LEGAL AND TECHNICAL REQUIREMENTS FOR TIME AND FREQUENCY METROLOGY

Michael A. Lombardi
NIST Time and Frequency Division
lombardi@nist.gov

Abstract - *Who needs time and frequency? This paper answers that question by discussing the technologies and applications that rely on precise time and frequency, and exploring their legal and technical requirements for measurement uncertainty. The technologies and applications discussed include financial markets, the wired and wireless telephone networks, radio and television broadcast stations, the electrical power grid, and radionavigation systems. The paper also discusses legal requirements for "everyday" metrology, including wristwatches, commercial timing devices, and radar devices used by law enforcement officers.*

INTRODUCTION

Time and frequency measurements occupy a special place and possess a certain mystique in the world of metrology. The unit of time interval, the second (s), and its reciprocal unit of frequency, the hertz (Hz), can each be measured with more resolution and less uncertainty than any other physical quantities. NIST and a handful of other laboratories can currently realize the second to uncertainties measured in parts in 10^{16} [1] and NIST has experimental standards already in place that promise uncertainties at least one or two orders of magnitude smaller [2]. These uncertainties represent the pinnacle of the metrology world, and have a "gee whiz" quality that attracts media attention and captures the public's imagination. These tiny uncertainties also attract attention from scientists and design engineers, because history has shown that as time and frequency uncertainties get smaller, new technologies are enabled and new products become possible.

For metrologists, however, it can be difficult to place the tiny uncertainties of state-of-the-art time and frequency measurements into their proper context. Most metrology work is performed in support of "real world" systems that require their measuring instruments and standards to be within a specified tolerance in order for the system to work properly. Thus, metrologists are concerned with questions such as: What type of frequency uncertainty is required for a police officer to know that a measurement of vehicle speed is valid? How close in frequency does a radio station have to be before it interferes with another station? What frequency tolerance does a telephone network need to avoid dropping calls? These questions can be answered by looking at the legal and technical requirements of time and frequency metrology, the topics of this paper. We'll explore these topics by first looking at the requirements for "everyday" metrology, and then move on to examine requirements for more advanced applications.

REQUIREMENTS FOR EVERYDAY METROLOGY

In "everyday" life, we check our wristwatches for the correct time, pay for time on parking meters and other commercial timing devices, play and listen to musical instruments, and drive our cars at or below the posted speed limit to avoid getting a traffic ticket. The modest time and frequency requirements of these activities are described in this section.

Wristwatches

Wristwatches are unique devices, the only metrological instruments that we actually wear. Most wristwatches contain a tiny quartz oscillator that runs at a nominal frequency of 32 768 Hz. There are no legally required uncertainties for wristwatches, but one major manufacturer specifies their watches as accurate to within 15 s per month, or about 0.5 s per day, a specification that seems to be typical for the quartz watch industry. This translates to an allowable frequency uncertainty of about 0.2 Hz, or a dimensionless uncertainty near 6×10^{-6}.

Commercial Timing Equipment and Field Standard Stopwatches

Commercial timing equipment includes devices such as parking meters, taxicab meters, and coin operated timers used in laundries and car washes. *NIST Handbook 44* [3], used by all 50 states as the legal basis for regulating commercial weighing and measuring devices, uses the terms *overregistration* and *underregistration* when defining the legal requirements of commercial timing devices. Overregistration means that the consumer received more time than they paid for, underregistration means that they received less time than they paid for. The laws are intended to protect consumers, and underregistration is of much greater concern. For example, a person who pays for 10 minutes on a parking meter is legally entitled to receive close to 10 minutes before the meter expires, but no law is broken if the meter runs for more than 10 minutes. Table 1 summarizes the legal requirements of commercial timing devices [3]:

Table 1. Legal Requirements of Commercial Timing Devices.

Commercial Timing Device	Overregistration		Underregistration	
	Requirement	Uncertainty	Requirement	Uncertainty
Parking Meter	None	NA	10 s per minute 5 minutes per half hour 7 minutes per hour	11.7 % to 16.7 %
Time clocks and time recorders	3 s per hour, not to exceed 1 minute per day	0.07 % to 0.08 %	3 s per hour, not to exceed 1 minute per day	0.07 % to 0.08 %
Taximeters	3 s per minute	5 %	6 s per minute	10 %
Other Timing Devices	5 s for any interval of 1 minute or more	NA	6 s per minute	10 %

Commercial timing devices are often checked with field standard stopwatches. Most modern stopwatches are controlled by quartz oscillators, and they typically meet or exceed the performance of a quartz wristwatch (see above). However, they are often calibrated against audio timing signals from NIST radio station WWV or a similar source, and the uncertainty of the calibration is limited by the human reaction time involved in starting and stopping the timer [4]. Thus, the legally required measurement uncertainty is typically 0.01 % or 0.02 % (1 or 2 parts in 10^4). NIST Handbook 44 [3] specifies 15 s for a 24 hour interval, or 0.017 %. Some states and municipalities have their own laws. For example, the state of Pennsylvania code [5] states that an electronic stopwatch shall comply with the following standards:

> *(i) The common crystal frequency shall be 32,768 Hz with a measured frequency within plus or minus 3 Hz, or approximately .01% of the standard frequency.*
>
> *(ii) The stopwatch shall be accurate to the equivalent of plus or minus 9 seconds per 24-hour period.*

Musical Pitch

The pitch of a musical tone is a function of the speed at which air has been set in motion. The speed is measured as the number of complete vibrations – backwards and forwards – made by a particle of air in one second. When pitch is produced by a vibrating column of air, the pitch of the same length of pipe varies with temperature: for a 1 °F difference, pitch will vary by 0.001 Hz [6].

The international standard for musical pitch was first recognized in 1939, and reaffirmed by the International Organization for Standardization in 1955 and 1975 [6, 7]. It defined international standard pitch as a system where A above "middle" C (known as A4) is tuned to 440 Hz. A 440 Hz tone is broadcast by NIST radio stations WWV and WWVH for use as a musical reference [8].

The ability of the human ear to discriminate between differences in pitch depends upon many factors, including the sound volume, the duration of the tone, the suddenness of the frequency change, and the musical training of the listener. However, the *just noticeable difference* in pitch is often defined as 5 cents, where 1 cent is 1/100 of the ratio between two adjacent tones on a piano's keyboard. Since there are 12 tones in a piano's octave, the ratio for a frequency change of 1 cent is the 1200th root of 2. Therefore, raising a musical pitch by 1 cent requires multiplying by the 1200th root of 2, or 1.00057779. By doing this five times starting at 440 Hz, we can determine that 5 cents high is about 441.3 Hz, or high in frequency by about 0.3 % [8]. Some studies have shown that trained musicians can distinguish pitch to within 2 or 3 cents, or to within 0.1 % or better. Thus, frequency errors of 0.1 % or larger can change the way that music sounds for some listeners.

Law Enforcement

Law enforcement officers use radar devices to check vehicle speed. These devices are normally calibrated by pointing them at tuning forks whose oscillations simulate vehicle speed. For example, a radar device might be calibrated by checking it with a tuning fork labeled 30 mph (miles per hour) to test the low range, and another fork labeled 90 mph to test the high range. The nominal frequency of the tuning fork varies depends upon the radar device being used; a K-band tuning fork labeled 30 mph will oscillate at a higher frequency than an X-band fork with the same label.

To meet legal requirements that vary from state to state, tuning forks must be periodically calibrated, often with a frequency counter or an oscilloscope. A frequency uncertainty of 0.1 % (1×10^{-3}) is sufficient for tuning fork calibrations. Although this seems like a coarse requirement, a frequency uncertainty of 0.1% translates directly to a speed uncertainty (for example, 0.03 mph at 30 mph, 0.09 mph at 90 mph) for either X-band or K-band radar devices. This is insignificant when you consider that speeding tickets are seldom issued unless a motorist exceeds the posted speed limit by at least several miles per hour [9].

REQUIREMENTS FOR FINANCIAL MARKETS

To protect investors from securities fraud and to ensure that financial transactions occur in an orderly fashion that can be audited if necessary, financial markets often require all recorded events to be time tagged to the nearest second. For example, after an August 1996 settlement with the Securities Exchange Commission (SEC) involving stock market fraud related to the improper execution of trades, the National Association of Securities Dealers (NASD) needed a way to perform surveillance of the NASDAQ market center. As a result, the NASD developed an integrated audit trail of order, quote, and trade information for NASDAQ equity securities known as OATS (Order Audit Trail System).

OATS introduced many new rules for NASD members, including requiring all members to synchronize their computer system and mechanical clocks every business day before the market opens to ensure that recorded order event time stamps are accurate. To maintain clock synchronization, clocks should be checked against the standard clock and resynchronized, if necessary, at predetermined intervals throughout the day, so that the time kept by all clocks can always be trusted. NIST time was chosen as the official time reference for NASDAQ transactions.

NASD OATS Rule 6953, Synchronization of Member Business Clocks, applies to all member firms that record order, transaction, or related data to synchronize all business clocks. In addition to specifying NIST time as the reference, it requires firms to keep a copy of their clock synchronization procedures on-site. One part of the requirements [10] reads as follows:

> *All computer system clocks and mechanical time stamping devices must be synchronized to within three seconds of the National Institute of Standards and Technology (NIST) atomic clock. Any time provider may be used for synchronization, however, all clocks and time stamping devices must remain accurate within a three-second tolerance of the NIST clock. This tolerance includes all of the following:*
>
> - *The difference between the NIST standard and a time provider's clock;*
> - *Transmission delay from the source; and*
> - *The amount of drift of the member firm's clock.*
>
> *For example, if the time provider's clock is accurate to within one second of the NIST standard, the maximum allowable drift for any computer system or mechanical clock is two seconds.*

Prior to the development of OATS, brokerage houses often used clocks and time stamp devices that recorded time in decimal minutes with a resolution of 0.1 minutes (6 s). The new OATS requirements forced the removal of these clocks. All transactions are now time tagged to the nearest second, but up to 3 seconds of clock drift is allowed between synchronizations.

REQUIREMENTS FOR BROADCASTING

Unlike time metrology, which has origins that date back thousands of years, frequency metrology was not generally discussed until about 1920, when commercial radio stations began to appear. Radio pioneers such as Marconi, Tesla, and others were not aware of the exact frequencies (or even the general part of the spectrum) that they were using. However, when the number of radio broadcasters began to proliferate, keeping stations near their assigned frequencies became a major problem, creating an instant demand for frequency measurement procedures and for frequency standards [11]. Today, with stable quartz and atomic oscillators readily available, keeping broadcasters "on frequency" is relatively easy, but all broadcasters must follow Federal Communications Commission (FCC) regulations as described below.

FCC Requirements for Radio and Television Broadcasting

The FCC specifies the allowable carrier frequency departure tolerances for AM and FM radio stations, television stations, and international broadcast stations [12]. These tolerances are specified as a fixed frequency across the broadcast band of ± 20 Hz for AM radio, ± 2000 Hz for FM radio, and ± 1000 Hz for the audio and video television carriers, and as a dimensionless tolerance of 0.0015 % for international shortwave broadcasters. The allowable uncertainties are converted to scientific notation and summarized in Table 2.

Table 2. FCC Requirements for Broadcast Carrier Frequency Departure.

Broadcast	Tolerance	Low End of Band		High End of Band	
		Carrier	Uncertainty	Carrier	Uncertainty
AM radio	± 20 Hz	530 kHz	3.8×10^{-5}	1710 kHz	1.2×10^{-5}
FM radio	± 2000 Hz	88 MHz	2.3×10^{-5}	108 MHz	1.9×10^{-5}
Television	± 1000 Hz	55.25 MHz (channel 2 video)	1.8×10^{-5}	805.75 MHz (channel 69 audio)	1.2×10^{-6}
International	0.0015 %	3 MHz	1.5×10^{-5}	30 MHz	1.5×10^{-5}

Frequency Requirements for Color Television Subcarriers

For historical design reasons, the chrominance subcarrier frequency on analog color televisions is 63/88 multiplied by 5 MHz, or about 3.58 MHz. To ensure adequate picture quality for television viewers, federal regulations specify that the frequency of this subcarrier must remain within ± 10 Hz of its nominal value, and the rate of frequency drift must not exceed 0.1 Hz per second [13]. This corresponds to an allowable tolerance of ± 0.044 Hz in the 15 734.264 Hz horizontal scanning frequency, a dimensionless frequency uncertainty near 3×10^{-6}.

REQUIREMENTS FOR ELECTRIC POWER DISTRIBUTION

The electric power system in North America consists of many subsystems that interconnect into several massive grids that span the continent. The system delivers the 60 Hz AC frequency to many millions of customers by matching power generation levels to transmission capability and load patterns. The entire power system relies on time synchronization, and synchronization problems can lead to catastrophic failures. For example, the massive August 2003 blackout in the eastern regions of the United States and Canada was at least partially caused by synchronization failures [14].

The timing requirements of the power industry vary (Table 3), because different parts of the system were designed at different times, and the entire system has evolved over many years. The older parts of the system have less stringent timing requirements because they were designed using technologies that predated the Global Positioning System (GPS). The newer parts of the system rely on the ability of GPS to provide precise time synchronization over a large geographic area.

Since electrical energy must be used as it is generated, generation must be constantly balanced with load, and the alternating current produced by a generator must be kept in approximate phase with every other generator. Generation control requires time synchronization of about 10 ms. Synchronization to about 1 ms is required by event and fault recorders that supply information used to correct problems in the grid and improve operation. Stability control schemes prevent unnecessary generator shutdown, loss of load, and separation of the power grid. They require synchronization to about 46 μs (± 1° phase angle at 60 Hz), and networked controls have requirements one order of magnitude lower, or to 4.6 μs (± 0.1° phase angle at 60 Hz). Traveling wave fault locators find faults in the power grid by timing waveforms that travel down power lines at velocities near the speed of light. Because the high voltage towers are spaced about 300 meters apart, the timing requirement is 1 μs, or the period of a 300 meter wavelength [15]. Newer measurement techniques, such as synchronized phasor measurements, require time synchronization to Coordinated Universal Time (UTC) to within 1 μs, which corresponds to a phase angle accuracy of 0.022° for a 60 Hz system. A local time reference must be applied to each phasor measurement unit, and GPS is currently the only system that can meet the requirements of synchrophasor measurements [16].

The 60 Hz frequency delivered to consumers is sometimes used as the resonator for low priced electric clocks and timers that lack quartz oscillators. The legally allowable tolerance for the 60 Hz frequency is only ± 0.02 Hz, or 0.033 % [17], but under normal operating conditions the actual tolerance is much tighter.

Table 3. Time synchronization requirements for the electric power industry.

System Function	Measurement	Time Requirement
Generation Control	Generator phase	10 ms
Event Recorders	Time tagging of records	1 ms
Stability Controls	Phase angle, ± 1°	46 μs
Networked Controls	Phase angle, ± 0.1°	4.6 μs
Traveling wave fault locators	300 meter tower spacing	1 μs
Synchrophasor measurements	Phase angle, ± 0.022°	1 μs

REQUIREMENTS FOR TELECOMMUNICATION SYSTEMS

Telecommunication networks make use of the stratum hierarchy for synchronization as defined in the *ANSI T1.101* standard [18]. This hierarchy classifies clocks based on their frequency accuracy, which translates into time accuracy relative to other clocks in the network. The best clocks, known as Stratum 1, are defined as autonomous timing sources. This means that they require no input from other clocks, other than perhaps a periodic calibration. Stratum-1 clocks are normally atomic oscillators or GPS disciplined oscillators (GPSDOs), and have an accuracy specification of 1×10^{-11}. Stratum clocks lower than level 1 require input and adjustment from another network clock. The specifications for stratum levels 1, 2, 3, and 3E are shown in Table 4. The "pull-in range" determines what type of input accuracy is required to synchronize the clock. For example, a "pull-in-range" of $\pm 4 \times 10^{-6}$, means that the clock can be synchronized by another clock with that level of accuracy.

Table 4. Stratum timing requirements for clocks in telecommunication networks.

Stratum Levels	Stratum-1	Stratum-2	Stratum-3E	Stratum-3
Frequency accuracy, adjustment range	1×10^{-11}	1.6×10^{-8}	1×10^{-6}	4.6×10^{-6}
Frequency stability	NA	1×10^{-10}	1×10^{-8}	3.7×10^{-7}
Pull-in range	NA	1.6×10^{-8}	4.6×10^{-6}	4.6×10^{-6}
Time offset per day due to frequency instability	0.864 μs	8.64 μs	864 μs	32 ms
Interval between cycle slips	72.3 days	7.2 days	104 minutes	169 s

Requirements for Telephones (land lines)

The North American 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, or once every 125 μs. When a telephone connection is established between two voice channels originating from different clocks, the time error needs to be less than one half of the sample period, or 62.5 μs. Half the period is used to indicate the worst case, which exists when two clocks of the same stratum are moving in opposite directions. If the time error exceeds 62.5 μs, a cycle slip occurs resulting in loss of data, noise on the line, or in some cases, a dropped call. The use of Stratum-1 clocks throughout a network guarantees that cycle slips occur only once every 72.3 days (62.5 μs divided by 0.864 μs of time offset per day). In contrast, Stratum-3 clocks could produce cycle slips as often as every 169 s (Table 4), an unacceptable condition. Thus if resources allow, the use of Stratum-1 clocks is certainly desirable for network providers.

Requirements for Mobile Telephones

Mobile telephone networks depend upon precise time and frequency. Code division multiple access (CDMA) networks have the most stringent requirements. CDMA networks normally comply with the *TIA/EIA IS-95* standard [19] that defines base station time as GPS time. Thus, nearly all CDMA base stations contain GPSDOs (more than 100,000 CDMA base stations are equipped with GPS in North America). The time requirement is ± 10 μs, even if GPS is unavailable for up to 8 hours. During normal operation, base stations are synchronized to within 1 µs. The frequency requirement is 5×10^{-8} for the transmitter carrier frequency, but the carrier is normally derived from the same GPSDO as the time, and is usually much better than the specification.

Although not yet as popular as CDMA in the United States, the Global System for Mobile Communications (GSM) is the most popular standard for mobile phones in the world, currently used by over a billion people in more than 200 countries. GSM is a time division multiple access (TDMA) technology that works by dividing a radio frequency into time slots and then allocating slots to multiple calls. Unlike CDMA, GSM has no time synchronization requirement that requires GPS performance, but the uncertainty requirement for the frequency source is 5×10^{-8}, generally requiring a rubidium or a high quality quartz oscillator to be installed at each base station [20]. Unlike CDMA subscribers, GSM subscribers won't necessarily have the correct time-of-day displayed on their phones. The base station clock is sometimes (but not always) synchronized to the central office master clock system.

Requirements for Wireless Networks

Although they operate at much higher frequencies than those of the radio and television stations discussed earlier, wireless networks based on the IEEE 802.11b and 802.11g have a similar acceptable tolerance for carrier frequency departure of $\pm 2.5 \times 10^{-5}$. The specifications call for the transmit frequency and the data clock to be derived from the same reference oscillator [21].

REQUIREMENTS FOR CALIBRATION LABORATORIES

Calibration laboratories with an accredited capability in frequency usually maintain either a rubidium, cesium, or a GPSDO as their primary frequency standard. This frequency standard is used to calibrate time base oscillators in test equipment such as counters and signal generators. The test equipment is generally calibrated in accordance with manufacturer's specifications, which typically range from a few parts in 10^6 for low priced devices with non-temperature controlled quartz oscillators to parts in 10^{11} for devices with rubidium time bases. Therefore, a frequency standard with an uncertainty of 1×10^{-12} allows a laboratory to calibrate nearly any piece of commercial test equipment and still maintain a test uncertainty ratio that exceeds 10:1. For these reasons, calibration laboratories seldom have a frequency uncertainty requirement of less than 1×10^{-12}. Laboratories that require monthly certification of their primary frequency standard can subscribe to the NIST Frequency Measurement and Analysis service, and continuously measure their standard with an uncertainty of 2×10^{-13} at an averaging time of one day [22]. Laboratories that do not need certification can often meet a 1×10^{-12} uncertainty requirement by using a GPSDO and a frequency measurement system with sufficient resolution.

Requirements for Voltage Measurements

The uncertainty in voltage measurement in a Josephson voltage standard (JVS) is proportional to the uncertainty in frequency measurement. Typical high level direct comparisons of JVS systems at 10 V are performed at uncertainties of a few parts in 10^{11}. Therefore, each laboratory involved in a JVS comparison requires a frequency standard with an uncertainty of 1×10^{-11} or less at an averaging time of less than 10 minutes to ensure proper voltage measurement results [23]. This frequency requirement is generally met by using either a cesium oscillator or a GPSDO.

Requirements for Length Measurements

Since 1983, the meter has been defined as "the length of the path traveled by light in a vacuum during a time interval of 1 / 299 792 458 of a second." Thus, the definition of length is dependent upon the prior definition of time interval, and time and length metrology have a close relationship. Until recently, the best physical realizations of the meter had uncertainties several orders of magnitude larger than the uncertainty of the second, due to the techniques used to derive the meter [24]. However, the optical frequency standards [2] now being developed at national metrology institutes can also serve as laser wavelength standards for length metrology. As a result, the uncertainties of the best physical realizations of the second and the meter will probably track very closely in future years [25].

REQUIREMENTS FOR RADIONAVIGATION

Radionavigation systems, such as the ground-based LORAN-C system and the satellite based GPS system, have very demanding time and frequency requirements. The precise positioning uncertainty of these systems is entirely dependent upon precise time kept by atomic oscillators. In the case of GPS the satellites carry on-board atomic oscillators that receive clock corrections from earth-based control stations just once during each orbit, or about every 12 hours. The maximum acceptable contribution from the satellite clocks to the positioning uncertainty is generally assumed to be about 1 m. Since light travels at about 3×10^{-8} m/s, the 1 m requirement is equivalent to about a 3.3 ns ranging error. This means that the satellite clocks have to be stable enough to keep time (without the benefit of corrections) to within about 3.3 ns for about 12 hours. That translates to a frequency stability specification near 6×10^{-14}, which was the specified technical requirement during a recent GPS space clock procurement [26].

REQUIREMENTS FOR REMOTE COMPARISONS OF THE WORLD'S BEST CLOCKS

The current primary time and frequency standard for the United States is the cesium fountain NIST-F1, with uncertainties that have dropped below 1×10^{-15} [1]. NIST-F1 is routinely compared to the world's best clocks using time transfer techniques that involve either common-view measurements of the GPS satellites, or two-way time transfer comparisons that require the transmission and reception of signals through geostationary satellites. There are limits to the length of these comparisons, because it often not practical to continuously run NIST-F1 and comparable standards for more than 30 to 60 days. Therefore, to determine that a clock is accurate to within 1×10^{-15} relative to another clock, the time transfer technique used to compare the clocks needs to reach uncertainties lower than 1×10^{-15} in a reasonably short interval. Currently, both the carrier-phase GPS and the two-way time transfer techniques can reach uncertainties of about 2×10^{-15} at one day, reaching parts in 10^{16} after about 10 days of averaging [27]. Although these time transfer requirements might seem staggeringly high, keep in mind that the uncertainties of the world's best clocks will continue to get smaller [2] and time transfer requirements will become even more stringent in the coming years.

SUMMARY AND CONCLUSION

As we have seen, the world of time and frequency metrology is extensive, supporting applications that range from the everyday to the state-of-the-art. It has legal and technical uncertainty requirements that cover an astounding 15 orders of magnitude, from the parts per hundred (percent) uncertainties required by coin operated timers, to the parts in 10^{16} uncertainties required for remote comparisons of the world's best clocks. Table 5 summarizes the requirements for the applications discussed in this paper (listed in the order that they appear in the text).

Table 5. Summary of legal and technical time and frequency requirements.

Application or Device	Required Uncertainty	
	Time	Frequency
Wristwatches	0.5 s per day	6×10^{-6}
Parking Meters	7 minutes per hour	11.7%
Time Clocks and Recorders	1 minute per day	7×10^{-4}
Taximeters	6 s per minute	10%
Field Standard Stopwatches	9 s per day	1×10^{-4}
Musical Pitch	NA	1×10^{-3}
Tuning forks used for radar calibration	NA	1×10^{-3}
Stock Market time stamp	3 s absolute accuracy	NA
AM Radio Carrier frequency	NA	1.2×10^{-5}
FM Radio Carrier frequency	NA	1.9×10^{-5}
TV Carrier Frequency	NA	1.2×10^{-6}
Shortwave Carrier Frequency	NA	1.5×10^{-5}
Color TV subcarrier	NA	3×10^{-6}
Electric Power Generation	10 ms	NA
Electric Power Event Recorders	1 ms	NA
Electric Power Stability Controls	46 μs	NA
Electric Power Network Controls	4.6 μs	NA
Electric Power Fault Locators	1 μs	NA
Electric Power Synchrophasors	1 μs	NA
Telecommunications, Stratum-1 clock	NA	1×10^{-11}
Telecommunications, Stratum-2 clock	NA	1.6×10^{-8}
Telecommunications, Stratum-3E clock	NA	1×10^{-6}
Telecommunications, Stratum-3 clock	NA	4.6×10^{-6}
Mobile Telephones, CDMA	10 μs	5×10^{-8}
Mobile Telephones, GSM	NA	5×10^{-8}
Wireless Networks, 802.11g	NA	2.5×10^{-5}
Frequency Calibration Laboratories	NA	1×10^{-12}
Josephson Array Voltage Standard	NA	1×10^{-11}
GPS Space Clocks	NA	6×10^{-14}
State-of-the-art time transfer	< 1 ns	parts in 10^{16}

REFERENCES

[1] T.P. Heavner, S.R. Jefferts, E.A. Donley, J.H. Shirley, and T.E. Parker, "NIST-F1: recent improvements and accuracy evaluations," *Metrologia*, vol. 42, pp. 411-422, September 2005.

[2] S. A. Diddams, J. C. Bergquist, S. R. Jefferts, and C. W. Oates, "Standards of Time and Frequency at the Outset of the 21st Century," *Science*, vol. 306, pp. 1318-1324, November 19, 2004.

[3] T. Butcher, L. Crown, R. Suitor, J. Williams, editors, "Specifications, Tolerances, and Other Technical Requirements for Weighing and Measuring Devices," *National Institute of Standards and Technology Handbook 44,* 329 pages, December 2003.

[4] J. C. Gust, R. M. Graham, and M. A. Lombardi, "Stopwatch and Timer Calibrations," *National Institute of Standards and Technology Special Publication 960-12*, 60 pages, May 2004.

[5] State of Pennsylvania Code, 67 § 105.71(2), (2005).

[6] Lynn Cavanagh, "A brief history of the establishment of international standard pitch a = 440 Hz," *WAM: Webzine about Audio and Music*, 4 pages, 2000.

[7] International Organization for Standardization, "Acoustics – Standard tuning frequency (Standard musical pitch)," *ISO 16*, 1975.

[8] M. A. Lombardi, "NIST Time and Frequency Services," *National Institute of Standards and Technology Special Publication 432*, 80 pages, January 2002.

[9] U. S. Department of Transportation, "Speed-Measuring Device Performance Specifications: Down the Road Radar Module," *DOT HS 809 812*, 72 pages, June 2004.

[10] NASD, "OATS Reporting Technical Specifications," 281 pages, September 12, 2005.

[11] J. H. Dellinger, "Reducing the Guesswork in Tuning," *Radio Broadcast*, vol. 3, pp. 241-245, December 1923.

[12] Code of Federal Regulations 47 § 73.1545, (2004).

[13] Code of Federal Regulations 47 § 73.682, (2004).

[14] U.S. – Canada Power System Outage Task Force, "Final report on the August 14, 2003 blackout in the United States and Canada: Causes and Recommendations" April 2004. Available at: http://www.nerc.com/~filez/blackout.html

[15] K. E. Martin, "Precise Timing in Electric Power Systems," *Proceedings of the 1993 IEEE International Frequency Control Symposium*, pp. 15-22, June 1993.

[16] Power System Relaying Committee of the IEEE Power Engineering Society, "IEEE Standard for Synchrophasors for Power Systems," *IEEE Standard 1344-1995(R2001)*, 36 pages, December 1995, reaffirmed March 2001.

[17] North American Electric Reliability Council, "Generation, Control, and Performance," *NERC Operating Manual*, Policy 1, Version 2, October 2002.

[18] American National Standard for Telecommunications, "Synchronization Interface Standards for Digital Networks," *ANSI T1.101*, 1999.

[19] "Mobile Station-Base Station Compatibility Standard for Wideband Spread Spectrum Cellular Systems," *TIA/EIA Standard 95-B*, Arlington, VA: Telecommunications Industry Association, March 1999.

[20] European Telecommunications Standards Institute (ETSI), "GSM: Digital cellular telecommunication system (Phase 2+); Radio subsystem synchronization (GSM 05.10 version 8.4.0)," *ETSI TS 100 912*, 1999.

[21] LAN/MAN Standards Committee of the IEEE Computer Society, "IEEE Standard for Information technology -- Telecommunications and information exchange between systems -- Local and metropolitan area networks -- Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications -- Amendment 4: Further Higher Data Rate Extension in the 2.4 GHz Band," *IEEE Standard 802.11g*, 2003.

[22] M. A. Lombardi, "Remote frequency calibrations: The NIST frequency measurement and analysis service", *National Institute of Standards and Technology Special Publication 250-29*, 90 pages, June 2004.

[23] Y. Tang, M. A. Lombardi, D. A. Howe, "Frequency uncertainty analysis for Josephson voltage standard", Proceedings of the *2004 IEEE Conference on Precision Electromagnetic Measurements*, pp. 338-339, June 2004.

[24] B. W. Petley, "Time and Frequency in Fundamental Metrology," *Proceedings of the IEEE*, vol. 79, no. 7, pp. 1070-1076, July 1991.

[25] J. Helmcke, "Realization of the metre by frequency-stabilized lasers," *Measurement Science and Technology*, vol. 14, pp. 1187-1199, July 2003.

[26] T. Dass, G. Freed, J. Petzinger, J. Rajan, T. J. Lynch, and J. Vaccaro, "GPS Clocks in Space: Current Performance and Plans for the Future," *Proceedings of the 2002 Precise Time and Time Interval Meeting*, pp. 175-192, December 2002.

[27] T.E. Parker. S.R. Jefferts, T. P. Heavner, and E.A. Donley, "Operation of the NIST-F1 caesium fountain primary frequency standard with a maser ensemble, including the impact of frequency transfer noise," *Metrologia*, vol. 42, pp. 423-430, September 2005.