Time and Frequency from A to Z
An Illustrated Glossary

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A

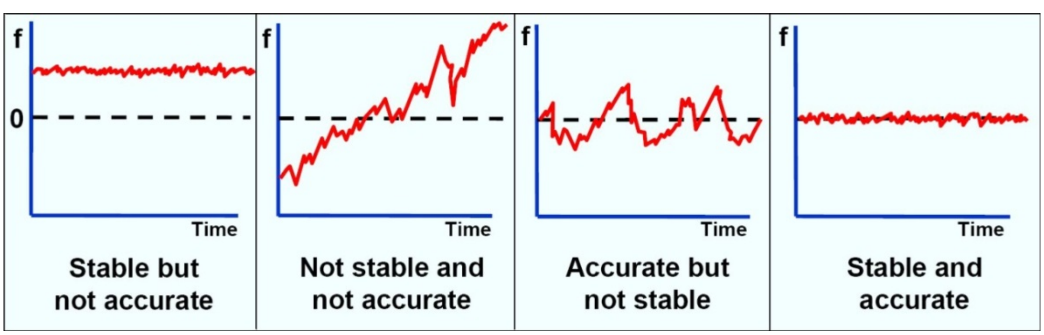
A440

A440 (sometimes called A4) is the 440 Hz tone that serves as the internationally recognized standard for musical pitch. A440 is the musical note A above middle C. NIST has broadcast A440 from radio station WWV since 1936. The tones can currently be heard during minute 2 of each hour on WWV, and during minute 1 on WWVH.

Tuning a piano is an example of a simple frequency calibration that is done with the human ear. The piano tuner listens to a standard audio tone, compares it to the same note on the piano, and adjusts the piano until it agrees with the audio standard. The smallest frequency offset that a piano tuner can hear depends upon several factors, including the musical training of the listener. However, the just noticeable difference is often defined as 5 cents, where 1 cent is 1/100 of the ratio between two adjacent tones on the piano's keyboard. Because 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. A 5 cent raise in pitch would require this to be done five times, and would equal 1.3 Hz when starting with a 440 Hz tone.

Accuracy

The degree of conformity of a measured or calculated value to its definition, related to the offset from an ideal value. In the time and frequency community, accuracy refers to the time offset or frequency offset of a device. For example, time offset is the difference between a measured on-time pulse and an ideal on-time pulse that coincides with UTC. Frequency offset is the difference between a measured frequency and a nominal frequency with zero uncertainty. The relationship between accuracy and stability is shown in the illustration.



The term uncertainty is usually preferred to accuracy when a quantitative measurement result is reported. Accuracy is often used in a qualitative sense. For example, we might say that an accurate time measurement was made with an uncertainty of 1 microsecond.

Active Frequency Standard

An atomic oscillator, usually a hydrogen maser, whose output signal is derived from the radiation emitted by the atom. Most commercially available atomic oscillators are passive frequency standards.

Aging

A change in frequency with time due to internal changes in an oscillator. Aging is usually a nearly linear change in the resonance frequency that can be either positive or negative, and occasionally, a reversal in direction of aging occurs. Aging occurs even when factors external to the oscillator, such as environment and power supply, are kept constant. Aging has many possible causes, including a buildup of foreign material on the crystal, changes in the oscillator circuitry, or changes in the quartz material or crystal structure. A high quality OCXO might age at a rate of $< 5 \times 10^{-9}$ per year, while a TCXO might age 100 times faster.

Allan Deviation

A non-classical statistic used to estimate stability. This statistic is sometimes called the Allan variance, but since it is the square root of the variance, its proper name is the Allan deviation. The equation for the Allan deviation (with non-overlapping samples) is

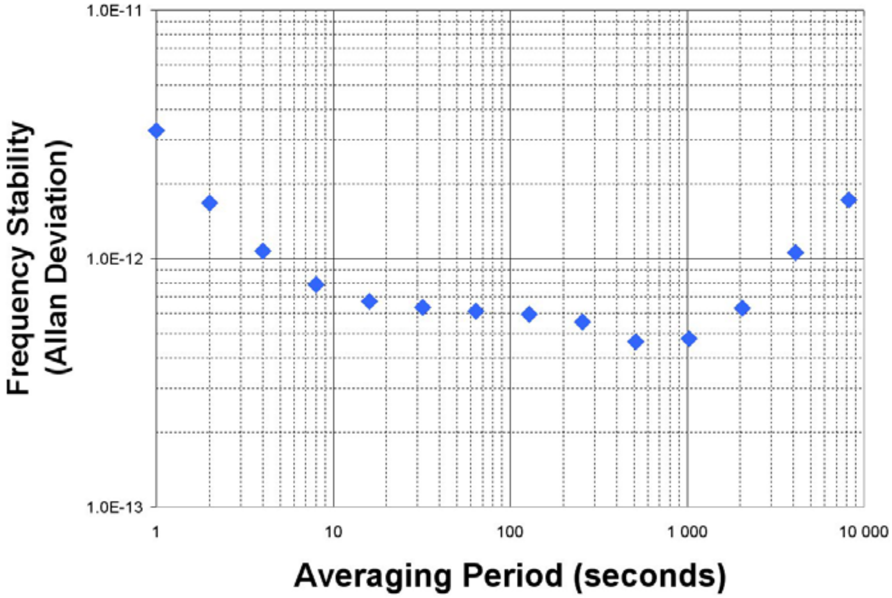
$$\sigma_y(\tau) = \sqrt{\frac{1}{2(M-1)} \sum_{i=1}^{M-1} (\bar{y}_{i+1} - \bar{y}_i)^2} \quad ,$$

where y_i is a set of frequency offset measurements that consists of individual measurements, y_1, y_2, y_3, and so on; M is the number of values in the y_i series, and the data are equally spaced in segments τ seconds long. Or

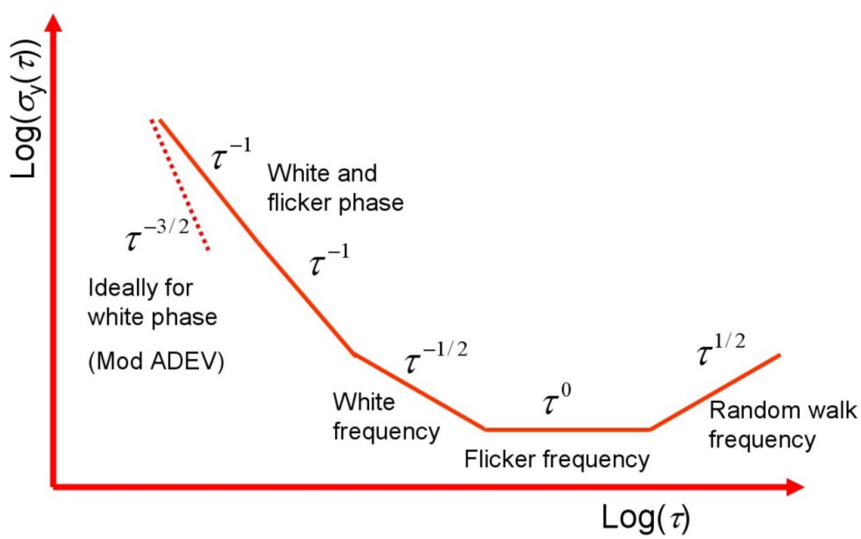
$$\sigma_y(\tau) = \sqrt{\frac{1}{2(N-2)\tau^2} \sum_{i=1}^{N-2} (x_{i+2} - 2x_{i+1} + x_i)^2} \ ,$$

where x_i is a series of phase measurements in time units that consists of individual measurements, x_1, x_2, x_3, and so on, N is the number of values in the x_i series, and the data are equally spaced in segments τ seconds long.

An Allan deviation graph is shown below. It shows the stability of the device improving as the averaging period gets longer, since some noise types can be removed by averaging. At some point, however, more averaging no longer improves the results. This point is called the noise floor, or the point where the remaining noise consists of nonstationary processes such as aging or random walk. The device in the graph has a noise floor of about 5×10^{-13} at $\tau = 1000$ s.



The Allan deviation is also used to identify types of oscillator and measurement system noise. The slope of the Allan deviation line can identify the amount of averaging needed to remove these noise types, as shown in the graph below. Note that the Allan deviation does not distinguish between white phase noise and flicker phase noise.



Ambiguity

The properties of a measurement or reading that allow it to have more than one possible meaning. For example, if a clock based on a 12-hour system displays 6 hours and 43 minutes, it could be morning or night. This means the clock is ambiguous to the hour, because 6 hours can represent two different times of day. A 24-hour clock eliminates the day/night ambiguity.

Artifact

A device with well-known metrological properties that is used as a travelling standard to transfer or compare measurement results between laboratories or within a laboratory.

Atomic Clock

A clock referenced to an atomic oscillator. Only clocks with an internal atomic oscillator qualify as atomic clocks. However, the term is often incorrectly used to refer to radio controlled clocks that receive a signal referenced to an atomic clock at another location.

Atomic Oscillator

An oscillator that uses the quantized energy levels in atoms or molecules as the source of its resonance. The laws of quantum mechanics dictate that the energies of a bound system, such as an atom, have certain discrete values. An electromagnetic field at a particular frequency can boost an atom from one energy level to a higher one. Or, an atom at a high energy level can drop to a lower level by emitting energy. The resonance frequency, f_o, of an atomic oscillator is the difference between the two energy levels divided by Planck's constant, h,

$$f_o = \frac{E_2 - E_1}{h}.$$

The principle underlying the atomic oscillator is that since all atoms of a specific element are identical, they should produce exactly the same frequency when they absorb or release energy. In theory, the atom is a perfect "pendulum" whose oscillations are counted to measure time interval. The national frequency standards developed by NIST and other laboratories derive their resonance frequency from the cesium atom, and typically use cesium fountain technology. Rubidium oscillators are the lowest priced and most common atomic oscillators, but cesium beam and hydrogen maser atomic oscillators are also sold commercially in much smaller quantities.

Atomic Time Scale (TA)

A time scale based on an atomic definition of the second. Elapsed time is measured by counting cycles of a frequency locked to an atomic or molecular transition. Atomic time scales differ from the earlier astronomical time scales, which define the second based on the rotation of the Earth on its axis. Coordinated Universal Time (UTC) is an atomic time scale, since it defines the second by counting energy transitions of the cesium atom.

Attosecond

A unit of time that represents one quintillionth of a second (10^{-18} s).

Automated Computer Time Service (ACTS)

A telephone time service operated by NIST that synchronizes computer clocks to UTC(NIST). Client computers can connect to the ACTS time servers using an analog modem and an ordinary telephone line. The phone number is (303) 494-4774.

B

Bandwidth

The range of frequencies that an electronic signal occupies on a given transmission medium. Any digital or analog signal has a bandwidth. In digital systems, bandwidth is often expressed as data speed in bits per second. In analog systems, bandwidth is expressed in terms of the difference between the highest-frequency signal component and the lowest-frequency signal component. For example, a typical voice signal on an analog telephone line has a bandwidth of about 3 kHz. An FM radio station has a bandwidth of 200 kHz, analog television (TV) broadcast signals have 6 MHz of bandwidth, and so on. As a general rule, systems with more bandwidth can carry more information.

Beat Frequency

The frequency produced when two signals are mixed or combined. The beat frequency equals the difference or offset between the two frequencies. Audible beat frequencies, often called beat notes, are used for simple frequency calibrations. For example, an amateur radio operator might calibrate a receiver dial by mixing the incoming signal from WWV with the signal from the receiver's beat frequency oscillator (BFO). This produces a beat note that sounds like a low frequency whistle. The receiver is tuned to the station, and the dial is moved up or down until the whistle completely goes away, a condition known as zero beat. Usually, headphones are used to listen for zero beat, since the receiver's speaker might not be able to produce the low frequency beat note signals. Because a person with average hearing can hear tones down to 20 or 30 Hz, an audio zero beat can calibrate a 10 MHz frequency to within two or three parts in 10^6.

BIPM

The Bureau International des Poids et Mesures (International Bureau of Weights and Measures) located near Paris, France. The task of the BIPM is to ensure worldwide uniformity of measurements and their traceability to the International System of Units (SI). The BIPM averages clock data from about 70 laboratories (including NIST) to produce a time scale called International Atomic Time (TAI). When corrected for leap seconds, TAI becomes Coordinated Universal Time (UTC), or the official international time scale. The BIPM publishes the time offset or difference of each laboratory's version of UTC relative to the international average. For example, the BIPM publishes the time offset between UTC and UTC(NIST). The work of the BIPM makes it possible for NIST and the other laboratories to adjust their standards so that they agree as closely as possible with the rest of the world.

C

Calibration

A comparison between a device under test and an established standard, such as UTC(NIST). When the calibration is finished it should be possible to state the estimated time offset and/or frequency offset of the device under test with respect to the standard, as well as the measurement uncertainty.

Carrier Frequency

The base frequency of a transmitted electromagnetic pulse or wave on which information can be imposed by varying the signal strength, varying the base frequency, varying the wave phase, or other means. This variation is called modulation. If the carrier frequency is derived from a source that is traceable to the International System (SI), the received signal can be used to calibrate other frequency sources.

The table lists the carrier frequencies of several radio transmissions commonly used as frequency standards. In metrology, an unmodulated signal from an oscillator (such as a 10 MHz sine wave) is also sometimes referred to as a carrier frequency.

Radio Signal	Carrier Frequency
WWVB	60 kHz
WWV	2.5, 5, 10, 15, 20 MHz
WWVH	2.5, 5, 10, 15 MHz
Global Positioning System (GPS)	1575.42 MHz (L1)
	1227.6 MHz (L2)

Carrier Phase Measurements

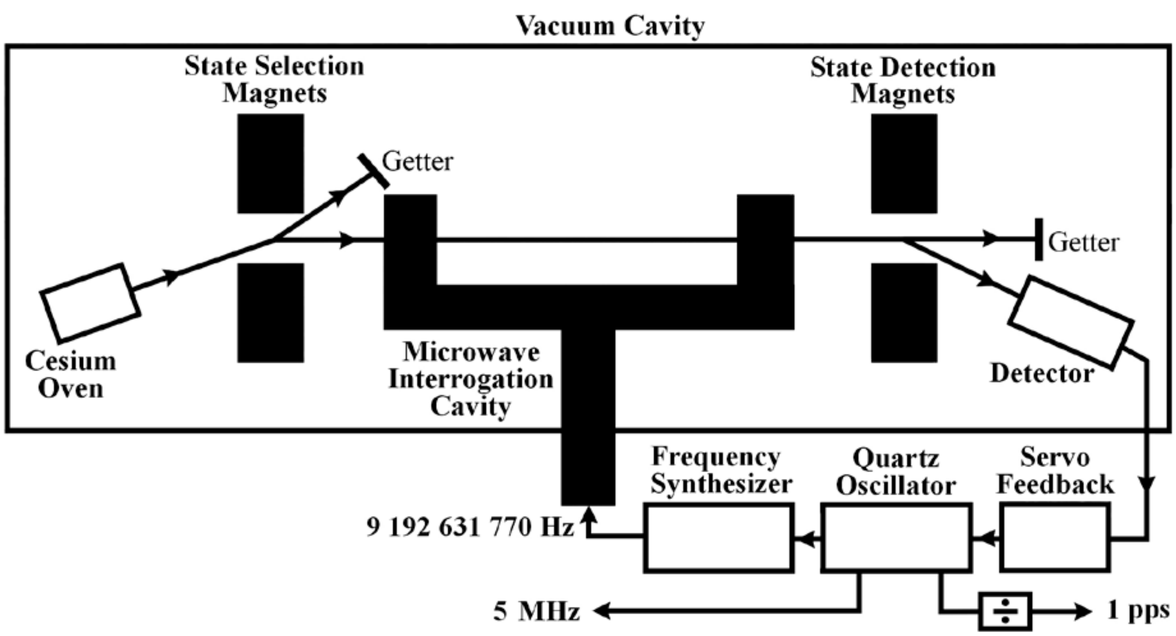
A type of calibration that uses the carrier frequency of a radio transmission as a measurement reference, rather than information modulated onto to the carrier, such as a time code or on-time marker. Carrier phase measurements have been made for many years using low frequency radio signals stations such as WWVB. However, the carrier phase measurements with the smallest uncertainties and highest resolution are made using satellite signals where the carrier frequencies are typically much higher.

Cesium Beam Oscillator

Cesium oscillators can be primary frequency standards since the SI second is defined from the resonance frequency of the cesium atom (^{133}Cs), which is 9,192,631,770 Hz. A properly working cesium oscillator should be close to its nominal frequency without adjustment, and there should be no change in frequency due to aging. However, environmental conditions (motion, vibration, magnetic fields, and so on) do cause small frequency shifts.

Commercially available oscillators use cesium beam technology. Inside a cesium oscillator, ^{133}Cs atoms are heated to a gaseous state in an oven. Atoms from the gas leave the oven in a high-velocity beam that travels through a vacuum tube toward a pair of magnets. The magnets serve as a gate that allows only atoms of a particular magnetic energy state to pass through a gate into a microwave cavity, where they are exposed to a microwave frequency derived from a quartz oscillator. If the microwave frequency matches the resonance frequency of cesium, the cesium atoms change their magnetic energy state.

The atomic beam then passes through another magnetic gate near the end of the tube. Only those atoms that changed their energy state while passing through the microwave cavity are allowed to proceed to a detector at the end of the tube. Atoms that did not change state are deflected away from the detector. The detector produces a feedback signal that continually tunes the quartz oscillator in a way that maximizes the number of state changes so that the greatest number of atoms reaches the detector. Standard output frequencies are derived from the locked quartz oscillator as shown in the illustration.

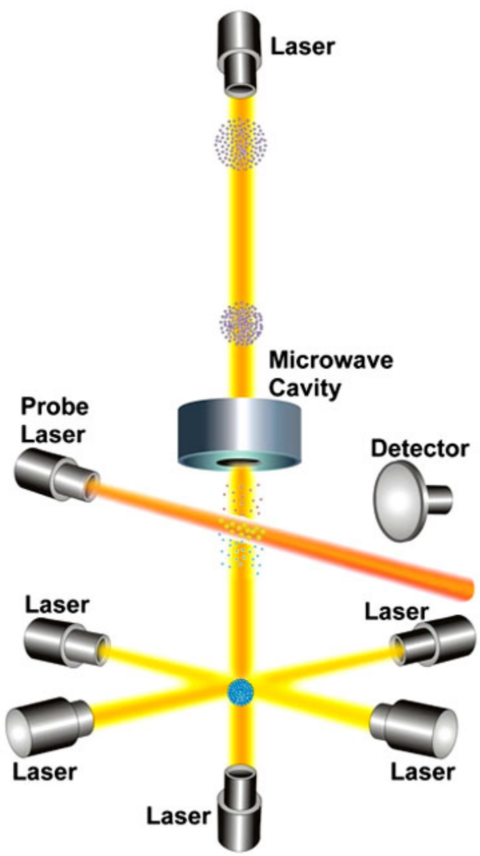


The Q of a commercial cesium standard is a few parts in 10^8. The beam tube is typically less than 0.5 m in length, and the atoms travel at velocities of greater than 100 meters per second inside the tube. This limits the observation time to a few milliseconds, and the resonance width to a few hundred hertz. The stability at 1 second is typically 5×10^{-12}, and can reach a few parts in 10^{14} after one day of averaging. The frequency offset is typically near 1×10^{-13} after a brief warm-up period.

Cesium Fountain Oscillator

The current state-of-the-art in cesium oscillator technology, the cesium fountain oscillator is named after its fountain-like movement of cesium atoms. A cesium fountain named NIST-F2 serves as the primary standard of time interval and frequency for the United States.

A cesium fountain works by releasing a gas of cesium atoms into a vacuum chamber. As indicated in the illustration, six infrared laser beams are directed at right angles to each other at the center of the chamber. The lasers gently push the cesium atoms together into a ball. In the process of creating this ball, the lasers slow down the movement of the atoms and cool them to temperatures a few millionths of a degree above absolute zero. This reduces their thermal velocity to a few centimeters per second.



Vertical laser beams gently toss the ball upward and then all of the lasers are turned off. This little push is just enough to loft the ball about a meter high through a microwave-filled cavity. Under the influence of gravity, the ball then stops and falls back down through the microwave cavity. The round trip up and down through the microwave cavity lasts for about 1 second, and is limited only by the force of gravity pulling the atoms downward. During the trip, the atomic states of the atoms might or might not be altered as they interact with the microwave signal. When their trip is finished, another laser is pointed at the atoms. Those atoms whose states were altered by the microwave signal emit photons (a state known as fluorescence) that are counted by a detector. This process is repeated many times while the microwave signal in the cavity is tuned to different frequencies. Eventually, a microwave frequency is found that alters the states of most of the cesium atoms and maximizes their fluorescence. This frequency is the cesium resonance.

The Q of a cesium fountain is about 10^{10}, or about 100 times higher than a traditional cesium beam. Although the resonance frequency is the same, the resonance width is much narrower (< 1 Hz), due to the longer observation times made possible by the combination of laser cooling and the fountain design. The combined frequency uncertainty of NIST-F2 is near 1×10^{-16}.

Characterization

An extended test of the performance characteristics of a clock or oscillator. A characterization involves more work than a typical calibration. The device under test is usually measured for a long period of time (days or weeks), and sometimes a series of measurements is made under different environmental conditions. A characterization is often used to determine the types of noise that limit the uncertainty of the measurement, and the sensitivity of the device to environmental changes.

Chip Scale Atomic Clock (CSAC)

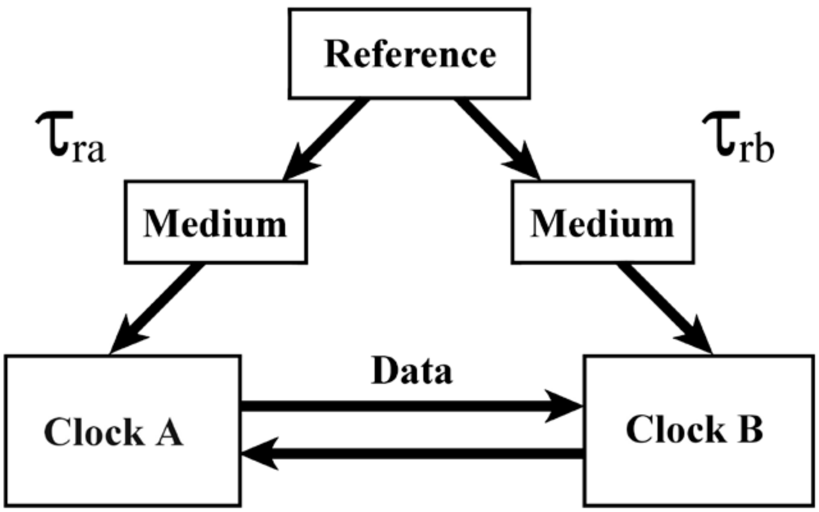
Miniature atomic clocks, known as chip scale atomic clocks (CSACs), were first reported on at NIST in 2001. These devices are now sold commercially and are notable for their small size and very low power consumption. Their stability is typically a few parts in 10^{11} at $\tau = 1$ day. They can be based on either cesium or rubidium resonance. It seems likely that CSACs will eventually be embedded in many types of commercial products as their price decreases and their performance improves.

Clock

A device that generates periodic, accurately spaced signals for timekeeping applications. A clock consists of at least three parts: an oscillator, a device that counts the oscillations and converts them to units of time interval (such as seconds, minutes, hours, and days), and a means of displaying or recording the results.

Common-View

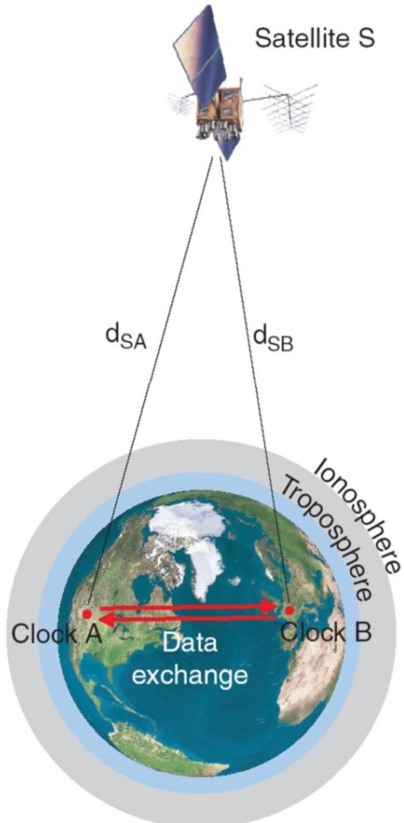
A measurement technique used to compare two clocks or oscillators at remote locations. The common-view method involves a reference transmitter (R) and two receivers (A and B). The transmitter is in common view of both receivers. Both receivers compare the simultaneously received signal to their local clock and record the data. Receiver A receives the signal over the path τ_{ra} and compares the reference to its local clock (R - Clock A). Receiver B receives the signal over the path τ_{rb} and records (R - Clock B). The two receivers then exchange and difference the data as shown in the graphic.



Common-view directly compares two clocks or oscillators to each other. Errors from the two paths τ_{ra} and τ_{rb}) that are common to the reference cancel out, and the uncertainty caused by path delay is nearly eliminated. The result of the measurement is (Clock A - Clock B) - (τ_{ra} - τ_{rb}).

Unlike the one-way methods, the common-view method cannot synchronize clocks in real time, because data from both receiving sites must be transferred and processed before the final measurement results are known. However, the Internet makes it possible to transfer and process the data very quickly. Therefore, common-view data can synchronize clocks in near real time, a method now commonly employed by NIST and other laboratories.

Common-view measurements were made for many years using land based transmitters as the reference. Today, nearly all common-view measurements use a satellite as the reference transmitter, as shown in the illustration. The best common-view satellite time transfer techniques now enable clocks to be compared over transcontinental distances with uncertainties of just a few nanoseconds.



Coordinated Universal Time (UTC)

The international atomic time scale that serves as the basis for timekeeping for most of the world. UTC is a 24-hour timekeeping system. The hours, minutes, and seconds expressed by UTC represent the time-of-day at the Earth's prime meridian (0° longitude) located near Greenwich, England.

UTC is calculated by the Bureau International des Poids et Measures (BIPM) in Sevres, France. The BIPM averages data collected from more than 450 atomic time and frequency standards located at about 70 laboratories, including the National Institute of Standards and Technology (NIST). As a result of this averaging, the BIPM generates two time scales, International Atomic Time (TAI), and Coordinated Universal Time (UTC). These time scales realize the International System (SI) second as closely as possible.

UTC runs at the same frequency as TAI. However, it differs from TAI by an integral number of seconds. This difference increases when leap seconds occur. When necessary, leap seconds are added to UTC on either June 30 or December 31. The purpose of adding leap seconds is to keep atomic time (UTC) within ±0.9 s of an older time scale called UT1, which is based on the rotational rate of the Earth. Leap seconds have been added to UTC at a rate averaging about six per decade, beginning in 1972.

The BIPM disseminates UTC as a “paper” time scale, publishing results once per month via the *Circular T* document. The world’s major timing laboratories use the published data from the BIPM to steer their clocks and oscillators and generate real-time versions of UTC, such as UTC(NIST).

UTC is the ultimate standard for time-of-day, time interval, and frequency measurements. Clocks synchronized to UTC display the same hour, minute, and second all over the world (and remain within one second of UT1). Oscillators syntonized to UTC generate signals that serve as reference standards for time interval and frequency.

Cycle Slip

A change in the signal tracking point of a carrier frequency that occurs during a measurement. Cycle slips introduce phase shifts equal (in time units) to the period of the carrier frequency, or to a multiple of its period. For example, if a WWVB receiver changes its signal tracking point during a measurement, a phase shift equal to a multiple of 16.67 microseconds (the period of 60 kHz) will result. Most cycle slips are caused by a temporary loss of lock due to signal interruption, or a weak or noisy signal.

D

Date

A number or series of numbers used to identify a given day with the least possible ambiguity. The date is usually expressed as the month, day of month, and year. However, integer numbers such as the Julian Date are also used to express the date.

Daylight Saving Time

The part of the year when clocks are advanced by one hour, effectively moving an hour of daylight from the morning to the evening. In 2007, the rules for Daylight Saving Time (DST) in the United States were changed for the first time since 1986. The new changes were enacted by the Energy Policy Act of 2005, which extended the length of DST by about one month in the interest of reducing energy consumption. DST will now be in effect for 238 days, or about 65% of the year, although Congress retained the right to revert to the prior law should the change prove unpopular or if energy savings are not significant. Under the current rules, DST in the U.S. begins at 2:00 a.m. on the second Sunday of March and ends at 2:00 a.m. on the first Sunday of November.

Daylight Saving Time is not observed in Hawaii, American Samoa, Guam, Puerto Rico, the Virgin Islands, and the state of Arizona (not including the Navajo Indian Reservation, which does observe).

Daytime Protocol

A time code protocol used to distribute time over the Internet. The daytime protocol is described in the RFC-867 document, and is implemented by the NIST Internet Time Service.

Dead Time

The time interval that elapses between the end of one measurement and the start of the next measurement. This time interval is generally called dead time only if information is lost. For example, when making measurements with a time interval counter, the minimum amount of dead time is the elapsed time from when a stop pulse is received to the arrival of the next start pulse. If a counter is fast enough to measure every pulse (if it can sample at a rate of 1 kHz, for instance, and the input signals are at 100 Hz), we can say there is no dead time between measurements.

Disciplined Oscillator (DO)

An oscillator whose output frequency is continuously adjusted (often through the use of a phase locked loop) to agree with an external reference. For example, a GPS disciplined oscillator (GPSDO) usually consists of a quartz or rubidium oscillator whose output frequency is continuously adjusted to agree with signals broadcast by the GPS satellites.

Doppler Shift

The apparent change of frequency caused by the motion of the frequency source (transmitter) relative to the destination (receiver). If the distance between the transmitter and receiver is increasing the frequency apparently decreases. If the distance between the transmitter and receiver is decreasing, the frequency apparently increases. To illustrate this, listen to the sound of a train whistle as a train comes closer to you (the pitch gets higher), or as it moves further away (the pitch gets lower). As you do so, keep in mind that the frequency of the sound produced at the source has not changed.

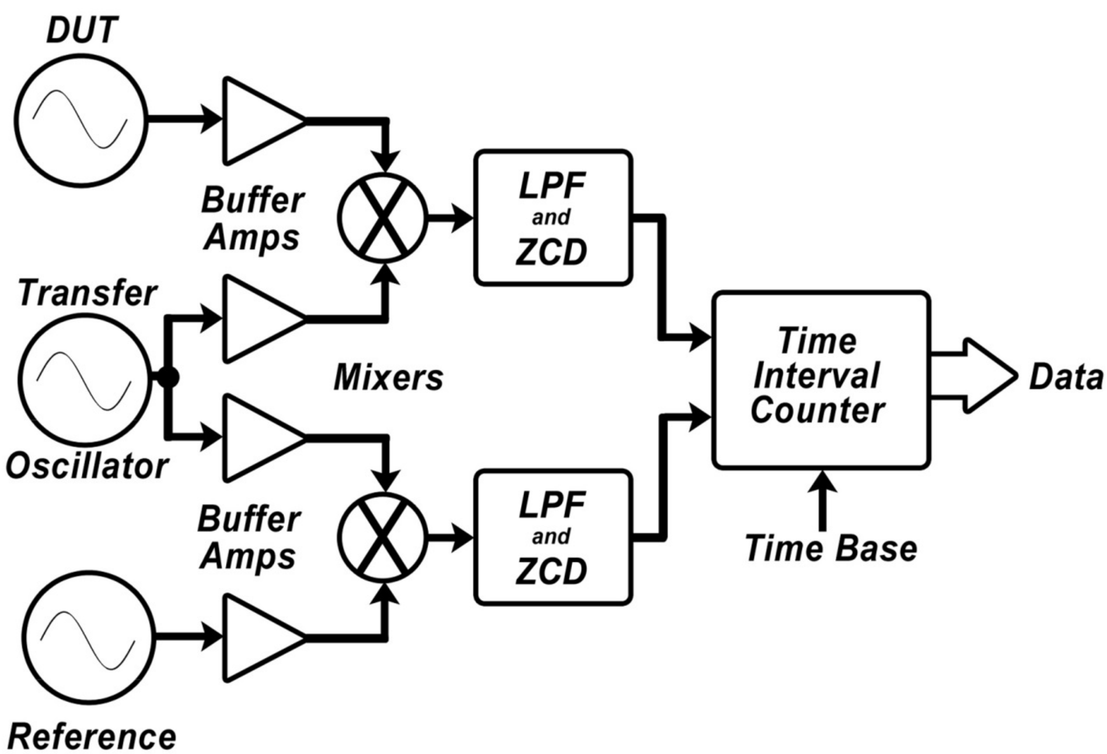
Drift (frequency)

The linear (first order) component of a systematic change in frequency of an oscillator over time. Drift is caused by aging, by changes in the environment, and by other factors external to the oscillator.

Dual Mixer Time Difference (DMTD) Measurement System

A measurement system that combines the best features of the time interval and heterodyne methods. The dual mixer time difference (DMTD) method uses a transfer oscillator and two double balanced mixers in parallel. The transfer oscillator is offset from the nominal frequencies by a small amount, typically by 10 Hz. The transfer oscillator does not have to be particularly stable or accurate because the noise it produces is common to both measurement channels and cancels when the phase difference is computed. Even so, the transfer oscillator signal is usually obtained by locking a frequency synthesizer to the reference oscillator. Typically, both the device under test (DUT) and the reference must have the same nominal frequency, usually 5 or 10 MHz, and DMTD systems are often designed to measure only one nominal frequency. However, the use of frequency synthesizers allows some DMTD systems to measure a number of DUT frequencies within a specified range (for example, from 1 to 30 MHz) and can even allow the DUT and the reference to have different nominal frequencies.

As shown in the diagram, the transfer oscillator signal is heterodyned with both the reference oscillator and the DUT to produce two beat frequencies. The two beat frequencies are out of phase by an amount proportional to the time difference between the DUT and reference, and this phase difference is measured with a time interval counter (TIC). Before being sent to the TIC, the beat frequencies pass through a low pass filter (LPF) that removes harmonics and a zero-crossing detector (ZCD) that determines the zero crossing of each beat frequency cycle. A DMTD system works best if the zero crossings are coincident or can be interpolated to a common epoch. Thus, a variable phase shifter is sometimes used to put the DUT signal nominally in phase with the reference before the DUT signal is mixed with the transfer oscillator. After the mixing process, some systems use an event counter to count the whole beat note cycles to eliminate the ambiguity of the zero crossings; other systems time-tag the zero crossings.



The resolution of a DMTD system is determined by the resolution of the TIC or the time-tagging hardware, divided by the heterodyne factor. For example, if the TIC resolution is 100 ns and the heterodyne factor is 10^6 (based on a 10 MHz nominal frequency and a 10

Hz beat frequency), then the DMTD resolution can be estimated at 10^{-7} s/10^{6} or 0.1 ps. This high resolution allows some DMTD systems to detect frequency changes in one second of 1×10^{-13}, or two or three orders of magnitude smaller than a typical frequency or time interval counter can do in the same one-second interval. Note that all components of a DMTD system must be carefully chosen for optimum stability and not all systems are stable enough to support their theoretical resolution.

DUT1

The current difference between UTC and to the astronomical time scale UT1. It is always a number ranging from -0.8 to +0.8 seconds, with a resolution of 0.1 seconds. This number is broadcast by WWV, WWVH, WWVB, and ACTS, and can be added to UTC to obtain UT1.

E

Ensemble

A group of clocks or oscillators whose outputs are averaged to create a time scale. Typically, the relative value of each clock is weighted, so that the best clocks contribute the most to the average. The BIPM uses an ensemble of clocks located around the world to produce UTC, and NIST uses an ensemble of clocks located in Boulder, Colorado to produce UTC(NIST).

Ephemeris Time (ET)

An obsolete time scale based on the ephemeris second, which served as the SI second from 1956 to 1967. The ephemeris second was a fraction of the tropical year, or the interval between the annual vernal equinoxes, which occur on or about March 21. The tropical year was defined as 31,556,925.9747 ephemeris seconds. Determining the precise instant of the equinox is difficult, and this limited the uncertainty of Ephemeris Time (ET) to ±50 ms over a 9-year interval. ET was used mainly by astronomers, and was replaced by Terrestial Time (TT) in 1984.

Epoch

The beginning of an era (or event) or the reference date for a system of measurements.

F

Femtosecond (fs)

A unit of time that represents one quadrillionth of a second (10^{-15} s).

Flicker Noise

A type of low frequency noise where the power spectral density is inversely proportional to the frequency. For this reason, it is sometimes referred to as $1 / f$ noise.

Frequency

The rate of a repetitive event. If T is the period of a repetitive event, then the frequency f is its reciprocal, $1/T$. Conversely, the period is the reciprocal of the frequency, $T = 1 / f$. Because the period is a time interval expressed in seconds (s), it is easy to see the close relationship between time interval and frequency. The standard unit for frequency is the hertz (Hz), defined as the number of events or cycles per second. The frequency of electrical signals is often measured in multiples of hertz, including kilohertz (kHz), megahertz (MHz), or gigahertz (GHz).

Frequency Accuracy

The degree of conformity of a measured or calculated frequency to its definition. Because accuracy is related to the offset from an ideal value, frequency accuracy is usually stated in terms of the frequency offset.

Frequency Comb

The accurate measurement of optical frequencies had historically been difficult, involving large and complex chains of frequency-doubled and frequency-mixed lasers. This changed in the early part of the twenty-first century, with the invention of the self-referenced femtosecond laser frequency comb. These devices, which are now sold commercially, have made the linkage of optical to microwave frequencies, or optical to optical frequencies, relatively simple.

A self-referenced femtosecond laser frequency comb generates a series of discrete, equally frequency-spaced modes. The mode spacing, f_{rep}, is given by the repetition rate of a mode-locked laser, which is typically around 1 GHz. The frequency of an individual mode can be expressed as $f(m) = f_{\mathrm{o}} + m \times f_{\mathrm{rep}}$, where m is an integer. The frequency offset f_{o} is measured by a method called self-referencing. An optical standard can be compared to a conventional frequency standard by referencing the comb to a cesium standard or a GPSDO and then measuring the heterodyne beat frequency f_{beat} between the optical standard and the nearest tooth of the comb. This will lead to determination of the frequency of the optical standard in terms of f_{o}, f_{rep}, and f_{beat}, if the integer m is known.

Frequency combs also allow the ratio of two optical frequencies to be compared without being limited by the accuracy of conventional microwave standards. This has already resulted in frequency comb comparisons of optical standards with relative frequency differences of parts in 10^{19}.

Frequency Counter

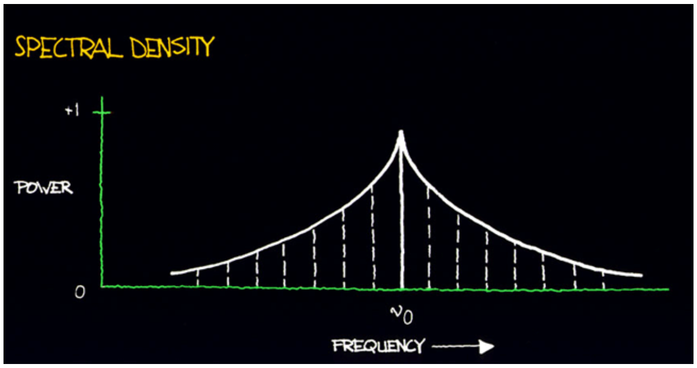
An electronic instrument or circuit that measures and displays the frequency of an incoming signal. Frequency counters are the most common instruments used to measure frequency. The measurements are referenced to the counter's time base oscillator, which is usually a quartz oscillator of unknown accuracy (typically no better than 1×10^{-8}). For this reason, the best available oscillator should be connected to the counter's external time base input. The smallest frequency offset that a frequency counter can detect with a single reading will be limited by the number of digits on the counter's display. For example, a 10-digit counter cannot detect a frequency change smaller than 1×10^{-9} without averaging when measuring a 10 MHz signal, but a 12-digit counter can reduce this value by two orders of magnitude to 1×10^{-11}.

Frequency Divider

An electronic instrument or circuit that converts an incoming signal to a lower frequency by removing a fixed number of cycles or pulses from the signal. For example, a circuit that divides by 1000 can accept a 1 MHz signal as an input, and produce a 1 kHz signal as an output. Dividers are commonly used to convert a standard frequency standard such as 5 MHz or 10 MHz to a 1 Hz signal that can be synchronized to UTC for timing applications.

Frequency Domain

The measurement domain where voltage and power are measured as functions of frequency. A spectrum analyzer can analyze signals in the frequency domain by separating signals into their frequency components and displaying the power level at each frequency. An ideal sine wave (perfect frequency) appears as a spectral line of zero bandwidth in the frequency domain. Real sine wave outputs are always noisy, so the spectral lines have a finite bandwidth, as shown in the graphic. Noise is usually present over a wide band of frequencies.

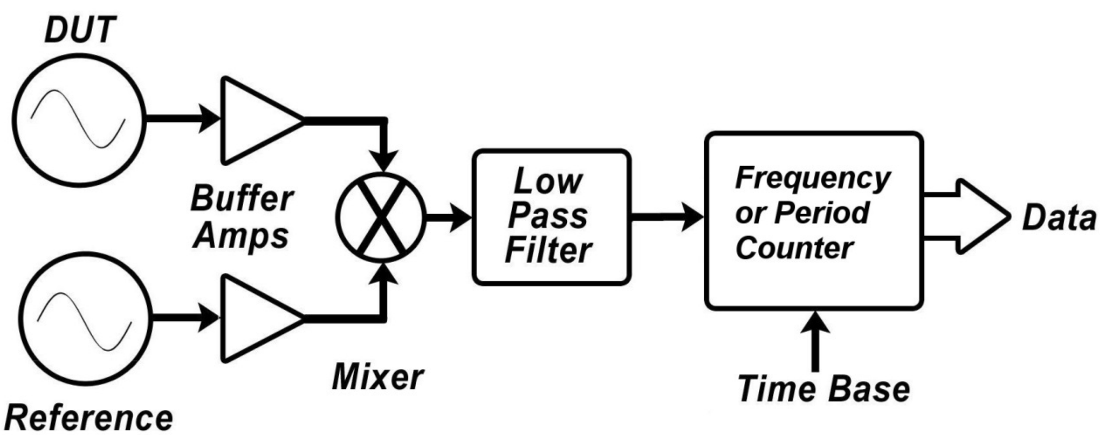


Frequency Drift

An undesired progressive change in frequency with time. Frequency drift can be caused by instability in the oscillator and environmental changes, although it often hard to distinguish between drift and oscillator aging. Frequency drift may be in either direction (resulting in a higher or lower frequency) and is not necessarily linear.

Frequency Mixer

An electronic instrument or circuit that accepts two input signals at two different frequencies, and produces an output frequency (called the beat frequency or difference frequency), that is equal to the difference of the two inputs. Frequency mixers are commonly employed in frequency measurement systems to convert a high frequency to a low frequency, and to obtain more measurement resolution. For example, a 5 MHz signal might be mixed with a 5,000,010 Hz signal. Measuring the 10 Hz beat frequency with a frequency counter (as opposed to the 5 MHz) allows the detection of smaller frequency changes, as shown in the graphic.



Frequency Multiplier

An electronic instrument or circuit that converts an incoming signal to a higher frequency by adding a fixed multiple of cycles or pulses to the signal. For example, a circuit that multiplies by 10 could accept a 1 MHz signal as an input, and produce a 10 MHz signal as an output.

Frequency Offset

The difference between a measured frequency and an ideal frequency with zero uncertainty. This ideal frequency is called the nominal frequency.

Frequency offset can be measured in either the frequency domain or the time domain. A simple frequency domain measurement involves directly counting and displaying the output frequency of the device under test with a frequency counter. The frequency offset is calculated as

$$f_{off} = \frac{f_{meas} - f_{nom}}{f_{nom}} \quad ,$$

where f_{meas} is the reading from the frequency counter, and f_{nom} is the specified output frequency of the device under test.

Frequency offset measurements in the time domain involve measuring the time difference between the device under test and the reference. The time interval measurements can be made with an oscilloscope or a time interval counter. If at least two time interval measurements are made, we can estimate frequency offset as

$$f_{off} = -\frac{\Delta t}{T},$$

where Δt is the difference between time interval measurements (phase difference), and T is the measurement period.

Frequency offset is usually expressed as a dimensionless number such as 1×10^{-10}, since the quantities being measured are typically very small. Using dimensionless values does not require knowledge of the nominal frequency. However, they can be converted to units of frequency (Hz) if the nominal frequency is known. To illustrate this, consider a device with a nominal frequency of 5 MHz and a frequency offset of $+1.16 \times 10^{-11}$. To find the frequency offset in hertz, multiply the nominal frequency by the offset:

$$(5 \text{ x } 10^{6})\ (+1.16 \text{ x } 10^{-11}) = 5.80 \text{ x } 10^{-5} = +0.0000580 \text{ Hz}$$

Then, add the frequency offset to the nominal frequency to get the actual frequency:

5,000,000 Hz + 0.0000580 Hz = 5,000,000.0000580 Hz

Frequency Shift

A sudden change in the frequency of a signal.

Frequency Stability

The degree to which an oscillating signal produces the same frequency for a specified interval of time. It is important to note the time interval; some devices have good short-term stability, others have good long-term stability. Stability doesn't tell us whether the frequency of a signal is right or wrong, it only indicates whether that frequency stays the same. The Allan deviation is the most common metric used to estimate frequency stability, but a number of similar statistics are also used.

Frequency Standard

An oscillator (usually an atomic oscillator) that is used as a reference source for frequency measurements. The frequency standard in a calibration laboratory is generally a cesium oscillator, a rubidium oscillator, or a GPS disciplined oscillator. The current frequency standard for the United States is a cesium fountain oscillator named NIST-F2.

Frequency Synthesizer

An electronic device or circuit that can produce a wide range of user selectable output frequencies. In order to produce a wide range of frequencies, frequency synthesizers typically contain several components, including frequency dividers, frequency multipliers, and phase locked loops.

G

Gigahertz (GHz)

A unit of frequency that represents one billion cycles per second (10^9 Hz).

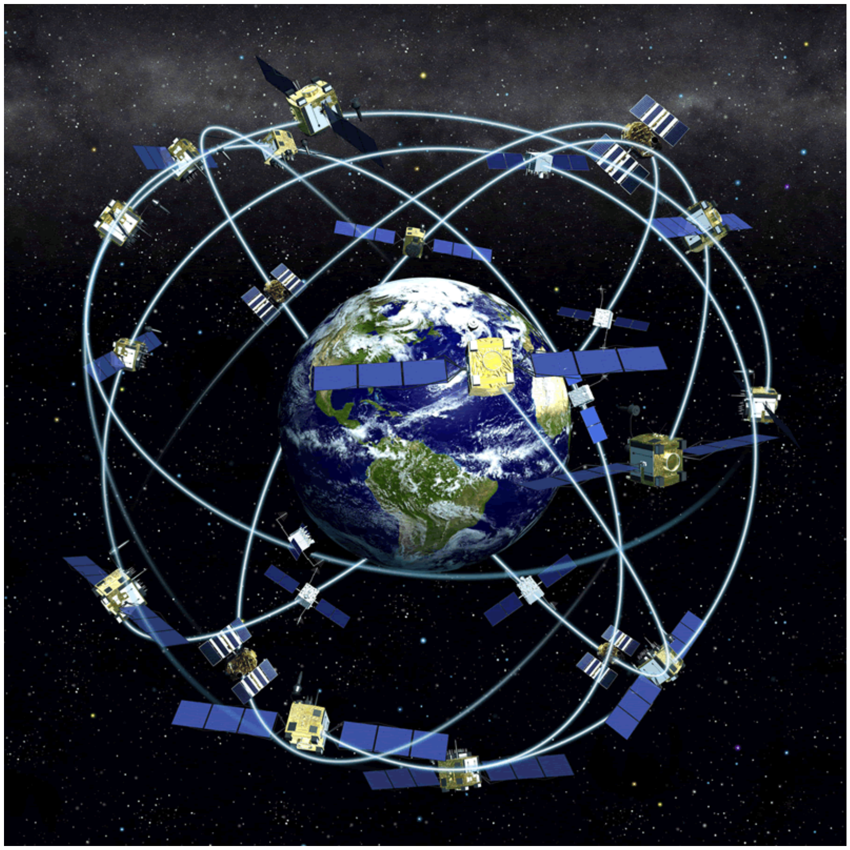
Global Navigation Satellite Systems (GNSS)

A satellite system that can be used to locate a user's receiver anywhere in the world. The Global Positioning System (GPS) was the first global navigation satellite system (GNSS), but has been followed by the three other systems listed in the table (note that BeiDou and Galileo are not fully operational as of 2016). In addition to being globally available systems for positioning and navigation, GNSS systems are widely used as references for time and frequency measurements. Some modern receivers can simultaneously receive signals from all four GNSS systems.

GNSS System	Controlling Region	Number of Satellites in Full Constellation
BeiDou	China	30
Galileo	European Union	30
GLONASS	Soviet Union	24
GPS	United States	32

Global Positioning System (GPS)

A constellation of satellites controlled and operated by the United States Department of Defense (USDOD). The constellation includes at least 24 satellites that orbit the Earth at a height of 20,200 km in six fixed planes inclined 55° from the equator. The orbital period is 11 h 58 m, which means that a satellite will orbit the earth twice per day. By processing signals received from the satellites, a GPS receiver can determine its own position with an uncertainty of less than 10 m.

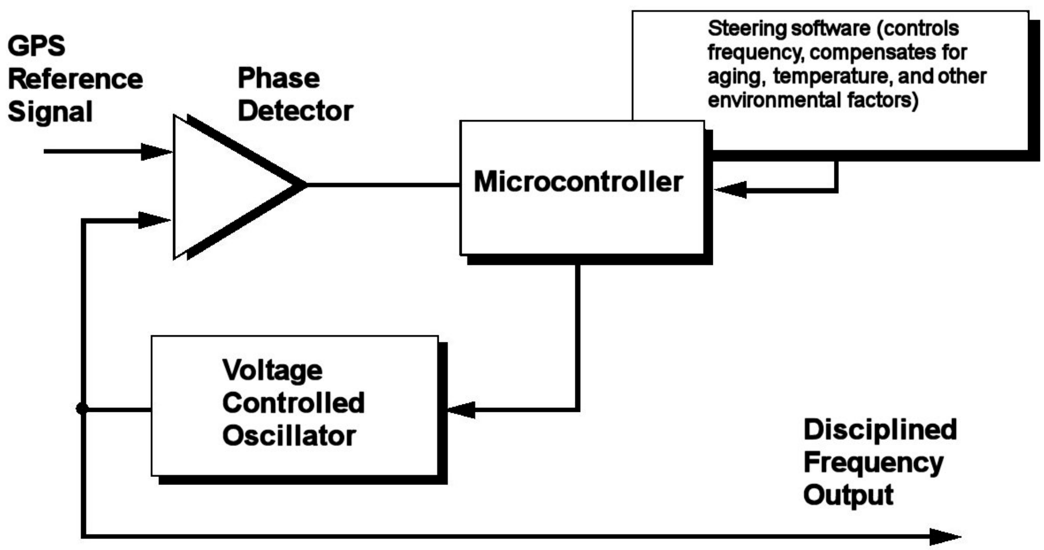


All GPS satellites broadcast on at least two carrier frequencies: L1, at 1575.42 MHz, and L2, at 1227.6 MHz (newer satellites also broadcast on L5 at 1176 MHz). Each satellite broadcasts a spread-spectrum waveform, called a pseudo-random noise (PRN) code on L1 and L2, and each satellite is identified by the PRN code it transmits. There are two types of PRN codes. The first type is a coarse acquisition (C/A) code with a chip rate of 1023 chips per millisecond. The second type is a precision (P) code with a chip rate of 10230 chips per millisecond. The C/A code is broadcast on L1, and the P code is broadcast on both L1 and L2. GPS reception is line-of-sight, which means that the antenna must have a clear view of the sky. The signals can be received nearly anywhere on Earth where a clear sky view is available.

The primary purpose of GPS is to serve as a radionavigation system, but it has also become the dominant system for the distribution of time and frequency signals. Each satellite carries a rubidium and/or cesium atomic clock that provides the reference for both the carrier and code broadcasts. The satellite clocks are continuously adjusted to agree with Coordinated Universal Time (UTC) as maintained by the United States Naval Observatory (USNO). There are several types of time and frequency measurements that involve GPS, including one-way, common-view, and carrier-phase measurements. GPS disciplined clocks and oscillators are commonly used as references for time and frequency measurements.

GPS Disciplined Oscillator (GPSDO)

A self-calibrating standard that is commonly used as a reference for frequency and time measurements. GPSDOs are sold commercially by a large number of manufacturers. The basic function of a GPSDO is to receive signals from the GPS satellites and to use the information contained in these signals to control the frequency of a local quartz or rubidium oscillator. A block diagram of one type of GPSDO is shown in the graphic.



GPS signals are kept in agreement with the Coordinated Universal Time scale maintained by the United States Naval Observatory, UTC(USNO). Nearly all GPSDOs use the coarse acquisition (C/A) code on the L1 carrier frequency (1575.42 MHz) as their incoming reference signal. The satellite signals can be trusted as a reference for two reasons: (1) they originate from atomic oscillators and (2) they must be accurate and stable to within parts in 10^{14} over a 12 hour averaging period in order for GPS to meet its specifications as a positioning and navigation system.

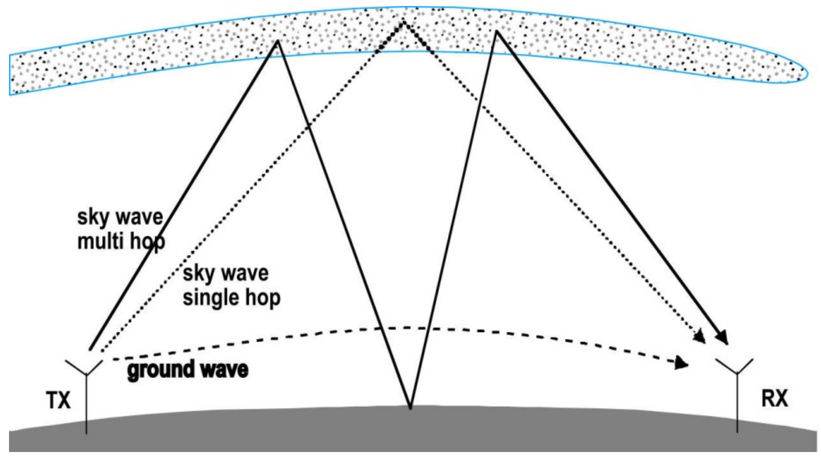
The best GPSDOs transfer as much of the inherent accuracy and stability of the satellite signals as possible to the signals generated by the local quartz or rubidium oscillator. Many modern GPSDOs have a frequency stability of 1×10^{-13} or less at $\tau = 1$ day. Time accuracy with respect to UTC is typically better than 100 nanoseconds if a delay constant is entered for the antenna cable.

Greenwich Mean Time (GMT)

A 24-hour time keeping system whose hours, minutes, and seconds represent the time-of-day at the Earth's prime meridian (0° longitude) located near Greenwich, England. Technically speaking, GMT no longer exists, since it was replaced by other astronomical time scales many years ago, and those astronomical times scales were subsequently replaced by the atomic time scale UTC. However, the term GMT is still incorrectly used by the general public. When heard today, it should be considered as a synonym for UTC.

Groundwave

A radio wave that propagates close to the surface of the Earth. Groundwave propagation is a characteristic of low frequency (LF) radio signals. Since the propagation or path delay of a groundwave signal remains relatively constant and much easier to predict, LF signals are better time and frequency references than high frequency (HF) signals, which are often dominated by skywave. The diagram shows groundwave and skywave propagation paths between a transmitter and receiver.



H

Hertz

The base unit of frequency, equivalent to one event, or one cycle per second. The abbreviation for hertz is Hz.

Heterodyne

A technique that generates new frequencies by mixing two or more signals together. For example, a superheterodyne radio receiver converts any selected incoming radio frequency by heterodyne action to a common intermediate frequency (such as the 455 kHz frequency used by many AM radios). The heterodyne technique is sometimes utilized to increase the resolution of time and frequency measurement systems, including the dual mixer time difference system, by converting the incoming signal from the device under test to a lower frequency.

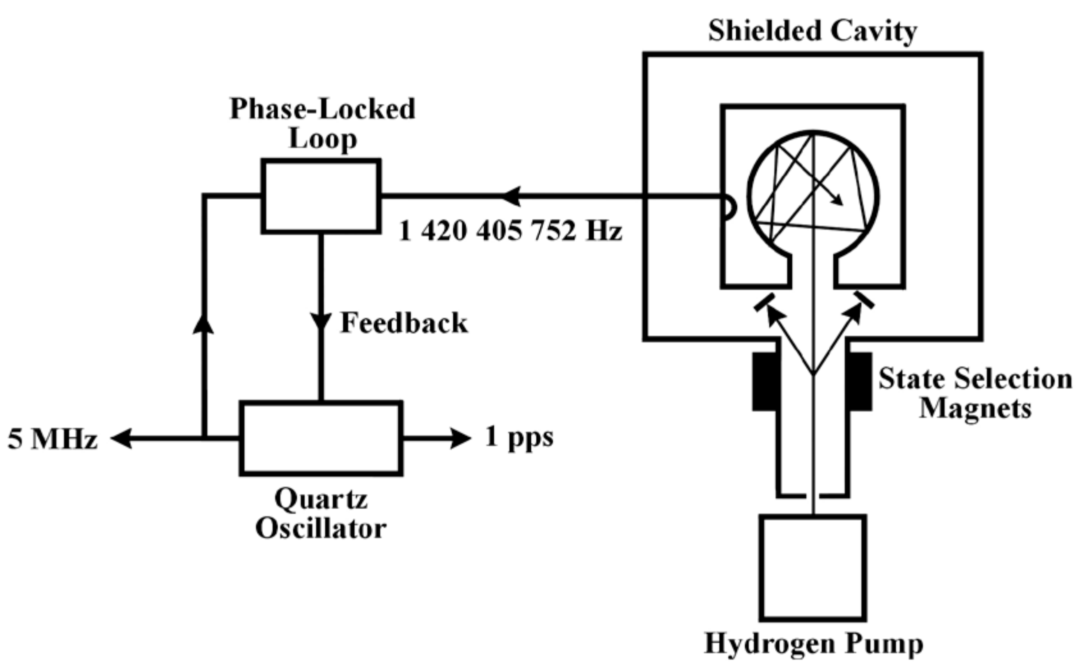
High Frequency (HF)

The area of the radio spectrum ranging from 3 to 30 MHz, commonly known as shortwave. The carrier frequencies of 5, 10, and 15 MHz within this spectrum are internationally allocated for time and frequency radio broadcasts, and are used by a number of stations, including NIST radio stations WWV and WWVH.

Hydrogen Maser

The hydrogen maser is the most elaborate and expensive commercially available frequency standard. The word maser is an acronym that stands for microwave amplification by stimulated emission of radiation. Masers operate at the resonance frequency of the hydrogen atom, which is 1,420,405,752 Hz.

A hydrogen maser works by sending hydrogen gas through a magnetic gate that only allows atoms in certain energy states to pass through. The atoms that make it through the gate enter a storage bulb surrounded by a tuned, resonant cavity. Once inside the bulb, some atoms drop to a lower energy level, releasing photons of microwave frequency. These photons stimulate other atoms to drop their energy level, and they in turn release additional photons. In this manner, a self-sustaining microwave field builds up in the bulb. The tuned cavity around the bulb helps to redirect photons back into the system to keep the oscillation going. The result is a microwave signal that is locked to the resonance frequency of the hydrogen atom and that is continually emitted as long as new atoms are fed into the system. This signal keeps a quartz oscillator in step with the resonance frequency of hydrogen, as shown in the figure.



The resonance frequency of hydrogen is much lower than that of cesium, but the resonance width of a hydrogen maser is usually just a few hertz. Therefore, the Q is about 10^9, or at least one order of magnitude better than that of a commercial cesium standard. As a result, the short-term stability is better than that of a cesium standard, typically less than 1×10^{-12} at $\tau = 1$ s, and reaching a noise floor of approximately 1×10^{-15} after about 1 day. However, when measured for more than a few days or weeks, a hydrogen maser might fall below a cesium oscillator's performance, due to changes in the cavity's resonance frequency over time.

I

International Atomic Time (TAI)

A time scale maintained internally by the BIPM, but seldom used by the general public. TAI realizes the SI second as closely as possible, and runs at the same frequency as Coordinated Universal Time (UTC). However, TAI differs from UTC by an integral number of seconds. This difference is related to leap seconds, and increases whenever a leap second occurs.

International Date Line

The line on the Earth, generally located at 180° longitude; that separates two consecutive calendar days. The date in the Eastern hemisphere, to the left of the line, is always one day ahead of the date in the Western hemisphere. The International Date Line passes through an area covered mainly by oceans, and therefore most of the line is located exactly halfway around the world from the prime meridian (0° longitude) that passes near Greenwich, England. However, there are a few zigs and zags in the date line to allow for local circumstances.

Internet Time Service (ITS)

A popular NIST service that allows client computers to synchronize their clock via the Internet to UTC(NIST). The service responds to time requests from any Internet client by sending time codes in the Daytime, Time, and NTP protocols. The ITS handles billions of timing requests every day.

Intrinsic Standard

A standard (such as a frequency standard) based on an inherent physical constant or an inherent or sufficiently stable physical property. Technically, all atomic oscillators are intrinsic standards. In practice, however, only cesium oscillators are considered as intrinsic time and frequency standards, because the SI definition of the second is currently based on a physical property of cesium.

Ion Trap

A device that allows ions to be trapped for long periods of time, during which the ions can be interrogated and their state changes observed. Since the ions are nearly motionless during the observation period, an ion trap can provide the basis for highly stable and accurate optical frequency standards that should eventually replace today's frequency standards.

Ionosphere

A region of the Earth's upper atmosphere that ranges from about 60 km to 1000 km in altitude, and that is divided into a number of defined layers (including the D, E, and F layers).

Ionospheric corrections are commonly applied when using radio signals for time transfer. For example, when using terrestrial signals such as WWV, it is necessary to know the height of the ionosphere and the number of times that a signal was reflected off the ionosphere, to estimate the propagation delay. These corrections can be large, many microseconds or even milliseconds in extreme cases. When using satellite signals, such as GPS, the signals are transmitted from above the ionosphere. Therefore, the ionospheric corrections are small (tens of nanoseconds or less) and are applied to compensate for the delay added to a signal as it passes through the ionosphere on its way to the Earth's surface.

IRIG Time Codes

The time codes originally developed by the Inter-Range Instrumentation Group (IRIG) for military use that are now utilized by both the public and private sectors, in addition to the military. There are many IRIG formats and several modulation schemes, but they are typically amplitude modulated on an audio sine wave carrier. The most common format is probably IRIG-B, which sends day of year, hour, minute, and second data on a 1 kHz carrier frequency, with an update rate of once per second.

J

Jitter

The abrupt and unwanted variations of one or more signal characteristics, such as the interval between successive pulses, the amplitude of successive cycles, or the frequency or phase of successive cycles. Although widely used in fields such as telecommunications, the term jitter is seldom used in time and frequency metrology, since terms such as phase noise are more descriptive.

Julian Day or Julian Date (JD)

An integer day number obtained by counting days from the starting point of noon on 1 January 4713 B.C. (Julian Day zero). One way of telling what day it is with the least possible ambiguity. The Modified Julian Date (MJD) has a starting point of midnight on November 17, 1858. You can obtain the MJD by subtracting exactly 2 400 000.5 days from the JD.

K

Kilohertz (kHz)

A unit of frequency that represents one thousand cycles per second (10^3 Hz).

L

Laser Cooling

A technique that uses laser beams to slow down the motion of atoms and cool them to temperatures a few millionths of a degree above absolute zero. This technique is used to improve the performance of cesium fountain clocks and other standards, since it increases the interrogation and observation time of the atoms.

Leap Day

The extra day added to a year to make it have 366 days. Leap days are added on February 29th during leap years.

Leap Second

A second added to Coordinated Universal Time (UTC) to make it agree with astronomical time to within 0.9 second. UTC is an atomic time scale, based on the performance of atomic clocks. Astronomical time is based on the rotational rate of the Earth. Since atomic clocks are more stable than the rate at which the Earth rotates, leap seconds are needed to keep the two time scales in agreement.

The first leap second was added on June 30, 1972. Since then, leap seconds have occurred at an average rate of less than one per year. Leap seconds are announced at least several months in advance and are implemented on either June 30th or December 31st. Although it is possible to have a negative leap second (a second removed from UTC), so far all leap seconds have been positive (a second has been added to UTC). Based on what we know about the Earth's rotation, it is unlikely that we will ever have a negative leap second.

Leap Year

Leap years are years with 366 days, instead of the usual 365. Leap years are necessary because the actual length of a year is about 365.242 days, not 365 days, as commonly stated. Basically, leap years occur every 4 years, and years that are evenly divisible by 4 (2004, for example) have 366 days. This extra day is added to the calendar on February 29th.

However, there is one exception to the leap year rule involving century years, such as the year 1900. Since the year is slightly less than 365.25 days long, adding an extra day every 4 years results in about 3 extra days being added over a period of 400 years. For this reason, only 1 out of every 4 century years is considered as a leap year. Century years are considered as leap years only if they are evenly divisible by 400. Therefore, 1700, 1800, 1900 were not leap years, and 2100 will not be a leap year. However, 1600 and 2000 were leap years, because those year numbers are evenly divisible by 400.

Line Width

Another name for resonance width. The term line width is generally used to refer to the resonance width of an atomic oscillator.

Long-Term Stability

The stability of a time or frequency signal over a long measurement interval, usually of at least 100 seconds. In most cases, long-term stability is used to refer to measurement intervals of more than one day.

LORAN-C

A ground based radionavigation system that operates in the LF radio spectrum at a carrier frequency of 100 kHz, with a bandwidth from 90 to 110 kHz. LORAN-C broadcasts are referenced to cesium oscillators and are used as a standard for time and frequency calibrations. LORAN-C stations are operated in several regions of the northern hemisphere outside of the United States. However, in accordance with the Department of Homeland Security (DHS) Appropriations Act, the U.S. Coast Guard terminated the transmission of all United States LORAN-C signals on February 8, 2010.

Low Frequency (LF)

The part of the radio spectrum ranging from 30 to 300 kHz. A number of standard time and frequency signals are broadcast in this region, including the 60 kHz signal from NIST Radio Station WWVB. These signals are most commonly used as time-of-day references for radio controlled clocks.

M

Maser

An acronym that stands for Microwave Amplification by Stimulated Emission of Radiation. In the field of time and frequency, the term is generally associated with the hydrogen maser.

Maximum Time Interval Error (MTIE)

A metric used to estimate the largest peak-to-peak variation in a digital signal. MTIE can help detect sudden frequency or phase changes that cause data loss on a communications channel.

Megahertz (MHz)

A unit of frequency that represents one million cycles per second (10^6 Hz).

MCXO

An acronym for Microcomputer-Compensated Crystal Oscillator. An MCXO is a quartz oscillator that uses digital techniques to observe the frequency drift, and compensates for this drift through digital-to-analog conversion to a tuning port in the circuit. The stability of a MCXO is generally better than that of a TCXO, but worse than that of an OCXO.

Mean Solar Time

An astronomical time scale that is based on the average length of the day, called the mean solar day. The length of an average day is different from a true or apparent solar day, due to daily variations, over the span of a year, in the Sun's apparent angular speed across the sky when viewed by an observer on Earth. For example, in a true apparent solar time scale, noon is the instant when the Sun transits the local meridian and reaches its highest point in the sky. However, the Sun is at this point at a different time each day, varying over the course of a year from 14.2 minutes ahead of noon to 16.3 minutes behind it. Thus, the length of an average or mean solar day is used for a more uniform system of timekeeping.

Microsecond (µs)

A unit of time that represents one millionth of a second (10^{-6} s).

Millisecond (ms)

A unit of time that represents one thousandth of a second (10^{-3} s).

Modified Allan Deviation (MDEV)

A modified version of the Allan deviation statistic. Like the “normal” Allan deviation it is used to estimate frequency stability, but has the advantage of being able to distinguish between white and flicker phase noise. This makes it more suitable for estimating short-term stability than the normal Allan Deviation.

N

Nanosecond (ns)

A unit of time that represents one billionth of a second (10^{-9} s).

Network Time Protocol (NTP)

A standard protocol used to send a time code over packet-switched networks, such as the public Internet. The Network Time Protocol (NTP) was created at the University of Delaware, and is defined by the RFC-1305 document. The NTP packet includes three 64-bit time stamps and contains the time in UTC seconds since January 1, 1900 with a resolution of 233 picoseconds. The NTP format is supported by the NIST Internet Time Service.

Nominal Frequency

An ideal frequency with zero uncertainty. The nominal frequency is the frequency labeled on an oscillator's output. For this reason, it is sometimes called the nameplate frequency. For example, an oscillator whose nameplate or label reads 5 MHz has a nominal frequency of 5 MHz. The difference between the nominal frequency and the actual output frequency of the oscillator is the frequency offset.

O

Octave

The interval between two frequencies having a ratio of 2 to 1. Starting from a fundamental frequency, one octave higher is twice that frequency; one octave lower is half that frequency. The concept of an octave is most widely known and most easily illustrated with musical notes. For example, a piano keyboard has a range of over seven octaves from the lowest frequency to the highest frequency note. There are eight keys on a piano that play the musical note A. Each musical note A has a frequency twice as high as the note in the previous octave, as shown in the table.

Musical Note	Frequency (Hz)
A0	27.5
A1	55
A2	110
A3	220
A4	440
A5	880
A6	1760
A7	3520

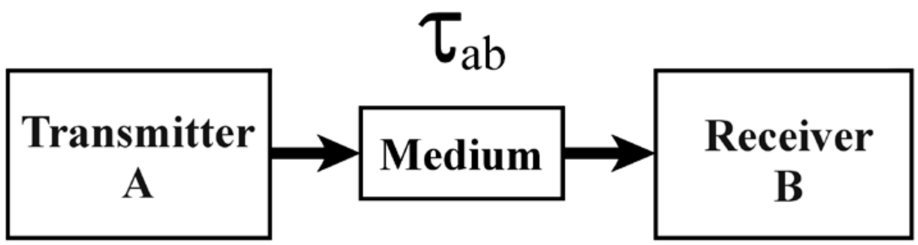
OCXO

An acronymn for Oven Controlled Crystal Oscillator. A type of quartz oscillator design that reduces environmental problems by enclosing the crystal in a temperature-controlled chamber called an oven. When an OCXO is turned on, it goes through a "warm-up" period while the temperatures of the crystal resonator and its oven stabilize. During this time, the performance of the oscillator continuously changes until it reaches its normal operating temperature. The temperature within the oven then remains constant, even when the outside temperature varies.

Because the environment is carefully controlled, OCXOs have excellent short-term stability. A typical OCXO might be stable to 1×10^{-12} at $\tau = 1$ s. The limitations in short-term stability are mainly due to noise from electronic components in the oscillator circuits. Long term stability is mainly limited by aging.

One Way Time and Frequency Transfer

A measurement technique used to transfer time and frequency information from one location to another. As shown in the figure, the reference transmitter, A, simply sends a time signal to the receiver, B, through a transmission medium.



The delay, τ_{ab}, over a transmission path is at least 3.3 microseconds per kilometer. If high accuracy time transfer is desired in a one-way system the physical locations (coordinates) of the two clocks must be known so that the path delay can be calculated. For frequency transfer, only the variability of the delay (the path stability) is important.

On Time Marker (OTM)

The part of a time code that is synchronized (at the time of transmission) to the UTC second.

Optical Frequency Standard

A frequency standard based on the optical transitions in ions and neutral atoms. Optical standards operate at much higher resonance frequencies than microwave standards based on cesium; the stabilized lasers that serve as their resonators typically operate at a frequency near 10^{15} Hz, as opposed to less than 10^{10} Hz for cesium. As a result, these standards potentially have accuracies and stabilities that are several orders of magnitude better than the best microwave standards. Optical frequency standards have been constructed at NIST utilizing single-ion techniques based on mercury ($^{199}Hg+$) and aluminum ($^{27}Al+$), as well as neutral atom techniques based on calcium (^{40}Ca), ytterbium (^{174}Yb), and strontium (^{87}Sr). The work on optical frequency standards has been exceptionally promising with the best devices demonstrating uncertainties in the low parts in 10^{18}. Thus, it now appears almost certain that the SI second will eventually be redefined based on one of these optical atomic transitions.

Oscillator

An electronic device used to generate an oscillating signal. The oscillation is based on a periodic event that repeats at a constant rate. The device that controls this event is called a resonator. The resonator needs an energy source so it can sustain oscillation. Taken together, the energy source and resonator form an oscillator. Although many simple types of oscillators (both mechanical and electronic) exist, the two types of oscillators primary used for time and frequency measurements are quartz oscillators and atomic oscillators.

Overtone Frequency

A multiple of the fundamental resonance frequency of a quartz oscillator that is used as the oscillator's output frequency. Most high stability quartz oscillators output either the third or fifth overtone frequency to achieve a high Q. Overtones higher than fifth are rarely used because they make it harder to tune the device to the desired frequency.

P

Passive Frequency Standard

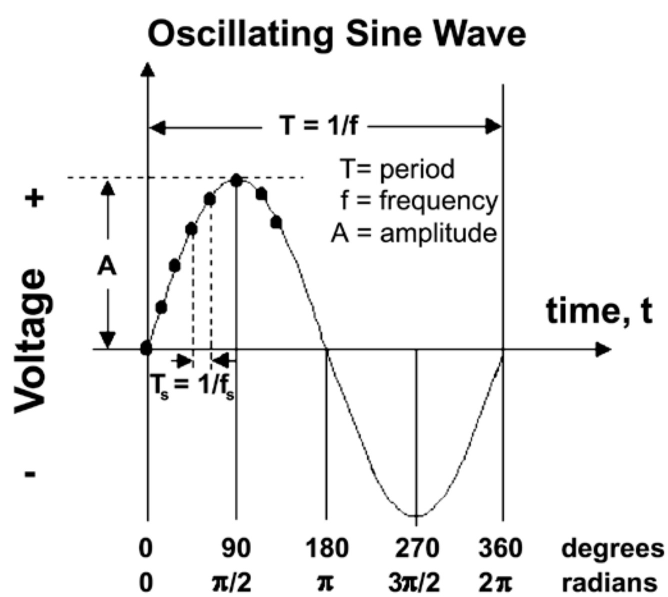
An atomic oscillator whose output signal is derived from an oscillator frequency locked to the atomic resonance frequency, instead of being directly output by the atoms. Unlike active frequency standards, the cavity where the atomic transitions take place does not sustain self-oscillation. Most commercially available atomic oscillators are passive frequency standards.

Path Delay

The signal delay between a transmitter and a receiver. Path delay is often the largest contributor to time transfer uncertainty. For example, consider a radio signal broadcast over a 1000 km path. Since radio signals travel at the speed of light (with a delay of about 3.3 μs/km), we can calibrate the 1000 km path by estimating the path delay as 3.3 ms, and applying a 3.3 ms correction to our measurement. Sophisticated time transfer systems, such as GPS, automatically correct for path delay. The absolute path delay is not important to frequency transfer systems because on-time pulses are not required, but variations in path delay still limit the frequency uncertainty.

Period

The period T is the reciprocal of a frequency, $T = 1 / f$. The period of a waveform is the time required for one complete cycle of the wave to occur. The relationship between period, frequency, and amplitude for a sine wave is illustrated in the graphic.



Phase

The position of a point in time (instant) on a waveform cycle. A complete cycle is defined as the interval required for the waveform to reattain its arbitrary initial value. The graphic in the entry for "Period" shows how 1 cycle constitutes 360° of phase. The graphic also shows how phase is sometimes expressed in radians, where one radian of phase equals approximately 57.3°. Phase can also be an expression of relative displacement between two corresponding features (for example, peaks or zero crossings) of two waveforms having the same frequency.

When comparing two waveforms, their phase difference or phase angle, is typically expressed in degrees as a number greater than -180°, and less than or equal to +180°. Leading phase refers to a wave that occurs "ahead" of another wave of the same frequency. Lagging phase refers to a wave that occurs "behind" another wave of the same frequency. When two waves differ in phase by -90° or +90°, they are said to be in phase quadrature. When two waves differ in phase by 180° (-180° is technically the same as +180°), they are said to be in phase opposition.

In time and frequency metrology, the phase difference is usually stated in units of time, rather than in units of phase angle. The time interval for 1° of phase is inversely proportional to the frequency. If the frequency of a signal is given by f, then the time t_{deg} (in seconds) corresponding to 1° of phase is

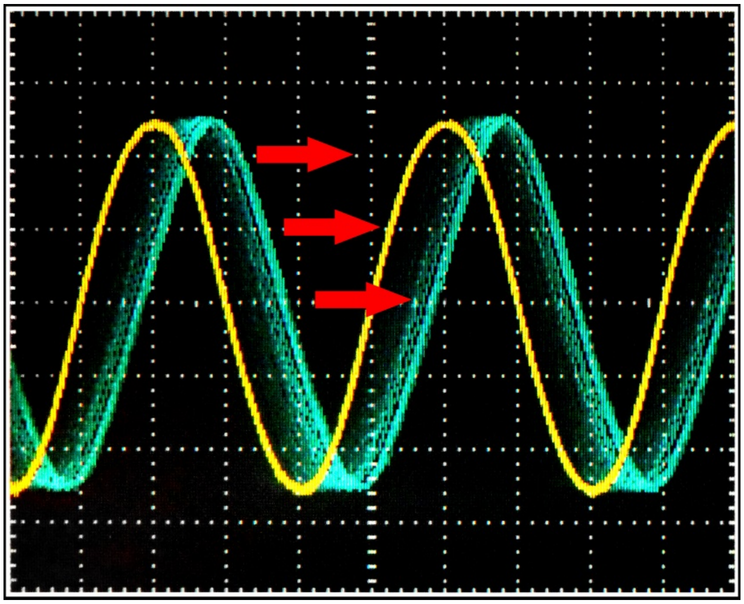
$$t_{\mathrm{deg}} = 1 / (360f) = T / 360 \ .$$

Therefore, a 1° phase shift on a 5 MHz signal corresponds to a time shift of 555 picoseconds. This same answer can be obtained by taking the period of 5 MHz (200 nanoseconds) and dividing by 360.

Phase Comparison

A comparison of the phase of two waveforms, usually of the same nominal frequency. In time and frequency metrology, the purpose of a phase comparison is generally to determine the frequency offset of a device under test (DUT) with respect to a reference.

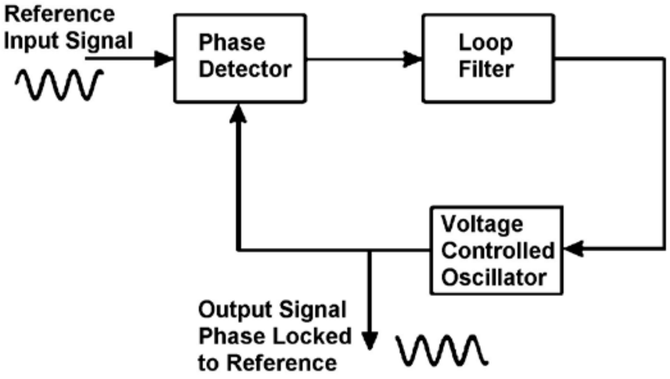
A simple phase comparison can be made by connecting two signals to a two-channel oscilloscope. The oscilloscope will display two sine waves as shown in the graphic. One sine wave is the test frequency, and the other represents a signal from the reference.



If the two frequencies were exactly the same, their phase relationship would not change and both would appear to be stationary on the oscilloscope display. Since the two frequencies are not exactly the same, the reference appears to be stationary and the test signal moves. By measuring the rate of motion of the test signal we can determine its frequency offset. More sophisticated phase comparisons with much smaller uncertainties can be made with instruments such as time interval counters or dual mixer time difference systems.

Phase Locked Loop (PLL)

An electronic circuit that is constantly adjusted to match in phase (and thus lock on) the frequency of an input signal. A typical PLL is shown in the diagram. It consists of a voltage-controlled oscillator (VCO) that is tuned using the output of a phase detector. If the VCO frequency departs from the reference frequency, the phase detector produces an error voltage that brings the VCO frequency back into agreement with the reference frequency, keeping it "locked".



Phase Noise

The rapid, short-term, random fluctuations in the phase of a wave. To a large extent, phase noise can be removed by averaging. The unit used to describe phase noise is dBc/Hz (dB below the carrier per Hz of bandwidth). Reports of phase noise measurement results should include both the bandwidth and the carrier frequency.

Phase Shift

A change in phase of a periodic signal with respect to a reference. A sudden change in phase is often referred to as a phase step.

Picosecond (ps)

A unit of time that represents one trillionth of a second (10^{-12} s).

Precision

The term precision can be ambiguous, because it has several meanings in time and frequency metrology. Due to its ambiguity, it is not often used in a quantitative sense. Normally, it refers to the degree of mutual agreement among a series of individual measurements, values, or results. In this case, precision is analogous to standard deviation. Precision might also be used to refer to the ability of a device to produce, repeatedly and without adjustments, the same value or result, given the same input conditions and operating in the same environment. This use of precision makes it analogous to repeatability, reproducibility, or even stability. In other instances, precision is used as a measure of a computer's ability to distinguish between nearly equal values. For example, a compiler or spreadsheet might have 32-bit precision when doing calculations with floating point numbers. In this case, precision is analogous to resolution.

Precision Time Protocol (PTP)

A standard protocol defined by the IEEE-1588 standard for sending time over packet-switched networks. The Precision Time Protocol (PTP) can potentially obtain much lower uncertainties than the Network Time Protocol (NTP), often less than 1 μs. However, unlike NTP, PTP is generally not implemented over the public Internet. Instead, it is typically utilized over private or local area networks where path delays can be better measured and estimated. The grandmaster clock is the time reference for all other clocks in a PTP system. The other clocks are designated as ordinary clocks, which have a single PTP port, and boundary clocks, which have multiple network connections and can bridge synchronization from one network segment to another.

Primary Standard

A standard that is designated or widely acknowledged as having the highest metrological qualities and whose value is accepted without reference to other standards of the same quantity. For example, cesium fountain standards are currently recognized as primary standards for time interval and frequency. These standards are evaluated by establishing maximum levels for the frequency shifts caused by environmental factors. By summing or combining the effects of these frequency shifts, it is possible to estimate the uncertainty of a primary standard without comparing it to other standards.

In the time and frequency field, the term primary standard is sometimes used to refer to any cesium oscillator, since the SI definition of the second is based on the physical properties of the cesium atom. The term primary standard is also commonly used, at least in a local sense, to refer to the best standard available at a given laboratory or facility.

Q

Quality Factor, Q

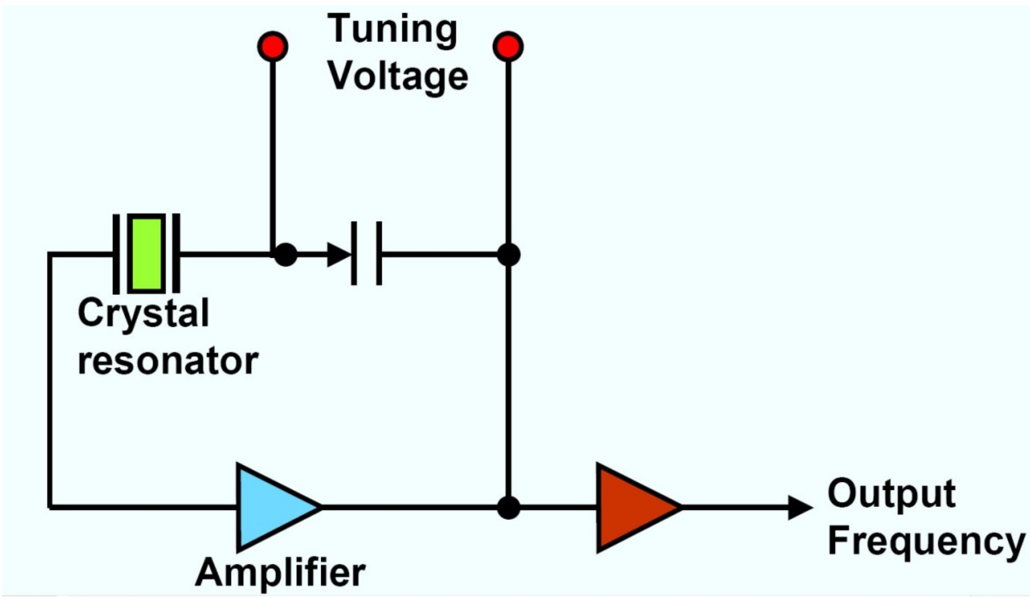
An inherent characteristic of an oscillator that influences its stability. The quality factor, Q, of an oscillator is defined as its resonance frequency divided by its resonance width. Obviously a high resonance frequency and a narrow resonance width are both advantages when seeking a high Q. Generally speaking, the higher the Q, the more stable the oscillator, since a high Q means that an oscillator will stay close to its natural resonance frequency. The table shows some approximate Q values for several different types of oscillators.

Oscillator Type	Quality Factor, Q
Tuning Fork	10^3
Quartz Wristwatch	10^4
OCXO	10^6
Rubidium	10^7
Cesium Beam	10^8
Hydrogen Maser	10^9
Cesium Fountain	10^{10}
Mercury Ion Optical Standard	10^{14}

Quartz Oscillator

The most common source of time and frequency signals. Billions of quartz oscillators are manufactured annually. Most are small devices built for wristwatches, clocks, and electronic circuits. However, quartz oscillators are also found inside test and measurement equipment, such as counters, signal generators, and oscilloscopes; and interestingly enough, inside every atomic oscillator.

A quartz crystal inside the oscillator is the resonator. It could be made of either natural or synthetic quartz, but all modern devices use synthetic quartz. The crystal strains (expands or contracts) when an electrical voltage is applied. When the voltage is reversed, the strain is reversed. This is known as the piezoelectric effect. Oscillation is sustained by taking a voltage signal from the resonator, amplifying it, and feeding it back to the resonator as shown in the diagram.



The rate of expansion and contraction is the resonance frequency, and is determined by the cut and size of the crystal. The output frequency of a quartz oscillator is either the fundamental resonance or a multiple of the resonance, called an overtone frequency. A typical Q for a quartz oscillator ranges from 10^4 to 10^6. The maximum Q for a high stability quartz oscillator can be estimated as $Q = 1.6 \times 10^7 / f$, where f is the resonance frequency in megahertz.

Environmental changes of temperature, humidity, pressure, and vibration can change the resonance frequency of a quartz crystal, but there are several designs that reduce these environmental effects. These include the TCXO, MCXO, and OCXO. These designs (particularly the OCXO) often produce devices with excellent short-term stability. The limitations in short-term stability are due mainly to noise from electronic components in the oscillator circuits. Long term stability is limited by aging. Due to aging and environmental factors such as temperature and vibration, it is hard to keep even the best quartz oscillators within 1×10^{-10} of their nominal frequency without constant adjustment. For this reason, atomic oscillators are used for applications that require better long-term stability and accuracy.

R

Radio Controlled Clock

A clock that automatically synchronizes to a signal received by radio. In the United States, the term is most commonly applied to clocks that receive a 60 kHz signal from NIST radio station WWVB. However, many different devices can now be considered radio controlled clocks, including smartphones, which typically receive time from GPS that is rebroadcast by the service provider.

Random Walk

A type of oscillator noise caused by environmental factors such as mechanical shock, vibration and temperature fluctuations which cause random shifts in frequency. As a general rule, random walk noise cannot be removed by averaging.

Ramsey Cavity

The microwave cavity typically found inside atomic frequency standards where the atoms are subjected to radiation near their resonance frequency. The cavity is part of an electronic circuit tuned to match the atomic resonance frequency as closely as possible. Named after Norman Ramsey, who was awarded the Nobel Prize in physics in 1989.

Reproducibility

The ability of a device or measurement to produce, repeatedly and without adjustments, the same value or result, given the same input conditions and operating in the same environment.

Resolution

The degree to which a measurement can be determined. For example, if a time interval counter has a resolution of 10 ns, it can produce a reading of 3340 ns or 3350 ns, but not a reading of 3345 ns. This is because 10 ns is the smallest significant difference that the instrument can measure. Any finer measurement would require more resolution. The specification for an instrument usually lists the resolution of a single measurement, sometimes called the single shot resolution. It is often possible to improve upon the single shot resolution by averaging, but resolution can limit the uncertainty of a measurement.

Resonance Frequency

The natural frequency of an oscillator. The resonance frequency is usually either divided or multiplied to produce the output frequency of the oscillator. The table below shows the resonance frequency for several types of oscillators. A high resonance frequency leads to a higher Q, and generally improves the stability.

Oscillator Type	Resonance Frequency (Hz)
Pendulum	**1**
Quartz Wristwatch	**32 768**
Hydrogen Maser[1]	**1 420 405 751.768**
Rubidium[2]	**6 834 682 610.904**
Cesium[3]	**9 192 631 770**

[1]See Hellwig, Vessot, Levine, Zitzewitz, Allan, and Glaze, *IEEE T. Instrum. Meas.*, IM-19(4), November 1970.

[2]The number for rubidium resonance (rounded to the millihertz) was obtained through measurements comparing a cesium fountain to a rubidium fountain, and has been recommended by the BIPM as a secondary representation of the SI second. See Mandache, Vian, Rosenbusch, Marion, Laurent, Santarelli, Bize, Clairon, Luiten, Tobar, and Salomon, *Proc. 2005 IEEE Intl. Freq. Cont. Symp.*, August 2005. Note that commercial rubidium standards can operate at resonance frequencies that differ from this value by a few hertz.

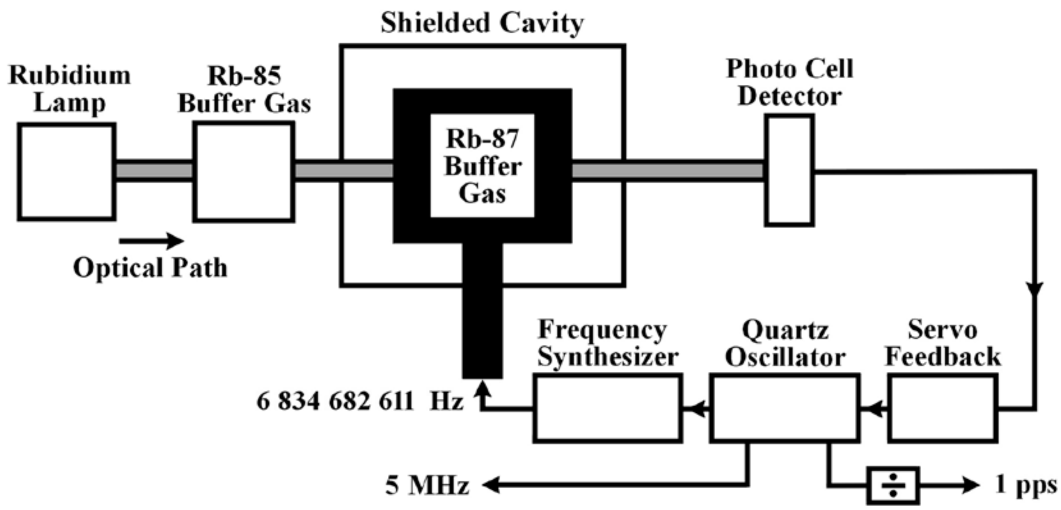
[3]The number for cesium resonance was first published in 1958 (Markowitz, Essen, Hall, and Parry, *Phys. Rev. Lett.*, 1(3), 1958) and has been used since 1967 by the International System (SI) to define the second, the base unit of time interval.

Resonance Width

The range of possible frequencies where a resonator can oscillate. Narrowing the resonance width of an oscillator leads to a higher Q, and generally improves the stability. For example, a resonator with a line width of 1 Hz will resonate only if it is within 1 Hz of the correct frequency.

Rubidium Oscillator

The lowest priced members of the atomic oscillator family, rubidium oscillators operate near 6.83 GHz, the resonance frequency of the rubidium atom (^{87}Rb), and use the rubidium frequency to control the frequency of a quartz oscillator. The optical beam from the rubidium lamp pumps the ^{87}Rb buffer gas atoms into a particular energy state. Microwaves from the frequency synthesizer induce transitions to a different energy state. This increase the absorption of the optical beam by the ^{87}Rb buffer gas. A photo cell detector measures how much of the beam is absorbed and its output is used to tune a quartz oscillator to a frequency that maximizes the amount of light absorption. The quartz oscillator is then locked to the resonance frequency of rubidium, and standard frequencies are derived from the quartz oscillator and provided as outputs as shown in the diagram.



Rubidium oscillators continue to become smaller and less expensive, and offer perhaps the best price to performance ratio of any oscillator. Their long-term stability is much better than that of a quartz oscillator and they are also smaller, more reliable, and less expensive than cesium oscillators.

The Q of a rubidium oscillator is about 10^7. Undesirable shifts in the resonance frequency are due mainly to collisions of the rubidium atoms with other gas molecules and aging effects in the lamp system. These shifts limit the long-term stability. Stability at 1 second is typically 1×10^{-11} and can be as small as 1×10^{-12} at one day. The frequency offset of a rubidium oscillator ranges from 5×10^{-10} to 5×10^{-12} after a warm-up period of a few minutes or hours, so they meet the accuracy requirements of most applications without adjustment.

S

Second

The duration of 9,192,631,770 periods of the radiation corresponding to the transition between two hyperfine levels of the ground state of the cesium-133 atom. The definition was added to the International System (SI) of units in 1967.

Short-Term Stability

The stability of a time or frequency signal over a short measurement interval, usually an interval of 100 seconds or less in duration.

Sidereal Time

An astronomical time scale that is based on the Earth's rate of rotation measured relative to the fixed stars. Thus a sidereal day is the time interval during which the Earth completes one rotation on its axis and some chosen star appears to transit twice consecutively on the observer's local meridian.

Because the Earth moves in its orbit about the Sun, a mean solar day is about four minutes longer than a sidereal day. Thus, a given star appears to rise four minutes earlier each night, relative to solar time, and different stars are visible at different times of the year.

Skywave

A radio wave that bounces off the ionosphere and returns back to Earth. Skywave propagation is a characteristic of HF radio signals, such as those transmitted by WWV. Since the path delay of a skywave signal is constantly changing and is difficult to model or predict, skywaves are not as suitable for time and frequency measurements as groundwave or satellite signals (see the graphic under “Groundwave”).

Solar Day

The day defined as one revolution of the Earth on its axis with respect to the Sun. Since the Earth's rotational period (one day) rate is much more variable than its period of revolution about the Sun (one year), the mean solar day is more useful for timekeeping, since it averages the length of the day over the course of a year.

Solar Time

An astronomical time scale that is based on the Earth's rate of rotation, measured with respect to either the "ficticious" mean Sun, or of the "true" apparent Sun. In the apparent solar time scale, noon is the instant when the Sun transits, i.e., crosses the local meridian and reaches its highest point in the sky, called Local Apparent Noon (LAN). Over the course of the year, the Sun has considerably different daily high points, lowest in the winter and highest in the summer, due to the tilt in the Earth's axis of about 23.44º. The daily variation, over the course of a year, in the Sun's apparent angular speed across the sky causes LAN to occur at a slightly different time each day. The variance in the apparent angular speed is due to a daily change in the Earth's distance from the Sun. In the late fall and early winter months, when the Earth is closer to the Sun (near or at perihelion), the Sun appears to travel faster (a greater angle per unit of time), than during the late spring and early summer months, when the Sun is farther away (near or at aphelion).

The difference between apparent and mean solar time is known as the "equation of time" and is a measure of the apparent Sun preceding or following the mean Sun by an interval than can be as much as 16 minutes. Therefore, mean solar time (based on the length of an average day) is more useful for uniform timekeeping than apparent solar time. In addition, since the Earth is much closer to the Sun than to other stars, one complete rotation of the Earth relative to the Sun (mean solar day) requires about four more minutes than one sideral day.

Stability

An inherent characteristic of an oscillator that determines how well it can produce the same frequency over a given time interval. Stability doesn't indicate whether the frequency is right or wrong, but only whether it stays the same. The stability of an oscillator doesn't necessarily change when the frequency offset changes. You can adjust an oscillator and move its frequency either further away from or closer to its nominal frequency without changing its stability at all (see the graphic under "Accuracy").

The stability of an oscillator is usually specified by a statistic such as the Allan deviation that estimates the frequency fluctuations of the device over a given time interval. Some devices, such as an OCXO, have good short-term stability and poor long-term stability. Other devices, such as a GPS disciplined oscillator (GPSDO), typically have poor short-term stability and good long-term stability. Specification sheets for quartz oscillators seldom quote stability numbers for intervals longer than 100 seconds. Conversely, a specification sheet for an atomic oscillator or a GPSDO might quote stability estimates for intervals ranging from one second to more than one day.

Standard

A device or signal used as the comparison reference for a measurement. A standard is used to measure or calibrate other devices. NIST is responsible for developing, maintaining and disseminating national standards for the United States for the basic measurement quantities (such as time interval), and for many derived measurement quantities (such as frequency).

Stop Watch

A device (usually a handheld device) used to measure time interval. Most stop watches are manually operated, a button is pushed to start and stop the measurement. The measurement is made using a quartz or mechanical time base. Stop watches are used for simple time interval measurements and calibrations. Their resolution is very coarse compared to a time interval counter, with 10 millisecond resolution being typical.

Stratum Clock

A clock in a telecommunications system or network that is assigned a number that indicates its quality and position in the timing hierarchy. The highest quality clocks, called stratum 1 clocks, have a frequency offset of 1×10^{-11} or less, which means that they can keep time to within about one microsecond per day. Only stratum 1 clocks may operate independently; other clocks are synchronized directly or indirectly to a stratum 1 clock.

Synchronization

The process of setting two or more clocks to the same time.

Syntonization

The process of setting two or more oscillators to the same frequency.

T

TCXO

A temperature-compensated crystal oscillator. A TCXO is a type of quartz oscillator that compensates for temperature changes to improve stability. In a TCXO, the signal from a temperature sensor is used to generate a correction voltage that is applied to a voltage-variable reactance, or varactor. The varactor then produces a frequency change equal and opposite to the frequency change produced by temperature. This technique does not work as well as the oven control used by an OCXO, but is less expensive. Therefore, TCXOs are used when high stability over a wide temperature range is not required.

Terahertz (THz)

A unit of frequency that represents one trillion cycles per second (10^{12} Hz).

Terrestrial Time (TT)

An astromonical time scale which equals TAI + 32.184 s. The uncertainty of TT is ±10 microseconds. It replaced the now obsolete Ephemeris Time scale in 1984.

Test Uncertainty Ratio (TUR)

A measurement or calibration compares a device under test (DUT) to a standard or reference. The standard should outperform the DUT by a specified ratio, called the Test Uncertainty Ratio (TUR). Ideally, the TUR should be 10:1 or higher. The higher the ratio, the less averaging is required to get valid measurement results.

Time

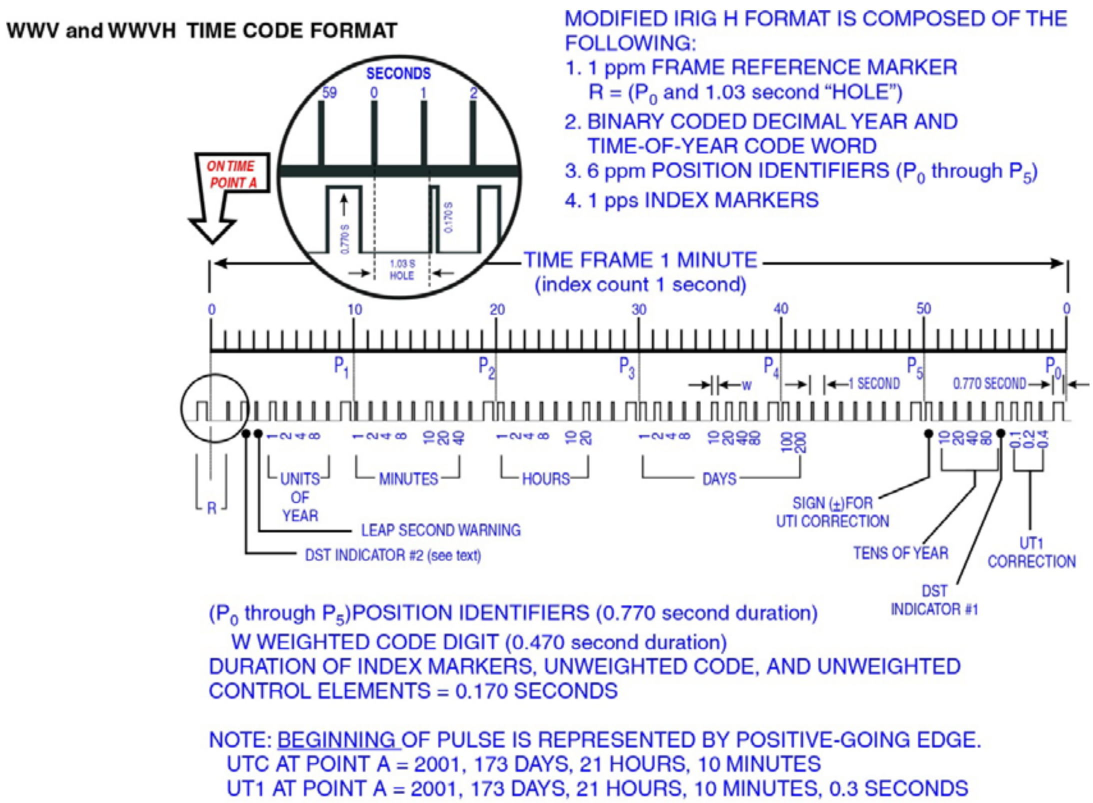
The designation of an instant on a selected time scale, used in the sense of time of day; or the interval between two events or the duration of an event, used in the sense of time interval.

Time Base

An oscillator found inside an electronic instrument that serves as a reference for all of the time and frequency functions performed by that instrument. The time base oscillator in most instruments is a quartz oscillator, often an OCXO. However, some instruments now use rubidium oscillators as their time base.

Time Code

A code (usually digital) that contains enough information to synchronize a clock to the correct time-of-day. Most time codes contain the UTC hour, minute, and second; the month, day, and year; and advance warning of daylight saving time and leap seconds. NIST time codes can be obtained from WWV, WWVH, WWVB, ACTS, and the Internet Time Service, and other systems such as GPS have their own unique time codes. The format of the WWV/WWVH time code is shown in the graphic.



Time Deviation

A statistic used to estimate time stability, based on the Modified Allan deviation. The time deviation is particularly useful for analyzing time transfer data, such as the results of a GPS common-view measurement.

Time Domain

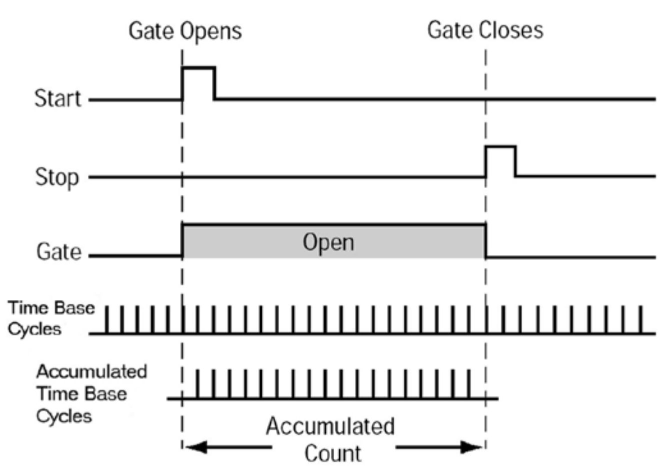
The measurement domain where voltage and power are measured as functions of time. Instruments such as oscilloscopes and time interval counters are often used to analyze signals in the time domain.

Time Interval

The elapsed time between two events. In time and frequency metrology, time interval is usually measured in small fractions of a second, such as milliseconds, microseconds, or nanoseconds. Coarse time interval measurements can be made with a stop watch. Higher resolution time interval measurements are often made with a time interval counter.

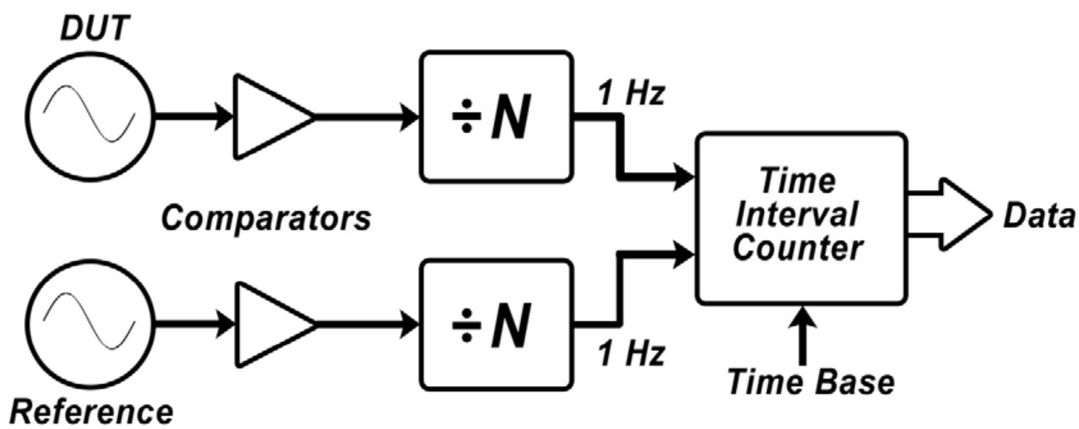
Time Interval Counter

An instrument used to measure the time interval between two signals. A time interval counter (TIC) has inputs for two electrical signals. One signal starts the counter and the other signal stops it. All TIC's contain several basic parts known as the time base, the gate, and the counting assembly. The time base provides evenly spaced pulses used to measure time interval. The gate controls when the time interval count begins and ends. Pulses passing through the gate are routed to the counting assembly. The counter can then be reset (or armed) to begin another measurement. The stop and start inputs are usually provided with controls that determine the trigger level at which the counter responds to input signals. The TIC begins measuring time interval when the start signal reaches its trigger level and stops measuring when the stop signal reaches its trigger level. The time interval is measured by counting cycles from the time base, as shown in the illustration.



The most important specification of a TIC is resolution. In simple TIC designs, such as the one in the illustration, the resolution is limited to the period of the TIC's time base frequency. For example, a TIC with a 10 MHz time base would be limited to a resolution of 100 ns. This is because the simplest TIC designs count whole time base cycles to measure time interval. To improve this situation, some TIC designers have multiplied the time base frequency to get more cycles and thus more resolution. For example, multiplying the time base frequency to 100 MHz makes 10 ns resolution possible, and 1 ns counters have even been built using a 1 GHz time base. However, modern counters increase resolution by detecting parts of a time base cycle through interpolation or digital signal processing. These methods have made 1 ns TICs commonplace, and even 1 picosecond TICs are available.

TICs are also commonly used to measure frequency in the time domain. However, when a TIC is used to measure frequency, it is not practical to work directly with standard frequency signals, such as 10 MHz. Instead, low frequency input signals must be used to start and stop the counter. As shown in the diagram, the solution is to use a frequency divider to convert standard frequency signals to a lower frequency, usually 1 Hz. The use of low-frequency signals reduces the problem of counter overflows and underflows (cycle ambiguity) and helps prevent errors that can occur when the start and stop signals are too close together.



Time of Day

The information displayed by a clock or calendar, usually including the hour, minute, second, month, day, and year. Time codes derived from a reference source such as UTC(NIST) are often used to synchronize clocks to the correct time of day.

Time Offset

The difference between a measured on-time pulse or signal, and a reference on-time pulse or signal, such as UTC(NIST). Time offset measurements are usually made with a time interval counter. The measurement result is usually reported in fractions of a second, such as milliseconds, microseconds, or nanoseconds.

Time Protocol

An Internet time code protocol defined by the RFC-868 document and supported by the NIST Internet Time Service. The time code is sent as a 32-bit unformatted binary number that represents the time in UTC seconds since January 1, 1900. The server listens for Time Protocol requests on port 37, and responds in either TCP/IP or UDP/IP formats. Conversion from UTC to local time (if necessary) is the responsibility of the client program. The 32-bit binary format can represent times over a span of about 136 years with a resolution of 1 second. There is no provision for increasing the resolution or increasing the range of years.

Time Scale

An agreed upon system for keeping time. All time scales use a frequency source to define the length of the second, which is the standard unit of time interval. Seconds are then counted to measure longer units of time interval, such as minutes, hours, and days. Modern time scales such as UTC define the second based on an atomic property of the cesium atom, and thus standard seconds are produced by cesium oscillators. Earlier time scales (including earlier versions of Universal Time) were based on astronomical observations that measured the frequency of the Earth's rotation.

Time Standard

A device that produces an on-time pulse that is used as a reference for time interval measurements, or a device that produces a time code used as a time-of-day reference.

Time Transfer

A measurement technique used to send a reference time or frequency from a source to a remote location. Time transfer involves the transmission of an on-time marker or a time code. The most common time transfer techniques are one-way, common-view, and two-way time transfer.

Time Zone

A geographical region that maintains a local time that usually differs by an integral number of hours from UTC. Time zones were initially instituted by the railroads in the United States and Canada during the 1880's to standardize timekeeping. Within several years the use of time zones had expanded internationally.

Ideally, the world would be divided into 24 time zones of equal width. Each zone would have an east-west dimension of 15° of longitude centered upon a central meridian. This central meridian for a zone is defined in terms of its position relative to a universal reference, the prime meridian (often called the zero meridian) located at 0° longitude. In other words, the central meridian of each zone has a longitude divisible by 15°. When the sun is directly above this central meridian, local time at all points within that time zone would be noon. In practice, the boundaries between time zones are often modified to accommodate political boundaries in the various countries. A few countries use a local time that differs by one half hour from that of the central meridian.

Converting UTC to local time, or vice versa, requires knowing the number of time zones between the prime meridian and your local time zone. It is also necessary to know whether Daylight Saving Time (DST) is in effect, since UTC does not observe DST. The table shows the difference between UTC and local time for the major United States time zones.

Time Zone	Difference from UTC During Standard Time	Difference from UTC During Daylight Time
Pacific	-8 hours	-7 hours
Mountain	-7 hours	-6 hours
Central	-6 hours	-5 hours
Eastern	-5 hours	-4 hours

Total Deviation

A statistic used to estimate oscillator stability. Total deviation reduces the estimation errors of the Allan deviation at long averaging times, and thus is well suited for estimating long-term stability.

Traceability

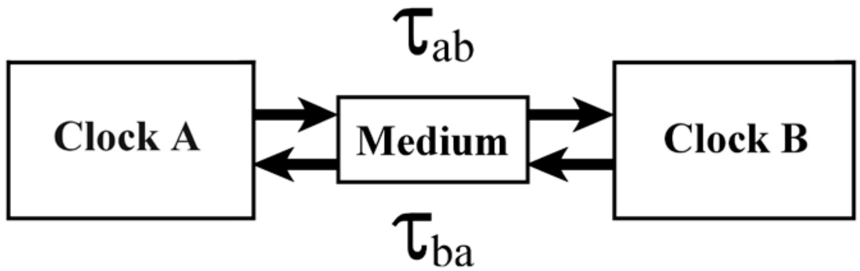
The property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty.

Tuning Fork

A metal two-pronged fork that, when struck, produces an almost pure tone of a predetermined frequency. Tuning forks are used for simple frequency calibrations, such as tuning musical instruments, and calibrating radar guns used by law enforcement agencies.

Two Way Time and Frequency Transfer

A measurement technique used to compare two clocks or oscillators at remote locations. The two-way method involves signals that travel both ways between the two clocks or oscillators that are being compared, as shown in the illustration.



A half-duplex channel is a one-way system that is “turned around” to retransmit a signal in the opposite direction. In this method, the one-way delay between the transmitter and receiver is estimated as one-half of the measured round trip delay. The delay estimate can be sent to the user and applied as a correction, or the transmitter can advance the signal so that it arrives at the user's site on time. The latter is how the NIST Automated Computer Time Service (ACTS) system works. Internet time transfers using the Network Time Protocol (NTP) also use a half-duplex technique.

A full-duplex system uses one-way signals transmitted simultaneously in both directions, often through a geostationary communications satellite. In this case data must be exchanged in both directions so that the two data sets can be differenced, as shown in the diagram.

U

Uncertainty

The parameter, associated with the result of a measurement, that characterizes the dispersion or range of values that could reasonably be attributed to the measurand. By convention, a “coverage area” of 2σ, known to metrologists as $k = 2$, is normally used for uncertainty numbers, indicating that there is an approximate 95% probability that the true value lies somewhere within the coverage area.

United States Naval Observatory (USNO)

Established in 1830, the USNO is one of the oldest scientific agencies in the United States. The USNO determines and distributes the timing and astronomical data required for accurate navigation and fundamental astronomy. It maintains a UTC time scale that is typically within 20 nanoseconds of UTC(NIST). Both NIST and the USNO can be considered official sources of time and frequency in the United States.

Universal Time (UT) Family

Before the acceptance of atomic time scales such as TAI and UTC in the 1960s, astronomical time scales were used for everyday timekeeping. These time scales are still used today, but mostly for applications related to astronomy. They are based on mean solar time. The mean solar second is defined as 1/86,400 of the mean solar day, where 86,400 is the number of seconds in the mean solar day. This mean solar second provides the basis for Universal Time (UT). Several variations of UT have been defined:

- **UT0** - The original mean solar time scale, based on the rotation of the Earth on its axis. UT0 was first kept by pendulum clocks. As better clocks based on quartz oscillators became available, astronomers noticed errors in UT0 due to polar motion, which led to the UT1 time scale.

- **UT1** - The most widely used astronomical time scale, UT1 is an improved version of UT0 that corrects for the shift in longitude of the observing station due to polar motion. Since the Earth's rate of rotation is not uniform, UT1 is not completely predictable, and has an uncertainty of ±3 milliseconds per day.

- **UT2** - Mostly of historical interest, UT2 is a smoothed version of UT1 that corrects for known deviations in the Earth's rotation caused by angular momenta of the Earth's core, mantle, oceans, and atmosphere.

V

VCXO

An acronym for voltage controlled crystal oscillator. A VCXO is a quartz oscillator whose frequency is adjusted by varying its input voltage.

W

Wavelength

The distance between identical points in the adjacent cycles of a waveform that is traveling in free space or in a guide structure such as a coaxial cable. The wavelength of radio signals is usually specified in meters, centimeters, or millimeters. In the case of infrared, visible light, ultraviolet, and gamma radiation, the wavelength is more often specified in nanometers (units of 10^{-9} meter) or Angstrom units (units of 10^{-10} meter). The wavelengths of the various frequency bands in the radio spectrum are shown in the table.

Wavelength is inversely related to frequency. The higher the frequency of the signal, the shorter the wavelength. If f is the frequency of the signal as measured in megahertz, and w is the wavelength as measured in meters, then

$$w = 300 / f \ ,$$

and conversely

$$f = 300 / w \ .$$

The table shows the frequency and wavelength ranges for the various frequency bands.

Band	Description	Frequency	Wavelength
VLF	Very Low	3 to 30 kHz	100 to 10 km
LF	Low	30 to 300 kHz	10 to 1 km
MF	Medium	300 to 3000 kHz	1 km to 100 m
HF	High	3 to 30 MHz	100 to 10 m
VHF	Very High	30 to 300 MHz	10 to 1 m
UHF	Ultra High	300 to 3000 MHz	1 m to 10 cm
SHF	Super High	3 to 30 GHz	10 to 1 cm
EHF	Extremely High	30 to 300 GHz	1 cm to 1 mm

White Noise

Noise having a frequency spectrum that is continuous and uniform over a specified frequency band. White noise is independent of frequency. Its spectrum looks flat because there is equal power per hertz over the specified frequency band.

WWV

The NIST radio station located near Fort Collins, Colorado. WWV broadcasts time and frequency information, including voice announcements of time, on carrier frequencies of 2.5, 5, 10, 15, 20, and 25 MHz.

WWVB

The NIST radio station located on the same site as WWV near Ft. Collins, Colorado. WWVB broadcasts a digital time on a carrier frequency of 60 kHz. The WWVB time code is used throughout North America to synchronize radio controlled clocks.

WWVH

The NIST radio station located on the Island of Kauai, Hawaii. WWVH broadcasts time and frequency information, including voice announcements of time, on carrier frequencies of 2.5, 5, 10, and 15 MHz.

X

XO

An acronym for a quartz crystal oscillator. It usually refers to the simplest types of quartz oscillators that have no compensation for the effects of temperature.

Y

Year

A year is a time interval whose duration is based on the period of the Earth's orbit around the Sun. The Gregorian calendar considers a calendar year to be either a common year of 365 days, or a leap year of 366 days, with the average year having a length of 365.2425 days. In astronomy, the Julian year is defined as being equal to exactly 365.25 days, with each day having 86,400 seconds.

Z

Zero Beat

The condition reached during a measurement or calibration when the beat frequency between two input signals is no longer detectable. Zero beat is often associated with audio frequency calibrations (such as the tuning of musical instruments), when the person performing the measurement can no longer hear the beat frequency or beat note.

Zulu

A term sometimes used in the military and in the navigation community as a synonym for Coordinated Universal Time (UTC). In military shorthand, the letter Z follows a time expressed in UTC. Zulu is not an official time scale, nor is it an official designation. The term originated because the word zulu is the radio transmission articulation for the letter Z, and the time zone located on the prime meridian is designated on many time zone maps by the letter Z.