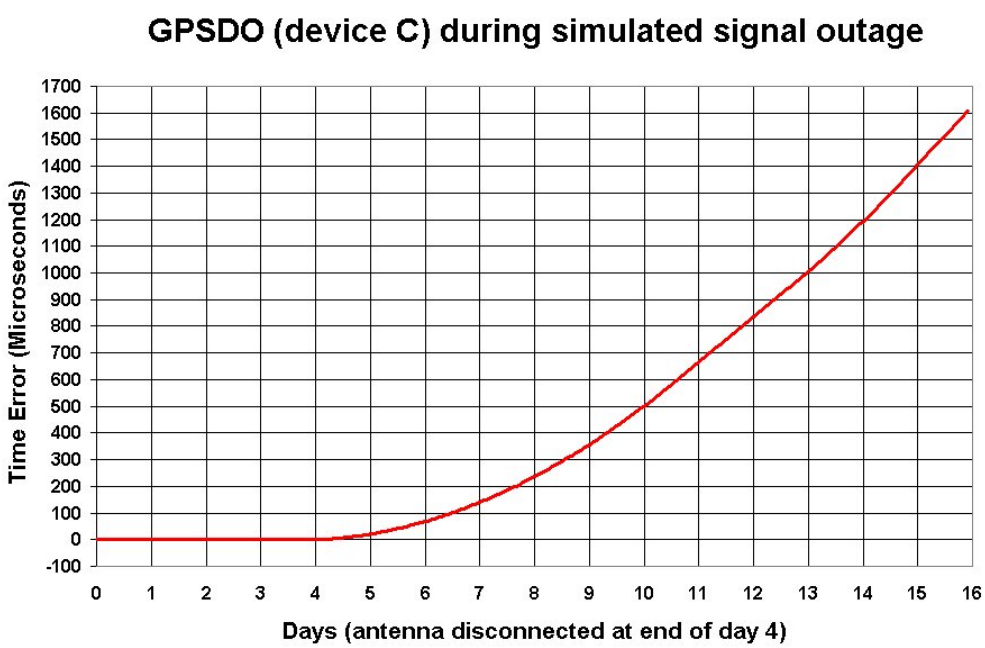

Figure 5. Phase plot of rubidium GPSDO with poor holdover capability during simulated signal outage.

Our simple test showed, however, that not all devices have effective holdover algorithms. Figure 5 shows a phase plot of device C before and after its antenna was disconnected. Device C immediately became a free running oscillator with an accuracy of parts in 10^{10}, which is typical for an unadjusted rubidium. This still allowed it to meet the CDMA specification for about 20 hours. In contrast, a TCXO is typically 100 to 1000 times less accurate than a rubidium, and without an effective holdover algorithm would be out of tolerance almost instantly. As noted earlier, there is no exact answer as to how long GPSDOs can continue to keep time to within ±10 μs in the absence of GPS. It is entirely device dependent, and could range from a few seconds in the worst case to more than a week in the best case.

7. Comparing LORAN frequency capability to industrial requirements

LORAN has been successfully used for many years as a frequency reference that easily meets ST1 PRS requirements. Figure 6 shows a 30 month phase comparison between an LDO locked to LORAN signals from Boise City, Oklahoma (9610-M), and the UTC(NIST) time scale located in Boulder, Colorado. Boise City is the closest LORAN station to Boulder, located about 432 km away. The frequency accuracy is estimated as 5×10^{-15} (using linear regression to determine the slope of the phase, shown as a red line on the graph) over the 30 month period.

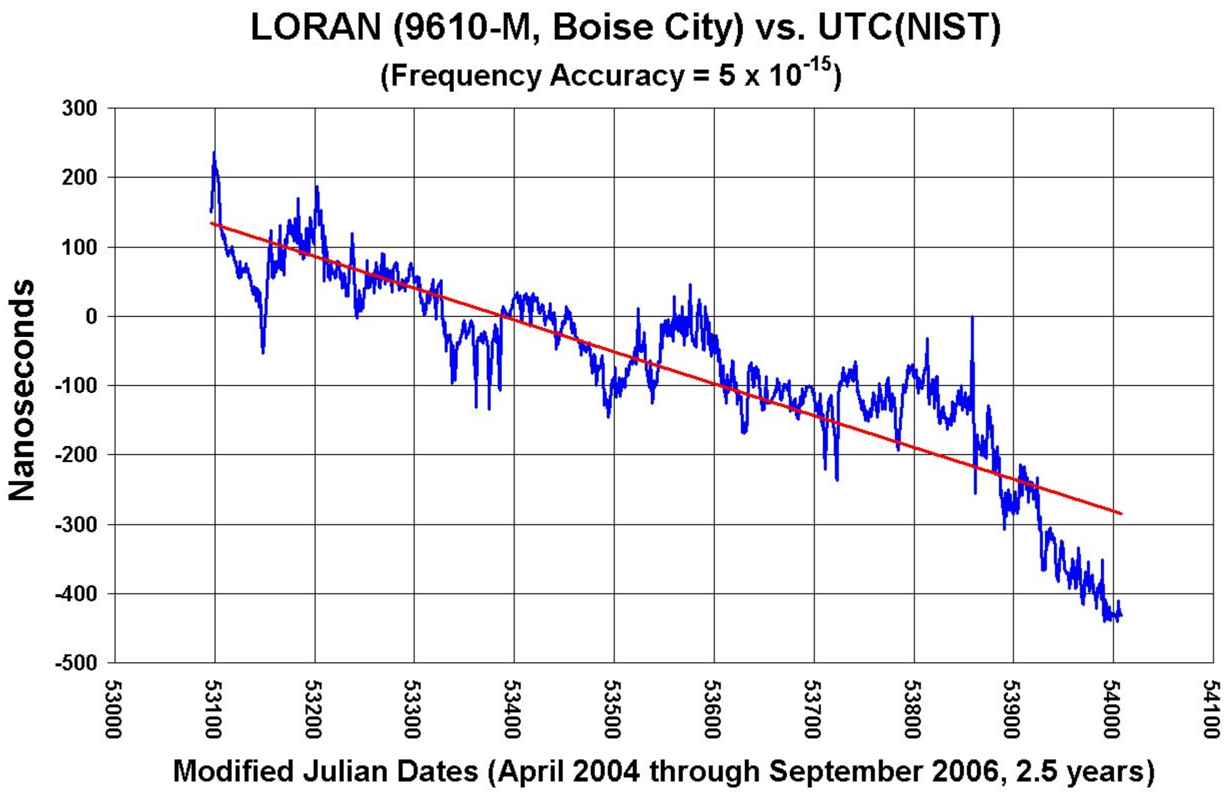

Figure 6. 30 month phase comparison between LORAN 9610-M and UTC(NIST).

Of course, the frequency accuracy over a given interval is limited by the frequency stability, which can be estimated with the Allan deviation [9]. Figure 7 shows the stability of the LDO for averaging times ranging from one day to 30 days. Frequency stability after one day of averaging was 2.9×10^{-13}, dropping below 1×10^{-13} after five days. To place these values in context, Figure 8 compares the stability of this same LDO to eight different GPSDOs that have been recently tested by NIST. The LDO (shown by the red bar on the graph) was more stable than five out of the eight tested GPSDOs. Few LDOs are available for testing, but the National Physical Laboratory (NPL) of the United Kingdom has tested a different model of LDO from the one tested at NIST. Their results were similar, 2×10^{-13} after 1 day of averaging [24].

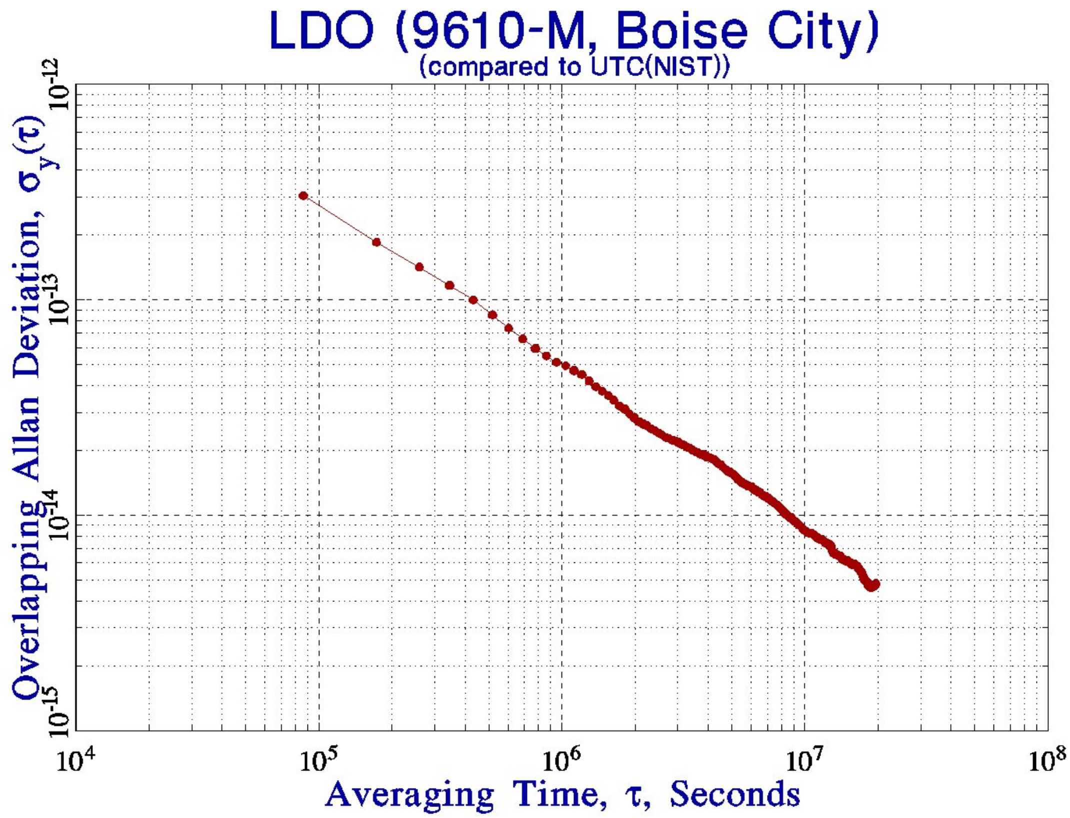

Figure 7. Frequency stability of LORAN 9610-M signals for averaging times ranging from one to 30 days.

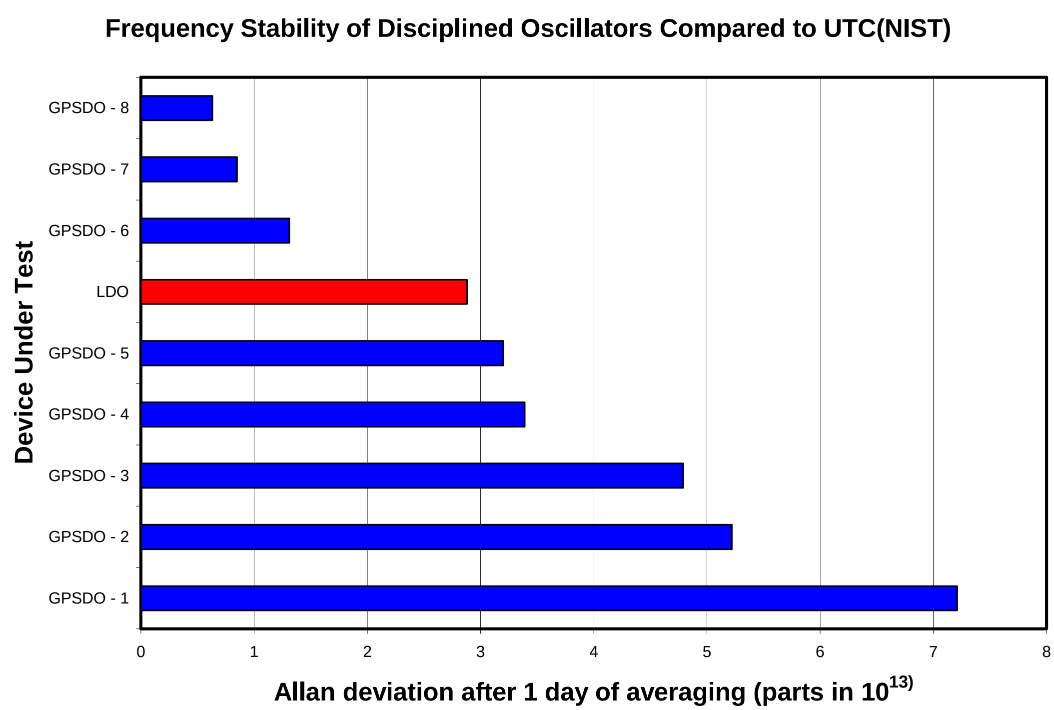

Figure 8. A comparison of LDO frequency stability to eight different GPSDOs.

8. Comparing LORAN timing capability to industrial requirements

To review LORAN timing capability, a discussion of the various forms of LORAN is necessary. Three forms are discussed here: legacy LORAN, the preexisting network that did not broadcast a time code, modernized LORAN, which provides a time code through the LORAN Data Channel (LDC) and improves the frequency control of the transmitters, and enhanced or eLORAN, which distributes differential corrections through the LDC that significantly improve the accuracy of the received time.

Legacy LORAN does not broadcast a time code, but does allow the receiver to generate an on-time 1 pulse per second (pps) signal that can be used as a synchronization reference. By specification, signals from the master stations of legacy LORAN are within 0.1 μs of UTC(USNO) as transmitted [25]. Received time can typically be recovered to well within ±5 μs, half the period of the 100 kHz carrier, by aligning a GRI pulse with the UTC second, a technique known as time of coincidence (TOC). Synchronization to within ±1 μs is possible with legacy LORAN and was claimed decades ago by national timing laboratories [26]. However, several factors can change the propagation delay between the transmitter and receiver and limit the accuracy. They include seasonal changes in ground conductivity, diurnal phase shifts at sunrise and sunset, and changes in temperature and precipitation due to weather conditions. There was often no easy way to calibrate a receiver and antenna system or to compensate for the delay biases. In addition, the TOC technique required another UTC time source and was never practical for unattended operation.

Modernized LORAN features new timing equipment installed at each transmitter site, including an ensemble of three cesium oscillators that is synchronized to within 0.02 μs of UTC(USNO) [27]. A new modulated pulse is used to generate the LDC. This pulse is added 1 millisecond after the eighth pulse on secondary stations, and between the existing eighth and ninth pulses on master stations. It delivers information to receivers that includes time of day, leap second information, differential corrections, and network health and status information (Table 3). The 120-bit LDC message is sent at a rate of five bits per Group Repetition Interval (GRI), requiring 24 GRIs, or a maximum of 2.38 s to transmit [28].

The first experimental time code broadcasts over the LDC were successfully completed from the station at Jupiter, Florida on October 18, 2005 [29], and five stations are broadcasting a time code as of October 2006. Pending government approval, at least 27 North American transmitters will eventually have time code capability. Legacy receivers will continue to work as before with signals broadcasting a time code, but they will be unable to decode the LDC or utilize any other new features. Modernized LORAN receivers should be able to routinely meet the ±1 μs accuracy requirement discussed in sections 4 and 5.

Table 3. Time and differential correction messages contained in LORAN data channel (LDC)

Time Message	Number of Bits	Resolution	Range
MSG Type	4		16
Time and Date	31	1 message epoch	97 to 163 years
Leap Seconds	6		64
Next leap second	1		
Station ID	3		8
Total Time Message	45		

Differential Message	Number of Bits	Resolution	Range
Message Type	4		16
Time Base Quality	2		
Reference ID	10		1024
Signal ID	3	2	16
Correction #1	11	2 ns	±2.046 μs
Correction #2	11	2 ns	±2.046 μs
Age/Quality	3		
Early skywave message warning	1		
Total	45		

eLORAN goes one step further than modernized LORAN by distributing differential corrections supplied by monitor sites. Differential corrections are computed based on signal measurements made by a network of far-field monitors operated by the United States Coast Guard (USCG) (Figure 9). The corrections are distributed via the LDC, and applied by receivers that demodulate and decode the LDC message. Calibrated receivers that apply the differential corrections are expected to be able to recover time accurate to within 0.1 μs [29], which is comparable to the performance of a GPSDO.

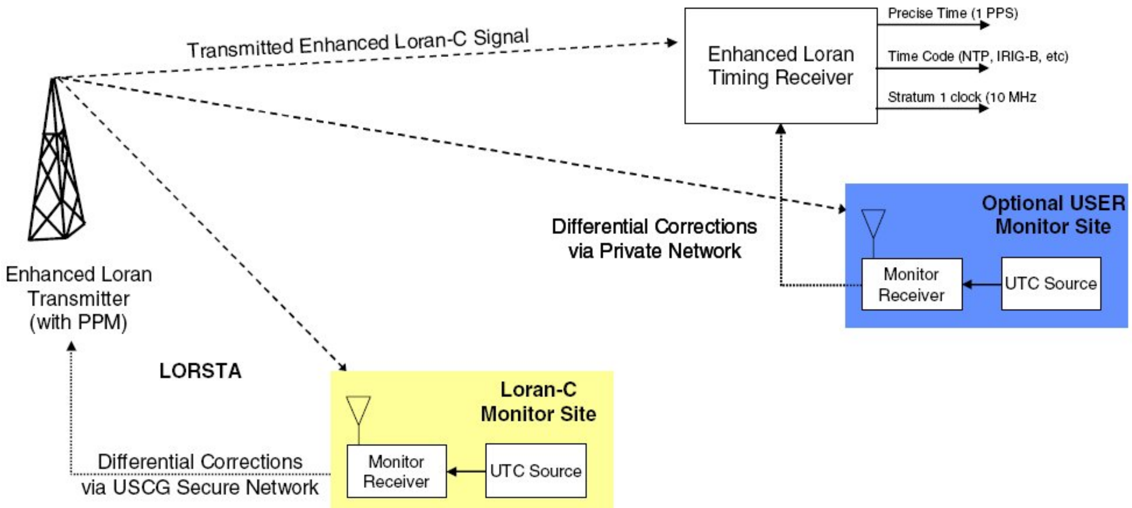

Figure 9. USCG monitoring sites provide the differential corrections included in eLORAN broadcasts.

9. LORAN's ability to serve as a redundant industrial timing source

After comparing the frequency and time capability of LORAN (Sections 7 and 8) to specific industrial timing requirements (Sections 3 through 5), it seems logical to believe that LORAN can serve as a functionally equivalent and redundant source of industrial timing to GPS if the modernized or eLORAN system is completed. In fact, LORAN has two advantages over GPS that could make it the first, rather than the second choice for some industrial timing applications. It is undoubtedly harder to jam [22, 30] and it can work with an indoor antenna [31].

There is, however, one major obstacle working against LORAN's acceptance as an industrial timing source. Few, if any, commercially available LDOs exist that can serve as "plug and play" replacements for GPSDOs. These devices not only have to appear on the marketplace, but they probably must be priced comparably to similar GPSDOs. Whether or not they do appear probably depends on whether or not the U.S. government provides a long-term commitment to LORAN.

10. Summary and Conclusion

Telecommunication networks and the electric power grid, two critical elements of the nation's infrastructure, both depend on GPS to meet their stringent timing requirements. As a result, the designers and maintainers of these systems should prepare for scenarios where GPS is unavailable, and be able to estimate how long they can operate without GPS. The length of a GPS outage that can be tolerated entirely depends upon the holdover capability of the GPSDOs in use. While some devices can meet requirements for hours or days without GPS, others will likely be out of tolerance within seconds or minutes. Thus, the deployment of a redundant timing system in as short a time frame as possible seems to be in the best interest of the United States. LORAN, in its modernized form, can meet all existing industrial timing requirements and appears to be the best and most logical choice to fulfill this role.

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