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

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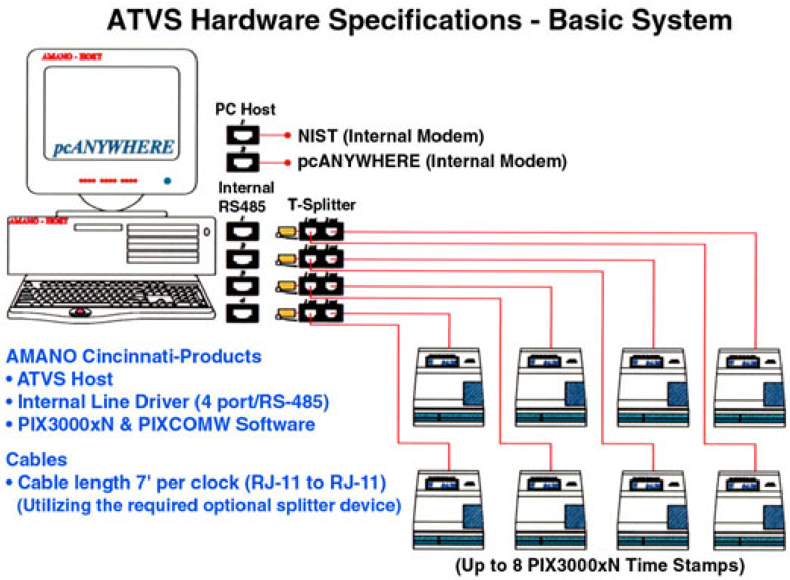
Introduction

- The time and frequency infrastructure for the United States consists of many millions of clocks and oscillators that affect nearly all areas of everyday life.
- The time and frequency infrastructure is anchored by providers that continuously broadcast time and frequency reference signals. These signals are routinely used to set the nation's clocks to the correct time, or the nation's oscillators to the correct frequency.
- GPS is the dominant broadcast reference source for time and frequency and the nation relies heavily upon GPS. However, several studies have shown that exclusive reliance on GPS is not a good idea, even if it were possible. Other signals are needed as backups and alternatives to GPS.
- This paper complements existing studies by defining, describing, and comparing the available broadcast sources of time and frequency in the United States. We place special emphasis on the potential role that eLORAN can play in the national time and frequency infrastructure.

Comparison of Time and Frequency Signal Providers

- We compare eLORAN not only to GPS but to all other United States time and frequency signal providers.
- We limit the comparison to the three topics we consider the most important:
  - **Time-of-Day synchronization of clocks to the nearest second**
  - **Precise time synchronization accurate to 1 millisecond or less**
  - **Frequency control of oscillators**
- We exclude providers whose signals originate from outside of the United States, or whose signals who do not contain a digital time code, are not designed to be machine readable, or whose accuracy is unknown.
- We quote uncertainties that can be used with respect to either of the two laboratories that maintain the national standards for time and frequency, NIST and the USNO. The UTC(NIST) and UTC(USNO) time scales are equivalent to each other and to Coordinated Universal Time (UTC) for nearly all applications.
- All 13 providers that we discuss can trace their signals back, directly or indirectly, to either UTC(NIST) or UTC(USNO).

ACTS



Amano Time Validation System (ATVS)

The PIX-3000xN Time Validation Unit and the PIX-COM Time Synchronization Software have been specially designed by Amano in compliance with the Order Audit Trail System (OATS) rules.

REQUIREMENT	OATS COMPLIANCE	✔ ATVS SOLUTION
Imprint format	• Y2K compliance and prints seconds YYYY/MM/DD HH:MM SS	✔ 1998/02/20 16:51 21s YYYY/MM/DD HH:MM SS
Time synchronization	• Time synchronization with Atomic time from NIST* at least once per day	✔ 1998/02/20 16:48 33■ • Self-validation mark • Self-validation Time Synchronization
Time deviation	• Within 3 seconds deviation per day	✔ • Less than 2.5 seconds deviation per day

* National Institute of Standards and Technology (NIST), Boulder, CO

- ACTS refers to the Automated Computer Time Service operated by NIST and a similar service operated by the USNO.
- ACTS synchronizes computer clocks and standalone clocks through ordinary telephone lines using analog modems.
- The NIST service still receives nearly 3 million telephone calls per year. A high percentage of the calls are from brokerage houses required by law to keep time within 3 seconds of UTC(NIST).

CDMA

- CDMA refers to signals from Code Division Multiple Access base stations used to transport mobile telephone calls. The TIA/EIA IS-95 standard specifies that GPS time is base station time, and all CDMA base stations contain GPS receivers. The timing requirement is 10 µs, even if GPS is unavailable for up to 8 hours. Base stations are normally synchronized to within 1 µs.
- CDMA depends upon GPS. The system will fail if GPS is unavailable for a prolonged period.
- The primary frequencies used are in the 800 and 1900 MHz regions, but other frequencies near 900, 1700, and 1800 MHz are sometimes used.
- Signals are typically usable within 30 miles of a base station, and base stations are plentiful throughout the United States.

eLORAN

Bit Assignments for Time and dLoran messages

(Format for aviation integrity msg TBD)

Time	# bits	Resolution	Range
MSG type	4		16
Time	31	1 msg epoch	97-163 yrs
Leap Secs	6		64
Next leap Sec	1		
sta ID	3		8
Total	45		
dLoran	# bits	Resolution	Range
MSG type	4		16
Time Base Quality	3		
Ref ID	10		1024
Sig ID	3	2	16
Corr # 1	10	2ns	+/- 1.022 usec
Corr # 2	10	2ns	+/- 1.022 usec
Age/Quality	5		
Total	45		

- eLORAN adds a 9^{th} pulse that is pulse position modulated, and will provide UTC, leap seconds, station ID, etc., through the LORAN data channel (LDC).
- A total of 29 North American stations will function as sources of UTC (independent of GPS), and only one station is needed to get accurate time.
- Total message is 120 bits sent at 5 bits per GRI. Requires 24 GRIs or maximum of 2.38 s to transmit.

From: Peterson, et al., “Differential Loran”, ILA 2003, November 2003

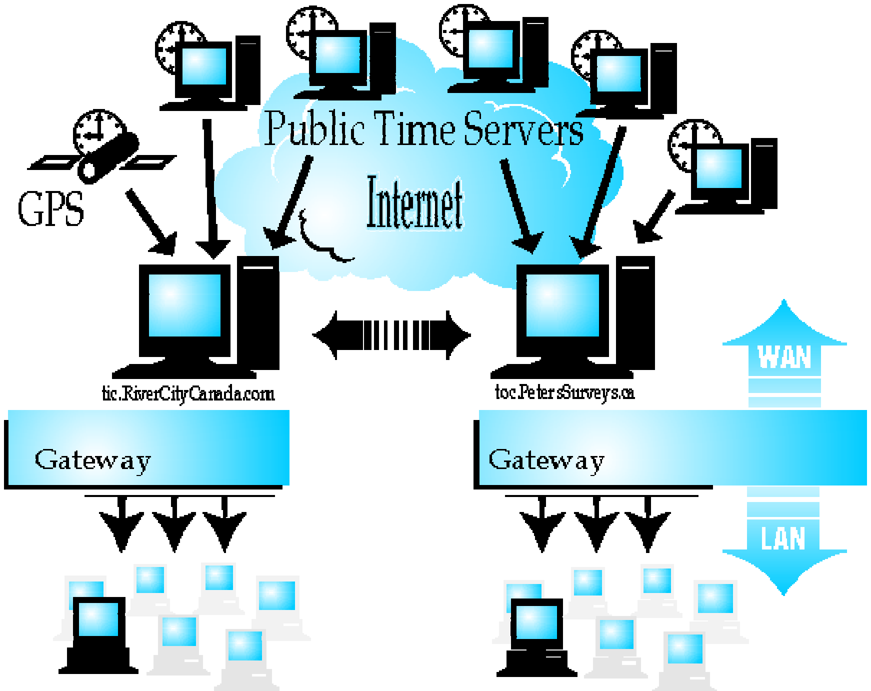
FLEX

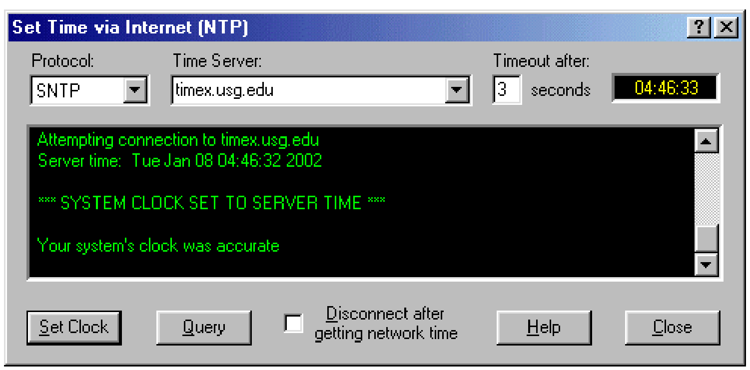
- FLEX is the paging protocol introduced by Motorola in 1993, used for both one-way and two-way systems.
- FLEX is a synchronous time-slot protocol that uses GPS as its time base, and thus is dependent upon GPS.
- The time code contains the month, day, year, hour, minute, second, plus DST and time zone information. Time as transmitted is local time on a forward link frequency near 931 MHz in metropolitan areas.

GPS

- GPS is 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.
- GPS is the dominant distribution source for high accuracy time and frequency information throughout the world.

NTP



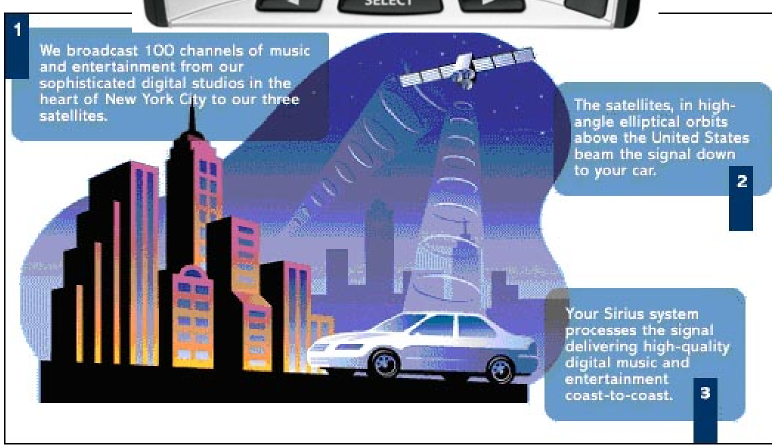


- NTP refers to the Network Time Protocol, the most widely used mechanism for time distribution via the Internet, defined by the RFC-1305 standard.
- NTP servers send a data packet that includes a 64-bit time code containing the time in UTC seconds since January 1, 1900.
- NTP servers typically use GPS, CDMA, WWVB, WWV, or another source as a reference. NIST and USNO NTP servers combine to handle more than 2.5 billion timing requests per day.

RDS

- RDS is the Radio Data System, a service carried by many FM radio stations on a 57 kHz subcarrier.
- More than 1000 FM radio stations in the United States utilize RDS as of 2005.
- RDS synchronizes clocks on car radios, clock radios, and other devices with FM reception capability.
- The time code contains the MJD, the UTC hour and minute, and a local time zone offset. The reference source varies from station to station.

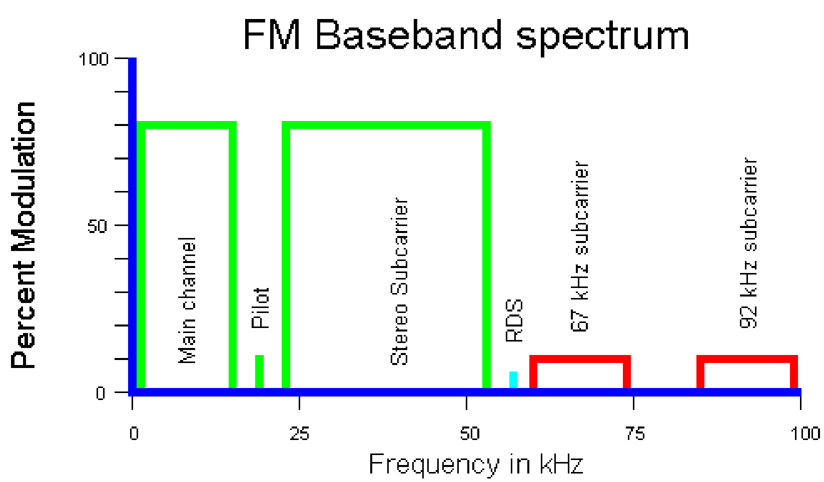
SDARS



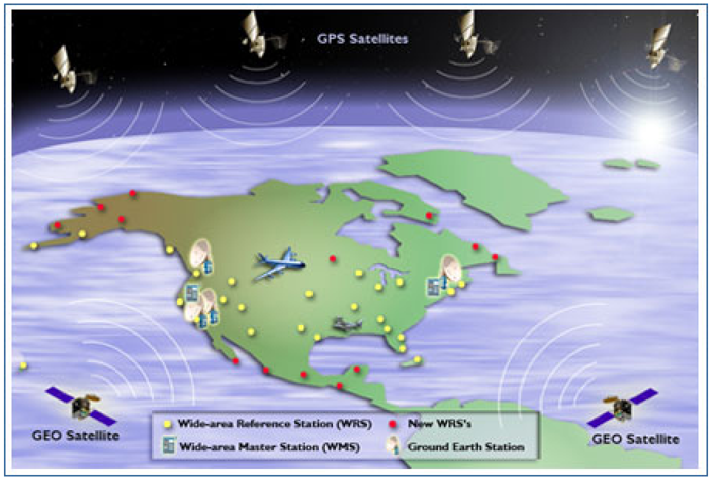
- SDARS refers to the Satellite Digital Audio Radio Service Providers who broadcast in the 2320 to 2345 MHz frequency band.
- Two commercial providers transmit signals from five satellites, three of which have an orbital period slightly longer than a day (Sirius), and two of which are geostationary (XM Radio).
- A time code is used to set clocks in satellite radios intended for automobile, home, and portable use.
- The time code reference and its exact format are believed to be proprietary.

SPOT

- SPOT is the Smart Personal Objects Technology developed by Microsoft and SCA Data Systems. SPOT uses a 67 kHz subcarrier leased by Microsoft from commercial FM radio stations.
- The SPOT time code includes time zone information and a DST correction. The format is believed to be proprietary.
- The FM station clock is synchronized every hour, typically via NTP with NIST servers.
- SPOT is similar to RDS, but uses more bandwidth and has a faster data rate (about 12K bit/s).
- Available from more than 200 FM stations in all 50 states.



WAAS

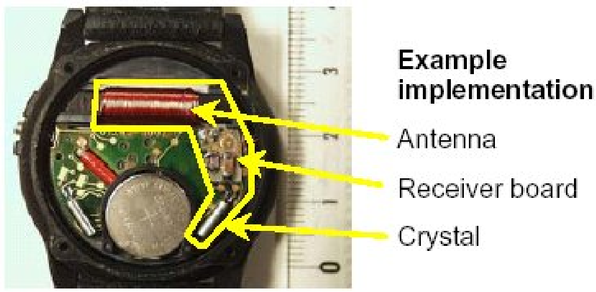


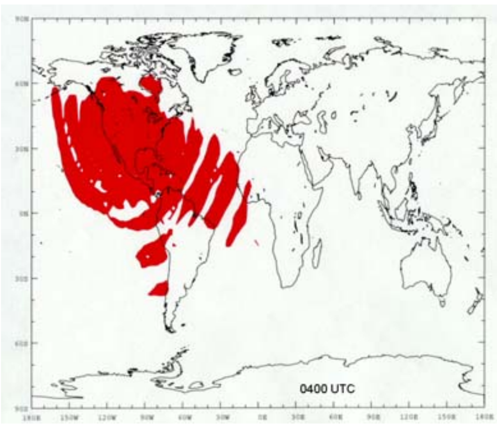
- WAAS is the GPS Wide Area Augmentation System developed by the Federal Aviation Administration (FAA).
- WAAS consists of about 25 ground reference stations that monitor GPS and forward data to master stations that create a GPS correction message. The correction message is uplinked to two geostationary satellites.
- The correction message is then broadcast through the geostationary satellites as an overlay on the GPS L1 frequency at 1575.42 MHz.
- WAAS was designed to augment or improve the performance of GPS, and if GPS is unusable for a given application, WAAS will probably also be unusable.

WWV

- WWV refers to the shortwave station WWV operated by NIST from Fort Collins, Colorado; and its sister station, WWVH, located on the island of Kauai in Hawaii.
- Both stations broadcast on 2.5, 5, 10, and 15 MHz, and WWV is also available on 20 MHz.
- These signals predate all other signals described in this talk (WWV dates to 1923, the time code to 1960). They are best known for audio time announcements, but the time code is widely used for legacy applications.

WWVB





- WWVB is the 60 kHz, 50 kW station operated by NIST from Fort Collins, Colorado
- WWVB is referenced to a local cesium time scale that is steered to agree with UTC(NIST), and is completely independent of GPS
- Millions of WWVB clocks/watches are sold each year, carried by nearly all retail stores. WWVB receivers are also embedded inside many consumer electronic products (even coffee makers!).

XDS

	bit 6	5	4	3	2	1	0
Start of "Misc." packet	0	0	0	0	1	1	1
Type = Time-of-Day	0	0	0	0	0	0	1
Minute	1	m_5	m_4	m_3	m_2	m_1	m_0
Hour	1	D	H_4	H_3	H_2	H_1	H_0
Date	1	L	D_4	D_3	D_2	D_1	D_0
Month	1	Z	-	M_3	M_2	M_1	M_0
Weekday (1 = Sunday)	1	-	-	-	W_2	W_1	W_0
Year (add 1990)	1	Y_5	Y_4	Y_3	Y_2	Y_1	Y_0
End of XDS packet	0	0	0	1	1	1	1

- XDS is television's Extended Data Service, sent using line 21, field 2 of the vertical blanking interval (VBI). The XDS time code is defined in the EIA-608-B standard.
- The XDS time code is sent by more than 300 Public Broadcasting System (PBS) television stations, reaching more than 90% of the U. S. population. The reference source is usually ACTS or NTP.
- The time is usually accurate to at least one half the video frame rate, or to within about 1/60 of a second, but frame "buffering" can reduce this accuracy.
- Many millions of TVs and VCRs routinely synchronize their clocks to XDS.
- XDS is available on terrestrial, cable, and satellite television signals.

Time-of-Day

- All 13 systems just described contain a time code. A time code is simply a machine readable message that can be used to set a clock or to time tag data.
- 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.
- Most time codes have a resolution of just 1 second, which is sufficient for most applications, where synchronizing a clock to the nearest second (±0.5 s) is all that is required.

Time-of-Day Coverage of eLORAN

(only Hawaii is excluded in U.S., redundant coverage in most areas)

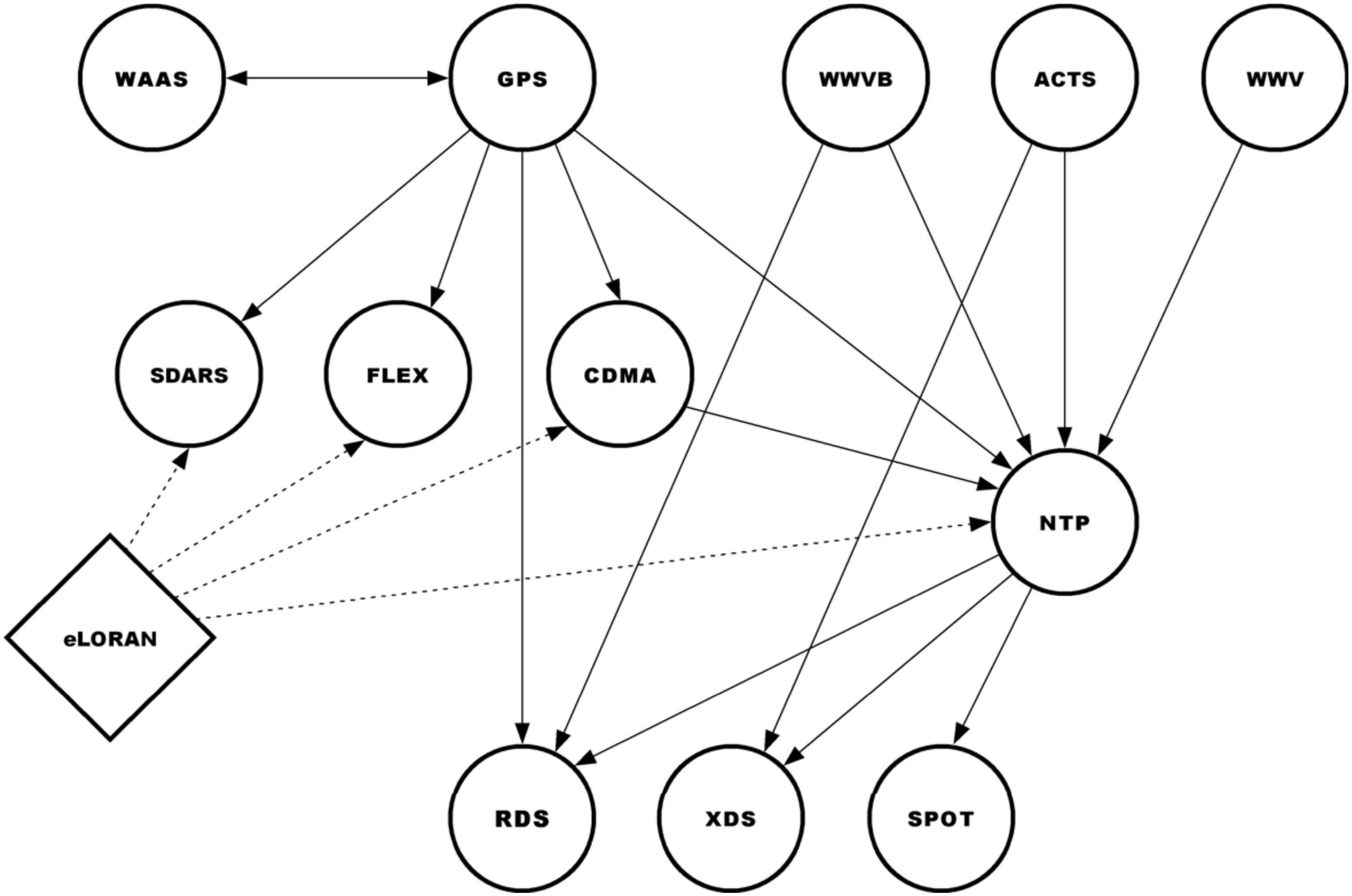
Time-of-Day Signal Providers (listed alphabetically)

Signal	Works Without Outside Antenna?	Information Contained in Time Code	Interval required to receive Time Code
ACTS	NA	NIST time code includes hour, minute, second, month, day, year, MJD , DST, leap second, UT1, server time advance. USNO time code includes hours, minutes, seconds, MJD, day of year.	< 1 s
CDMA	Yes	GPS time, the current UTC leap second offset to GPS time, local time offset to UTC including DST.	< 1 s
eLORAN	Yes	The time in LORAN message repetition intervals since January 1, 1958, leap second information, station ID, time corrections with 2 ns resolution.	< 2.38 s
FLEX	Yes	Date, local time, and time zone offset from UTC.	1.875 s
GPS	No	Week number, second within the week, and leap second offset between GPS time and UTC.	6 s for GPS time, 750 s for UTC
NTP	NA	UTC seconds since January 1, 1900 with a resolution of 200 ps.	< 1 s
RDS	Yes	MJD, UTC hour and minute, and the local time zone offset.	60 s
SDARS	Yes	7 byte UTC field used by XM Radio, but format is proprietary.	< 1 s
SPOT	Yes	Contains time and date, but format is proprietary.	< 1 s
WAAS	No	Similar to GPS, but frames are sent at different times and rates.	< 300 s
WWV	Not reliably	Minute, hour, day of year, year, the UT1 correction, DST and leap second indicators. Seconds are determined by counting pulses within the frame.	60 s
WWVB	Yes	Minute, hour, day of year, year, the UT1 correction, DST, leap year, and leap second indicators. Seconds are determined by counting pulses within the frame.	60 s
XDS	Depends upon medium	Hour, minute second, month, day, year, day of week, DST, and time zone information.	60 s

Potential Role of eLORAN as a Time-of-Day Reference Source

- The national time-of-day infrastructure depends upon providers who deliver time both directly and indirectly to end users.
- GPS is the dominant indirect time-of-day provider. While the number of standalone GPS clocks is relatively small, the numbers add up quickly when you consider that GPS is indirectly responsible for the time-of-day synchronization of many millions of cell phone clocks (through CDMA), of pager clocks (through FLEX), and of computer clocks (through NTP).
- Several sources probably synchronize more clocks directly than GPS.
  - **NTP** arguably synchronizes more clocks than any other system; due to the many millions of computer systems that use NTP to automatically synchronize their clocks.
  - **WWVB** dominates the consumer market as the synchronization source for millions of low-cost radio controlled clocks and wristwatches.
  - **CDMA** synchronizes millions of cell phone clocks.
  - **XDS** and **RDS** synchronize millions of clocks embedded in television and radio systems.
- Since legacy LORAN-C did not have a time code, eLORAN has no history as a time-of-day provider. However, 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 We think that eLORAN can:
  - Serve as an alternative to GPS as the indirect time-of-day source for systems such as CDMA, FLEX, and NTP.
  - Provide time-of-day directly to end users in the same fashion as WWVB, RDS, and XDS, with a trust factor that is certainly higher than RDS or XDS.
- Assuming that eLORAN receiving equipment becomes readily available, we think that eLORAN could quickly rank as high as second as an indirect provider. It will not immediately compete with systems such as GPS, WWVB, CDMA, RDS, XDS, and NTP as a direct provider, but it could potentially surpass some of those systems after several years of operation.

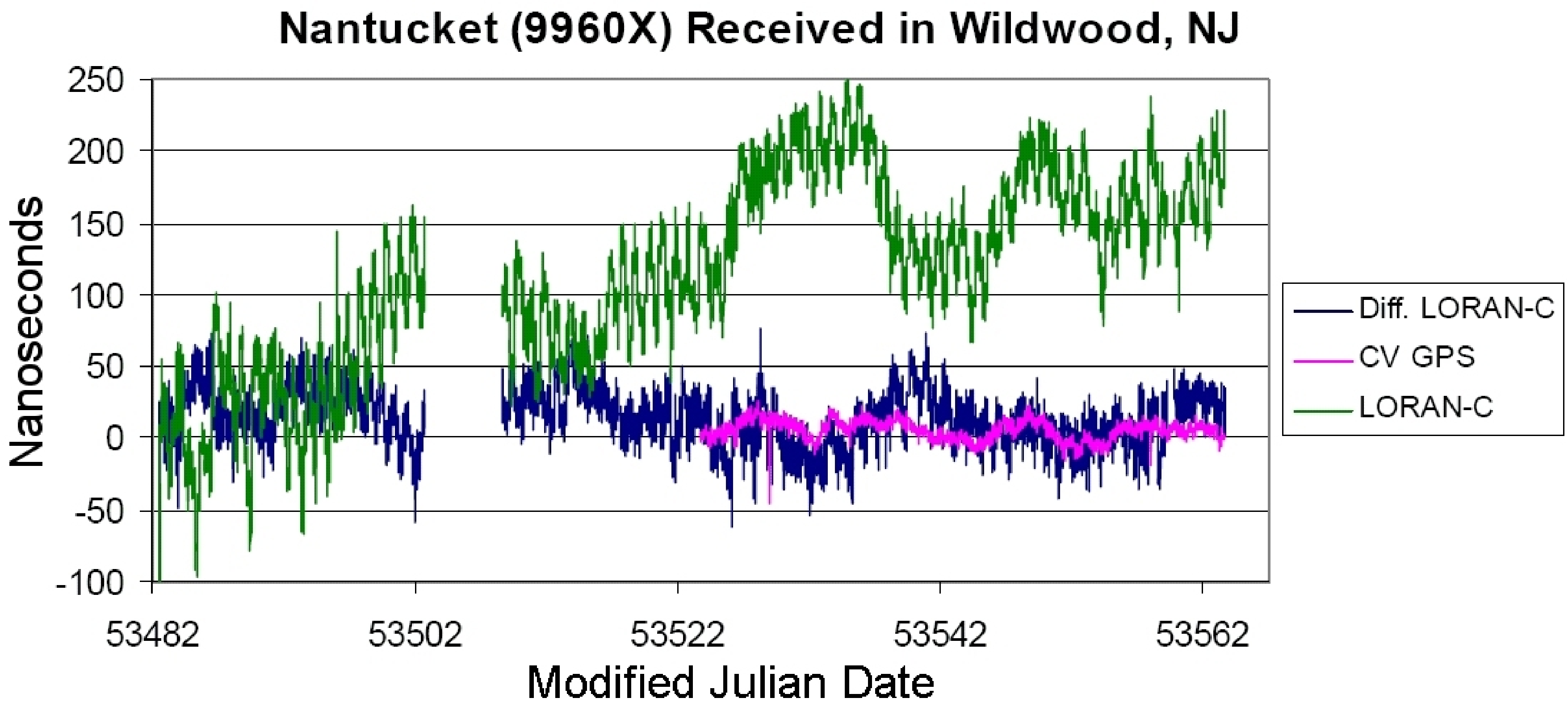
Flow Chart of Time-of-Day Infrastructure



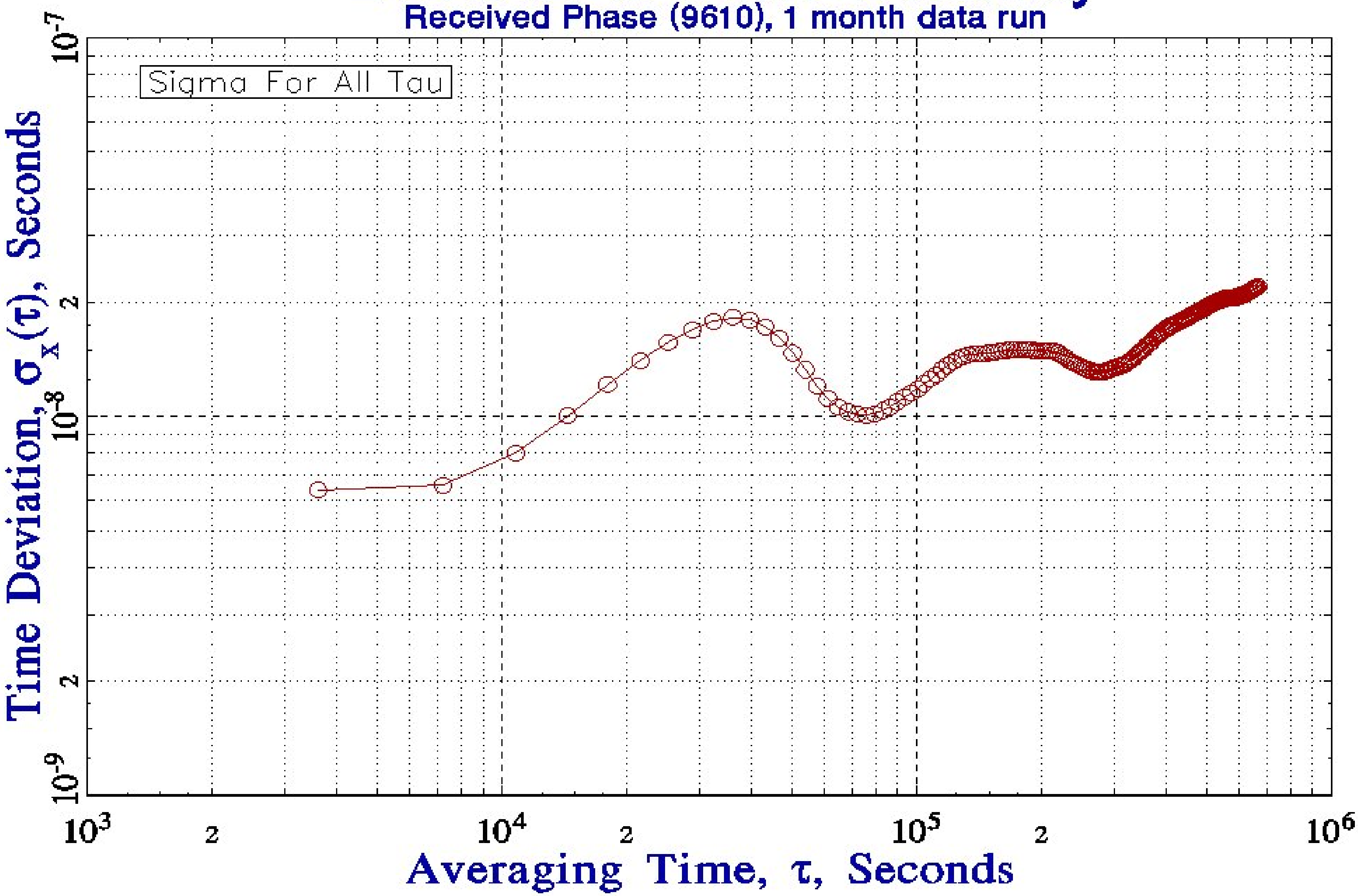
Precise Time Synchronization

- We define precise time synchronization as synchronization accuracy of 1 millisecond or less. 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.
- A stratum-1 timing reference requires frequency accurate to 1×10^{-11}. This allows relative time to be kept to within 1 microsecond per day. Keeping time within 1 microsecond of UTC can be done if it is possible to measure and compensate for all delays. Even if only a coarse knowledge of the delays is available, any stratum-1 source can easily achieve millisecond accuracy.

Precise Time Synchronization Capabilities of eLORAN



LORAN-C Time Stability



Precise Time Synchronization Providers (listed by accuracy)

Signal	Typical Uncertainty (microseconds)	Stratum-1 Source (1 μs per day)	Notes
GPS	< 0.1	Yes	An uncertainty of 100 ns is typical if the antenna cable delay to be calibrated and a delay constant is entered into the receiver, 20 ns is possible.
WAAS	< 0.1	Yes	An uncertainty of 100 ns is typical if the antenna cable delay to be calibrated and a delay constant is entered into the receiver, 20 ns is possible.
eLORAN	0.1	Yes	Requires the application of monitor corrections from the LDC and calibration of the receiver and antenna.
CDMA	100	Yes	An uncertainty of 100 μs assumes that a base station is located within 30 km of the user's location.
FLEX	100	Yes	Uncertainty depends upon the distance from the paging station, similar to CDMA.
WWVB	100	Yes	User must estimate and remove path delay to obtain 100 μs uncertainty.
WWV	1000	No	User must estimate and remove path delay to obtain 1 millisecond 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	Short and stable signal path, but the uncertainty is limited by the system clock, which is typically synchronized via NTP. Could be similar to CDMA if GPS were used.
SPOT	10000	No	Short and stable signal path, but the uncertainty is limited by the system clock, which is typically synchronized via NTP. Could be similar to CDMA if GPS were used.
XDS	16667	No	Generally accurate to at least one half the frame rate of NTSC video, or to approximately 1/60 of a second, but frame "buffering" can reduce this accuracy.
SDARS	Unknown	No	Method of synchronization and delays are not known.

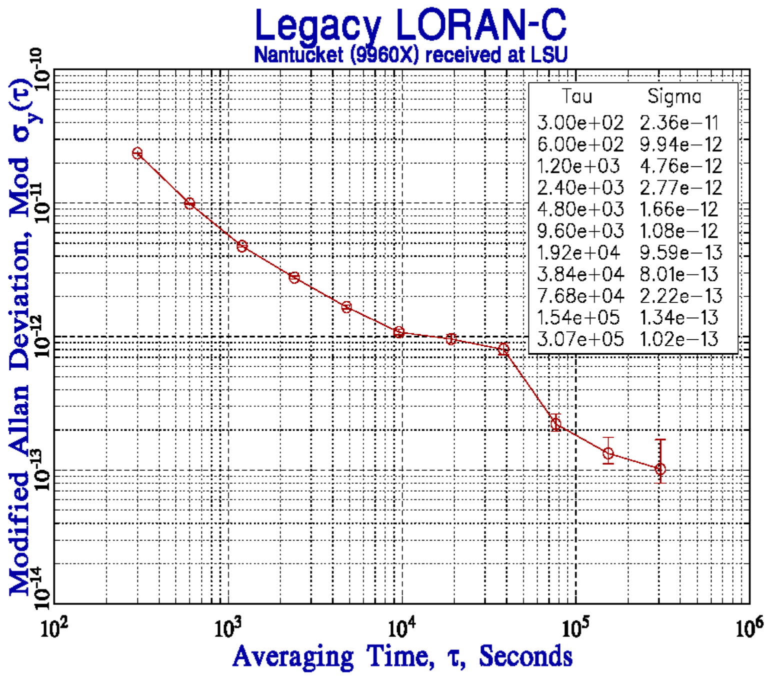
Potential Role of eLORAN as a Precise Time Synchronization Source

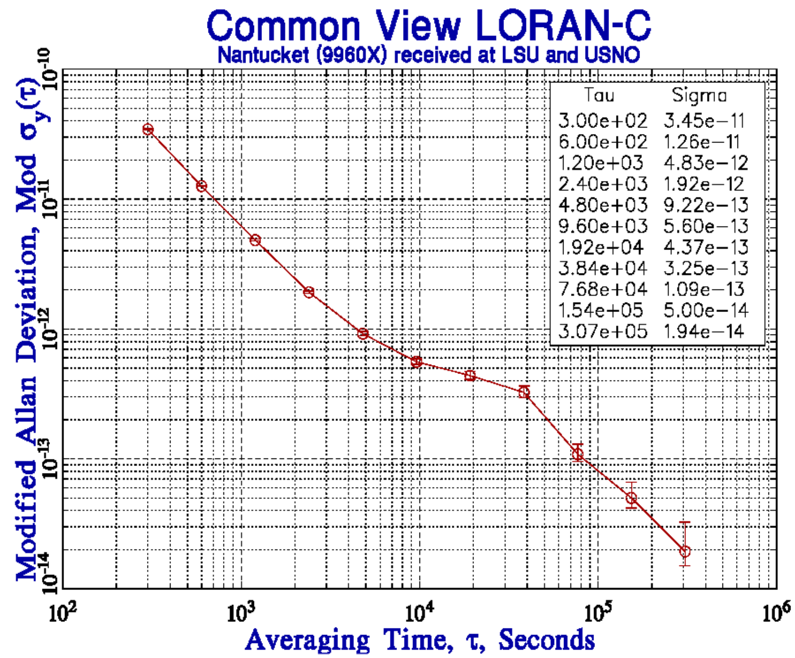
- Only five providers other than GPS can be considered a Stratum-1 time synchronization source. Three of these (WAAS, CDMA, and FLEX), are not independent of GPS and would not be available as a backup source in the event of a GPS failure. This leaves eLORAN and WWVB as the remaining backup sources.
- WWVB is completely independent of GPS, but is a less accurate timing source than eLORAN even if its users correct for path delay, and since there is only one station, its signals are not reliably received throughout the country. Therefore, it would not be a candidate for a critical application such as backup synchronization of the CDMA network.
- Therefore, we identify eLORAN as the best available backup source to GPS for precise time synchronization in the United States.

Frequency Control of Oscillators

- Frequency is usually provided in the form of a sine wave or square wave, generated by a quartz or atomic oscillator.
- Some signal providers are used to phase lock or frequency lock the output of a local oscillator so that it never needs to be calibrated or adjusted as long as the signal is continuously received.
- Devices that provide a continuously controlled frequency are known as disciplined oscillators.
- A Stratum-1 frequency source is accurate to 1×10^{-11}, a Stratum-2 frequency source is accurate to 1×10^{-8}.

Frequency Control Capabilities of eLORAN





Frequency Control Providers (listed by accuracy)

Signal	Received Uncertainty	Stratum-1 Source	Notes
GPS	1×10^{-13}	Yes	Dominant system for frequency control, with GPS disciplined oscillators commercially-available from a number of vendors
WAAS	1×10^{-13}	Yes	Excellent performance, but normally is an adjunct to GPS, and not a standalone frequency source.
eLORAN	2×10^{-13}	Yes	Stable ground wave signals and modulation that reduces the problem of cycle ambiguity make eLORAN the best frequency source that is not reliant on GPS.
CDMA	5×10^{-13}	Yes	Very good performance, essentially an “indirect” version of GPS that works indoors, with a smaller coverage area and some loss of accuracy. However, the allowable 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	The LF signal path is similar to eLORAN and the frequency uncertainty could potentially be equivalent. However, WWVB’s form of modulation makes cycle identification difficult, and cycle ambiguity is a problem over long paths.
WWV	1×10^{-9}	No	Uncertainty limited by the sky wave propagation of HF radio signals.
XDS	3×10^{-6}	No	The frequency uncertainty of television signals is normally limited by the allowable tolerance for the color burst oscillator, which is ±10 Hz at a nominal frequency near 3.58 MHz. This uncertainty can be 5 or 6 orders of magnitude smaller if the TV station uses an atomic oscillator.
SPOT	NA	No	FM radio signals have a stable line of sight path and could potentially be a stratum-1 frequency source, but there is no regulation of the broadcasts.
SDARS	NA	No	Could potentially be useful for frequency, but no information is currently available.
RDS	NA	No	FM radio signals have a stable line of sight path and could potentially be a stratum-1 frequency source, but there is no regulation of the broadcasts.
NTP	NA	No	Not usable as a continuous frequency source.
FLEX	NA	No	It is possible to extract a good frequency reference from the code, but the carrier is not required to be locked to GPS and might be unusable for frequency.
ACTS	NA	No	Not usable as a continuous frequency source.

Potential Role of eLORAN as a Frequency Control Source

- 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 the eLORAN is the best available backup source to GPS for frequency control in the United States.

Summary and Conclusions

- We have reviewed all of the available broadcast signals that anchor the time and frequency infrastructure in the United States.
- We conclude that eLORAN is 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 a leading provider of time-of-day information in the United States, a role that legacy LORAN-C was not able to fulfill.