Comparing LORAN Timing Capability to Industrial Requirements

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The “magic numbers” for industrial timing applications and what they mean

To meet all current requirements, an industrial timing source must be able to perform at these levels:

- **Frequency accuracy of $\pm 1 \times 10^{-11}$**
  - The fractional offset of the frequency being used with respect to its nominal value.
  - If the nominal frequency is 10 MHz, then a ST1 source must remain within ±100 µHz of 10 MHz at all times:
    - 10^{7} Hz $\times$ 10^{-11} = 10^{-4} Hz = 100 µHz
  - To put this in perspective, a frequency counter with 12 digits of resolution is needed to show a frequency accurate to 1×10^{-11} at 10 MHz without averaging. With a common 10-digit counter, it would appear to be “perfect”.

- **Time accuracy of ±1 microsecond**
  - Time accuracy refers to the time difference between a time source and Coordinated Universal Time (UTC).
  - The National Institute of Standards and Technology (NIST) and the United States Naval Observatory (USNO), maintain real-time UTC time scales called UTC(NIST) and UTC(USNO) respectively. They can be considered equivalent to each other for industrial timing purposes.
  - UTC(NIST) and UTC(USNO) have never differed by more than 0.043 µs since January 2000.
  - The requirement is best met by devices that can synchronize to UTC by themselves. Oscillators cannot do this by themselves, but GPS disciplined oscillators (GPSDOs) can.

Don't confuse accuracy with stability

- A common mistake when discussing requirements is to confuse accuracy with stability. This is probably because statistics used to estimated stability, particularly the Allan deviation (ADEV), are so widely used in time and frequency.

- The stability number is likely to be smaller than the accuracy number. Think of stability as the limit of the accuracy. The accuracy over a given averaging time can never be better than the stability over that same averaging time.

- For example, it is often believed that rubidium oscillators can meet the $\pm 1 \times 10^{-11}$ frequency accuracy requirement 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 meet the requirement *if they are periodically adjusted*. However, their "out of the box" turn-on accuracy is nearly always worse than $\pm 1 \times 10^{-11}$, and unadjusted rubidium oscillators can miss the requirement by one or two orders of magnitude.

The sources of time and frequency signals

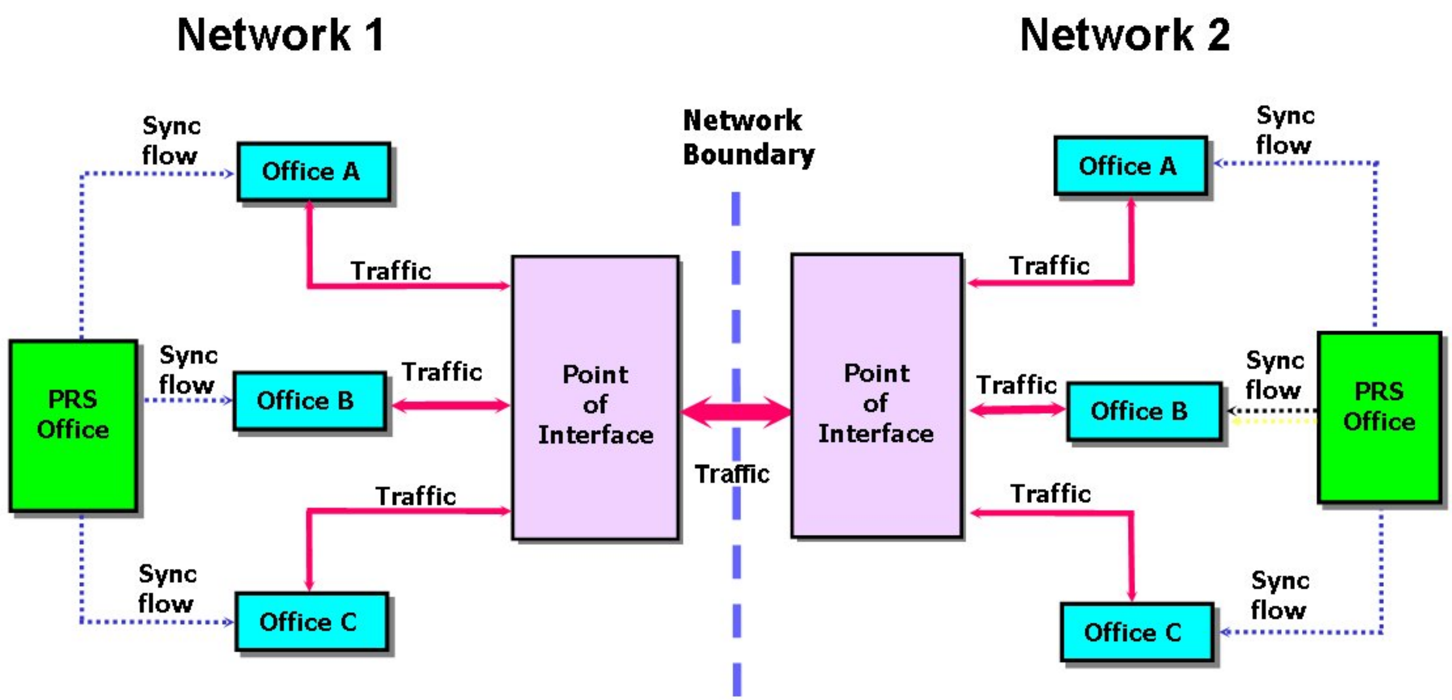
Source	Notes
TXCO OCXO	Quartz oscillators. They are not stable enough to meet any high level frequency requirements unless they are periodically adjusted. Cannot recover UTC by themselves.
Rubidium	Needs periodic adjustment to meet frequency accuracy requirements. Cannot recover UTC by itself.
Cesium	The primary standard of frequency, and can therefore meet any frequency requirement. Cannot recover UTC by itself, needs to be synchronized to something else to meet time accuracy requirements. Too expensive for widespread deployment.
GPSDO	Easily meets frequency accuracy requirements. Can recover UTC by itself, and is often **the only practical way** to meet time accuracy requirements. Cheap enough for wide spread deployment if a TCXO or OCXO is used. Easy to use. All of these reasons have led to a wide spread dependency on GPS, making industrial timing systems very vulnerable if GPS goes away.
LDO	Easily meets frequency accuracy requirements. Can meet time accuracy requirements if the modernized LORAN system is finished. If receivers become available, can potentially become a "plug and play" replacement for a GPSDO.

We’ll examine three industrial applications that are heavily dependent on GPS

- Primary reference source (PRS) requirements for telecommunication networks, including phone calls over land lines
- CDMA requirements for wireless phone calls
- Synchrophasor requirements for electric power distribution

A plesiochronous network
(the model for the current DS1/T1 system)

(plee-see-AH-krun-us, from Greek *plesos*, meaning close, and *chronos*, meaning time)



- There are now many telephone carriers with multiple primary reference sources, and no synchronization paths between carriers, but it still has to “look synchronous”.
- It works if each network stays within a frequency tolerance defined with respect to Coordinated Universal Time (UTC).

Primary Reference Source (PRS)

- The synchronization source for a network is called the Primary Reference Source (PRS) as defined by the ANSI T1.101 standard.
  - Alternately called the Primary Reference Clock (PRC) by the ITU G.811 standard. PRS and PRC mean the same thing, and the requirements are identical.

- ANSI 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)*

- Frequency accuracy of 1×10^{-11} is known as Stratum-1 (ST1).
  - A clock with ST1 accuracy will only gain or lose about 1 microsecond per day (actually 0.86 microseconds).

- Most telecomm providers use GPS disciplined oscillators as a PRS, because cesium oscillators are too expensive for widespread deployment, and rubidium oscillators can't meet the accuracy requirement without periodic calibration.

Cycle Slips

- Cycle slips occur when the time difference between two network clocks exceeds a given tolerance. This results in the loss of data, a pop or click on the line, and sometimes in a dropped call.
- The North American DS1/T1 system consists of digital data streams clocked at a frequency of 1.544 MHz. This data stream is divided into 24 voice channels, and each voice channel is sampled 8000 times per second, or every 125 microseconds. When the time error exceeds 125 microseconds, a cycle slip occurs.
- The slip rate, SR, can be calculated as

$$SR = \frac{T_{samp}}{F_{diff}}$$

- Where T_{samp} is the period of the sampling rate (a constant of 125 microseconds for the DS1/T1 system), and F_{diff} is the frequency difference between two clocks. A connection between two ST1 clocks results in only 1 cycle slip every 72.3 days.

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

CDMA Wireless Network Requirements

- The basic requirements for CDMA wireless telephones are listed in the *TIA/EIA Standard 95-B* (1999), with later standards such as the *TIA-97-B* and the *3GPP2 C.S0010-B* documenting new requirements. However, synchronization requirements have remained the same.

- CDMA System Time usually is GPS time, and more than 100,000 CDMA base stations are equipped with GPS in the United States.

- Mobile phone performance will significantly degrade if synchronization is lost, and eventually base stations within a coverage area will "collide" with each other and go off-line, causing cellular coverage to be lost in that area.

- There are two key requirements for CDMA system time:

  - **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.**

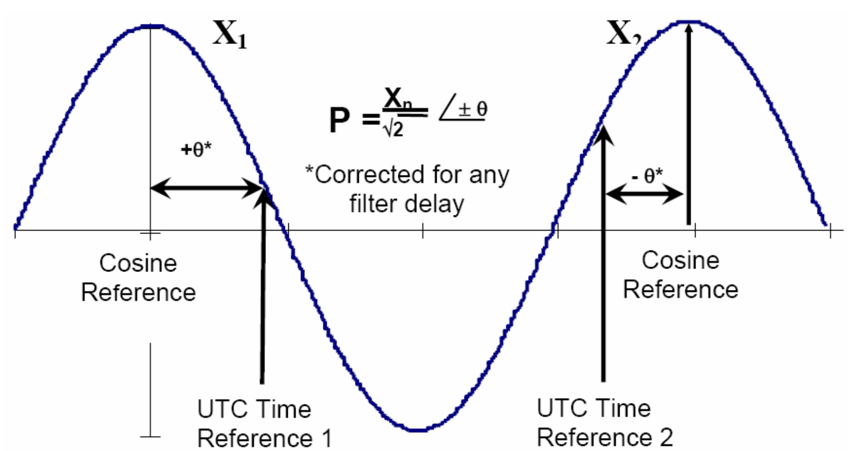
  - **With the external source of CDMA System Time disconnected, the base station *shall* maintain transmit timing within ±10 μs of CDMA System Time for a period of not less than 8 hours.**

GPS antennas can be found near every location that contains CDMA cellular equipment

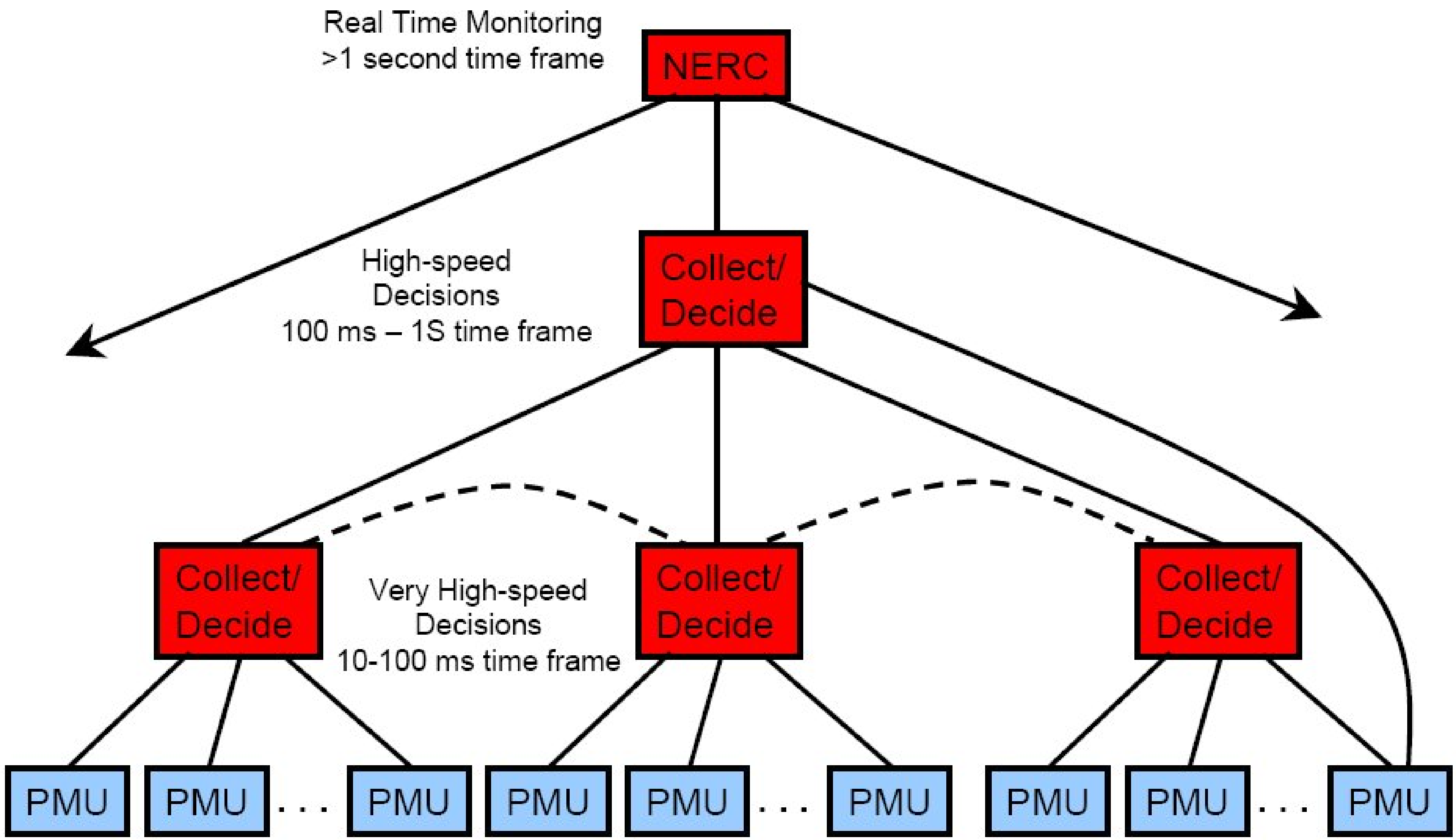
What, me worry about multipath? GPS antennas can have obstructed sky views and still meet CDMA requirements.

Synchrophasor Measurements

- A synchronized phasor, or synchrophasor, is defined as the magnitude and angle of a cosine signal as referenced to an absolute point in time.
- Synchrophasor measurements are often made with commercially available devices called phasor measurement units (PMUs). These devices contain GPS receivers that generate a time stamp. reception.
- PMU units measure positive sequence voltages and currents at power system substations. The measurements are time stamped and collected at a central site. The time stamps are aligned, and the result is a real-time measurement of the current state of the power system, as opposed to the “estimates” that were relied upon in past years. This information has become more critical as the electric power grid continues to expand, and as the system is pushed near its operating limit.



PMUs send data to computers that make real time decisions on how to best distribute power within the grid



IEEE Standard for Synchrophasors for Power Systems (IEEE C37.118-2005)

- The latest version of this standard was approved by IEEE in October 2005 and by ANSI in February 2006. It defines the requirements for synchrophasor measurements.

- The three-bit "fraction of second" field allows time tagging to a UTC time reference with a resolution of about 60 nanoseconds. The maximum allowable time error for the lowest level of compliance with the standard is ±26 µs (Section 4.4). **However, the desired accuracy level is ±1 µs which corresponds to a phase error of 0.022° for a 60 Hz system. The "synchronizing source" thus needs ±1 µs accuracy.**

- Some interesting language from the standard:

  - (Annex E.2) **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.

  - (Annex E.3) 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.

GPSDO Holdover Capability

- It is important to realize that the CDMA and synchrophasor requirements just discussed were designed around GPS capability. Therefore, as long as the GPS signal is available, the requirements are easily met. The concerns about GPS are due to its vulnerabilities, particularly its vulnerability to jamming from intentional and unintentional RF interference. If GPS is unavailable, there is generally no backup source, other than the local oscillator in the GPSDO.

- To simulate a GPS outage, the four GPSDOs that had been continuously running at NIST for multiple weeks or months. The NIST test was certainly not representative of the entire GPS marketplace, but it shows that there is no exact answer as to how long GPSDOs can continue to meet industrial timing requirements. It depends entirely on the specific model of GPSDO in use.

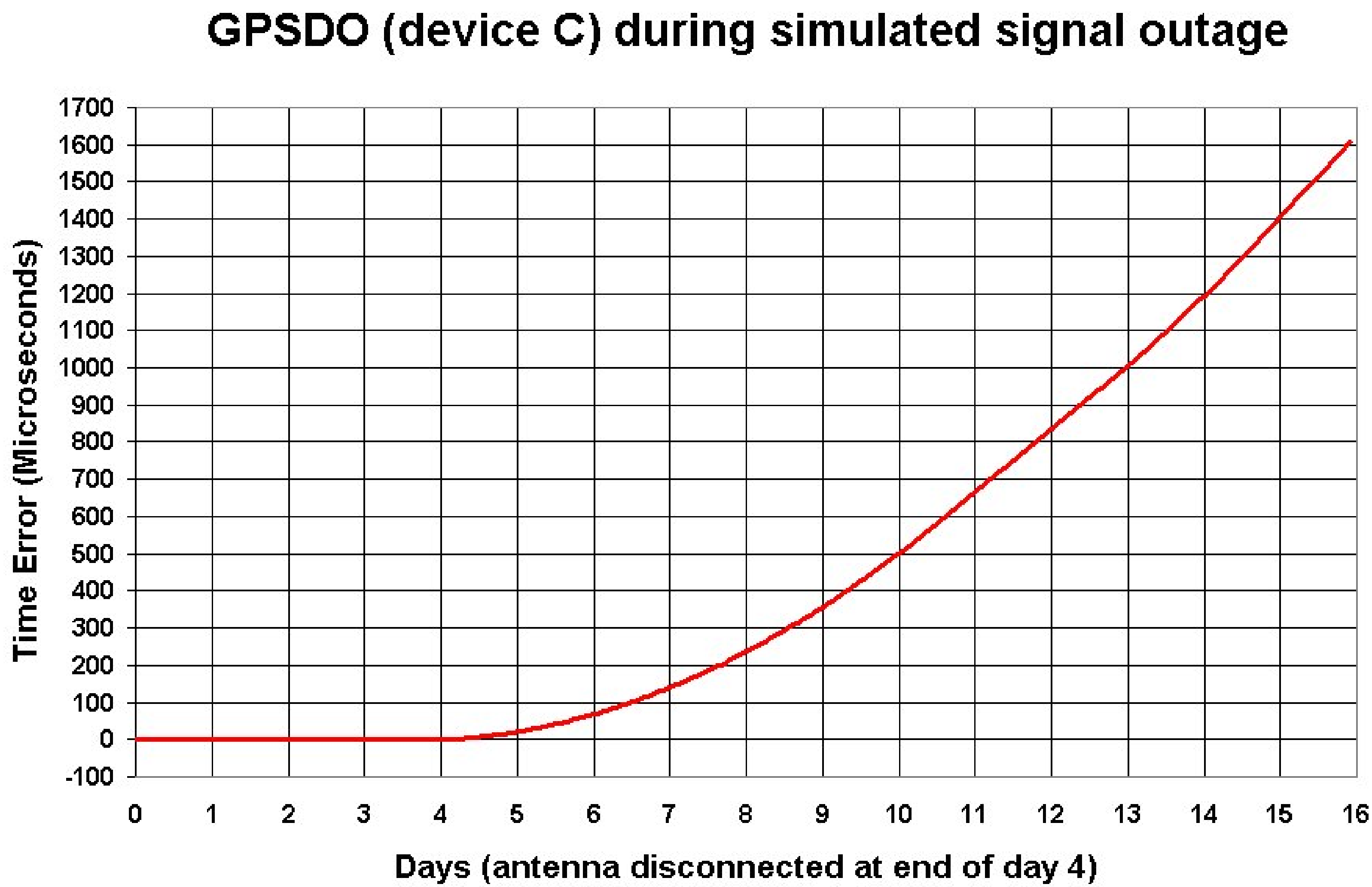
- Note that industry deploys more quartz based devices than rubidium devices due to lower cost. In theory, a rubidium should have much better holdover, but not always - D outperformed C in the test.

- Note that holdover capability will probably not help if GPS is spoofed.

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

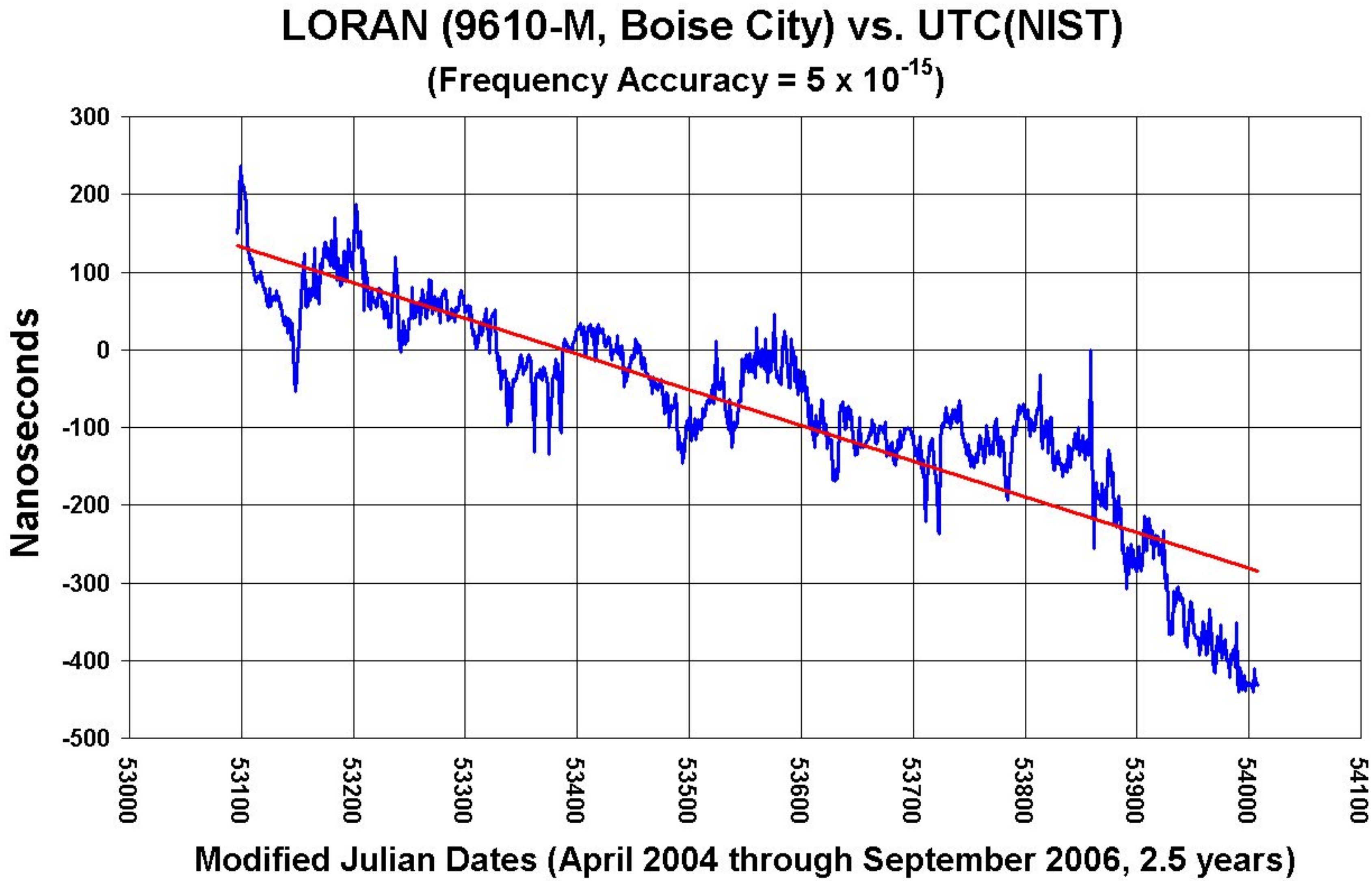
This rubidium GPSDO quickly became a free running oscillator (1×10^{-9}) when GPS was lost, with no apparent holdover software. A TCXO without holdover software would likely be 100 to 1000 times less accurate.



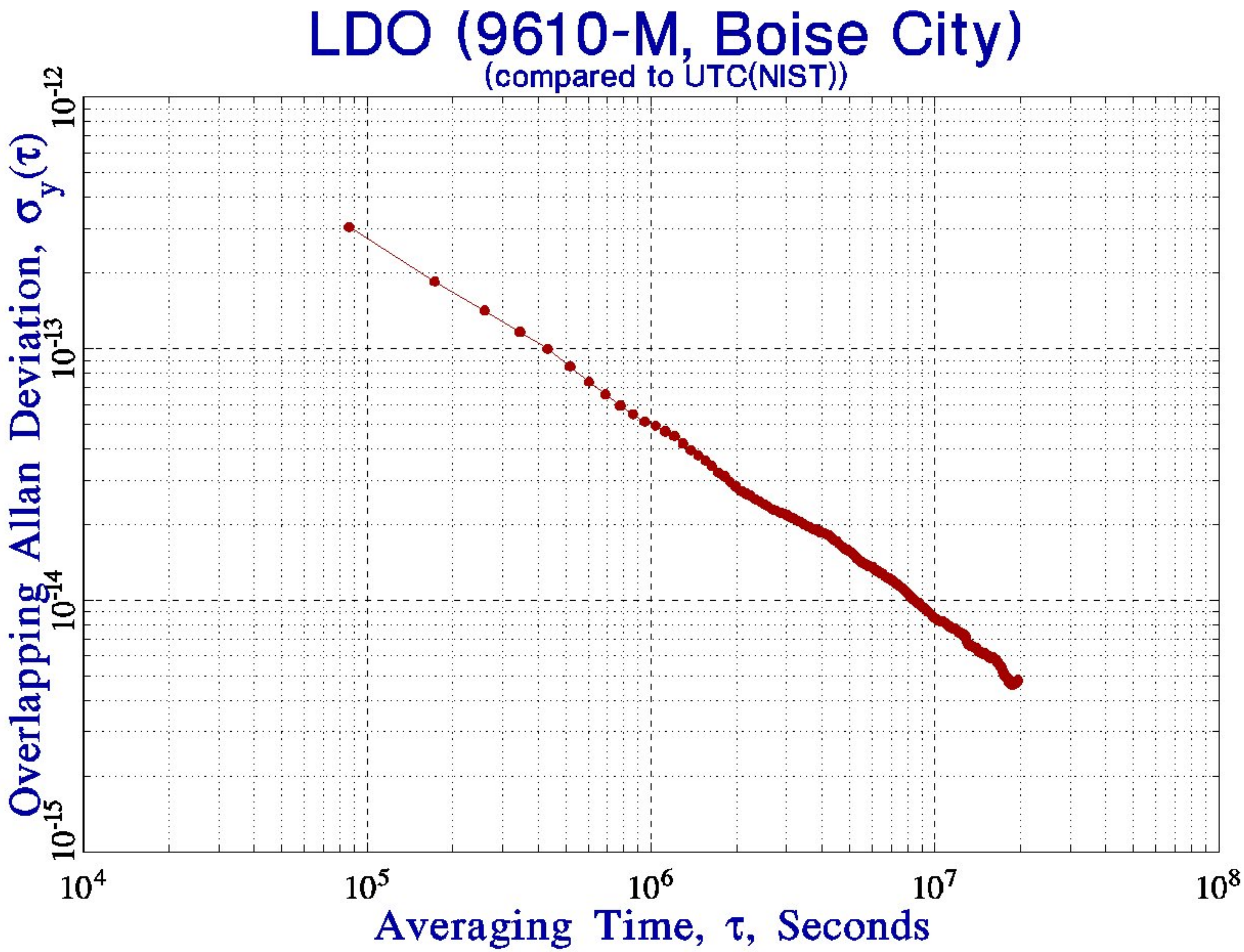
LORAN Timing Capability

- LORAN can meet the "magic numbers" for frequency and time
  - LORAN disciplined oscillators have been used for decades as frequency standards, although most units have been replaced in recent years by GPSDOs. Performance is comparable to GPS if the receiver is within 1000 kilometers of the transmitter. Frequency accuracy of 1×10^{-11} is easy to achieve.
  - Modernized, or eLORAN, makes it possible for receivers to recover UTC by themselves, by adding a time code to the broadcast. If LDOs can synchronize a 1 pps signal to within ±1 µs of UTC without any external input or calibration, they will be functionally equivalent to GPSDOs for industrial applications.

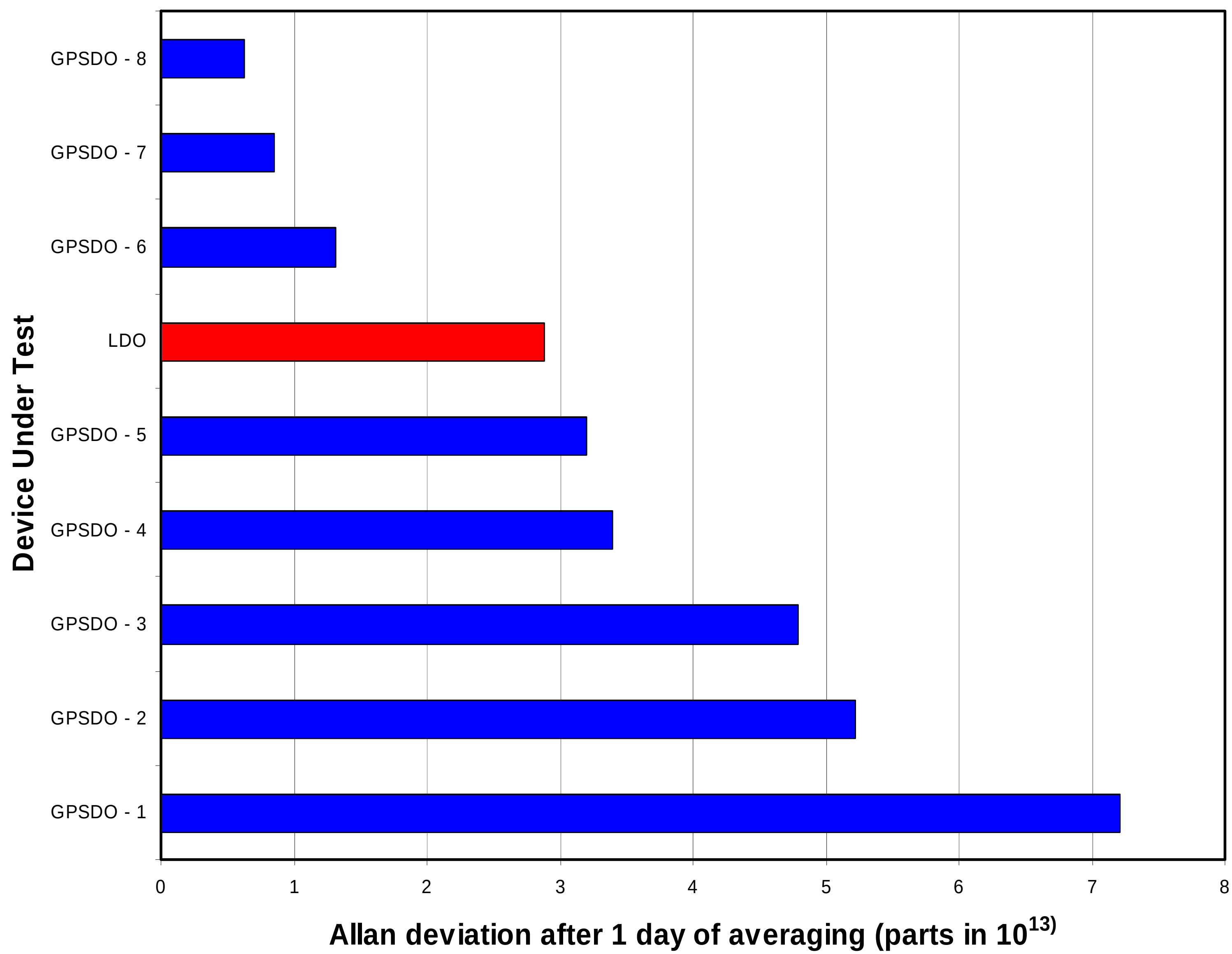
The frequency accuracy of LORAN exceeds all requirements



Frequency accuracy over a given interval is limited by the stability, but stability reaches parts in 10^{13} in one day



Frequency Stability of Disciplined Oscillators Compared to UTC(NIST)



eLORAN allows receivers to recover UTC time-of-day information from the LDC

Bit Assignments for Time and dLoran messages

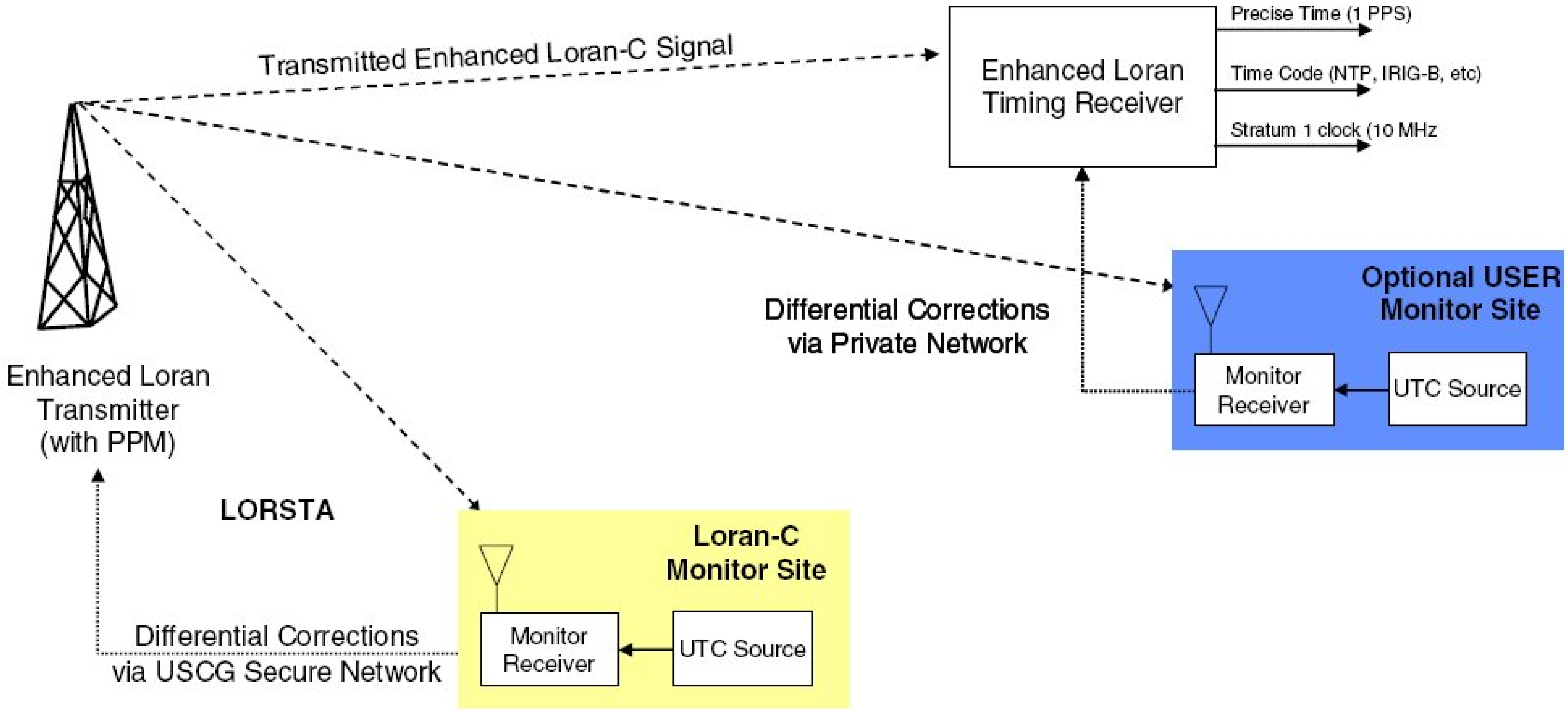
(Format for aviation integrity msg TBD)

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 9th pulse that is pulse position modulated, and will provide UTC, leap seconds, station ID, etc., through the LORAN data channel (LDC).
- At least 27 North American stations will broadcast time, and a receiver can recover time by receiving just one station. Five stations are doing it now.
- 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

LDOs should be able to recover UTC with sub-microsecond accuracy by using data obtained from the LDC



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

- 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 that could make it the first, rather than the second choice for some applications:
  - It is undoubtedly harder to jam.
  - It can work with an indoor antenna.

- However, for LORAN to win acceptance as a redundant source of industrial timing, commercially available LDOs must appear that can serve as "plug and play" replacements for GPSDOs. Whether or not they do appear probably depends upon whether or not the U. S. government provides a long-term commitment to LORAN.

Summary and Conclusions

- Telecommunications networks and the electric power grid, two critical elements of the nation's infrastructure, both heavily rely on GPS to meet their timing requirements. In many cases, they have no redundant source of timing, other than the holdover capability of their GPSDOs.
- The length of a GPS outage that can be tolerated often depends entirely on the type of GPSDOs being used. While some devices can meet requirements for hours or days without GPS, others will likely be out of tolerance within seconds or minutes.
- Because industry now depends so heavily on GPS timing, the deployment of a redundant timing system in as short a time frame as possible seems to be in the best interests of the United States.
- LORAN, in its modernized form, can meet all existing industrial timing requirements, and seems to be the logical choice to fulfill that role.