Time and Frequency From A to Z

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http://tf.nist.gov/general/glossary.htm

The following pages contain a static version of the document as it originally appeared when first pubished in March 2002.

Time and Frequency from A to Z: A to Al

A440

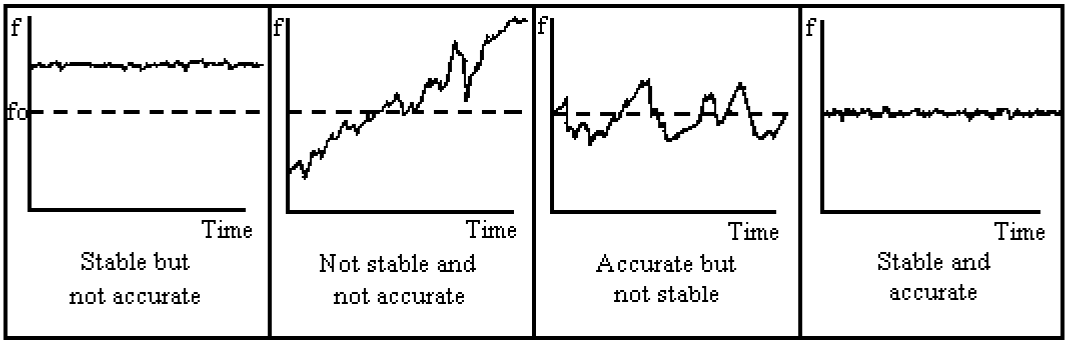
A440 (sometimes called A4) is the 440 Hz tone that serves as the internationally recognized standard for musical pitch. A440 is the musical note A above middle C. Since 1939, it has served as the audio frequency reference for the calibration of pianos and other musical instruments.

Tuning a piano is an example of a simple frequency calibration that is actually done with human ear. The piano tuner listens to a standard musical pitch and compares it to the note on the piano keyboard. The piano is then adjusted (by tightening or loosening strings), until it agrees with the audio standard. What is the smallest frequency offset that a piano tuner can hear? It depends on lots of factors, including the sound volume, the duration of the tone, the suddenness of the frequency change, and the musical training of the listener. However, the *just noticeable difference* is often defined as 5 *cents*, where 1 cent is 1/100 of the ratio between two adjacent tones on the piano's keyboard. Since there are 12 tones in a piano's octave, the ratio for a frequency change of 1 cent is the 1200th root of 2. Therefore, to raise a musical pitch by 1 cent, you would multiply by the 1200th root of 2, or 1.000577790. If you do this 5 times starting with 440 Hz, you'll see that 5 cents high is about 441.3 Hz, or high in frequency by 1.3 Hz.

NIST (then called the National Bureau of Standards) began broadcasting A440 from radio station WWV in 1936, several years before it was officially recognized as an audio frequency standard. The tones can currently be heard during minute 2 of each hour on WWV, and during minute 1 on WWVH. The 440 Hz tone is omitted, however, during the first hour of each UTC day.

Accuracy

Accuracy is the degree of conformity of a measured or calculated value to its definition. Accuracy is related to the offset from an ideal value. In the world of time and frequency, accuracy is used to refer 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 exactly with UTC. Frequency offset is the difference between a measured frequency and an ideal frequency with zero uncertainty. This ideal frequency is called the nominal frequency. The relationship between accuracy and stability is illustrated below.



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. It 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 x 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 is:

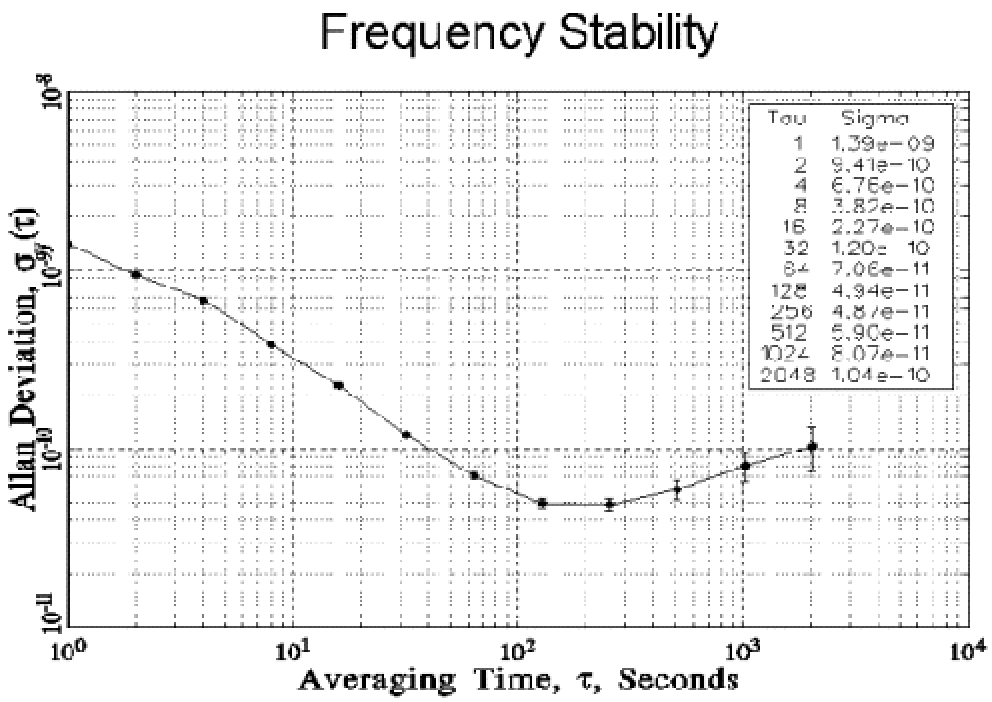
$$\sigma_y(\tau) = \sqrt{\frac{1}{2(M-1)} \sum_{i=1}^{M-1} (y_{i+1} - y_i)^2}$$

where yi 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:

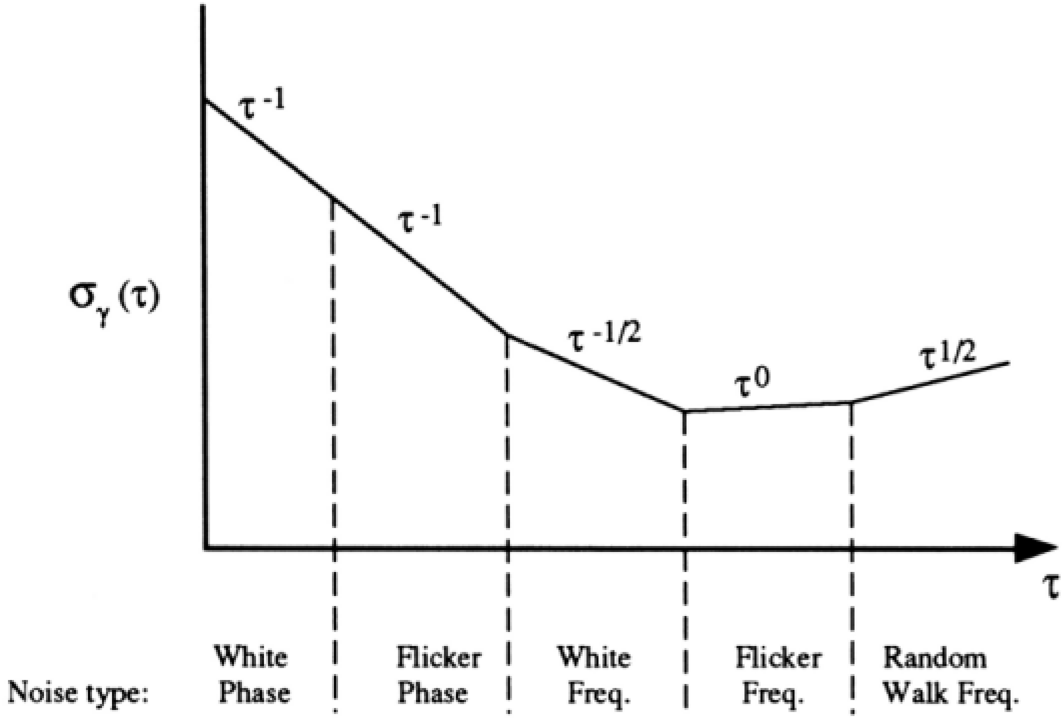
$$\sigma_y(\tau) = \sqrt{\frac{1}{2(N-2)\tau^2} \sum_{i=1}^{N-2} [x_{i+2} - 2x_{i+1} + x_i]^2}$$

where x_i is a set 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.

A graph of Allan deviation is shown below. It shows the stability of the device improving as the averaging period (τ) 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 like aging or random walk. The device in the graph has a noise floor of about 5 x 10^{-11} at τ = 100 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.



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Ambiguity

The properties of something 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, since 6 hours can represent two different times of day.

Atomic Clock

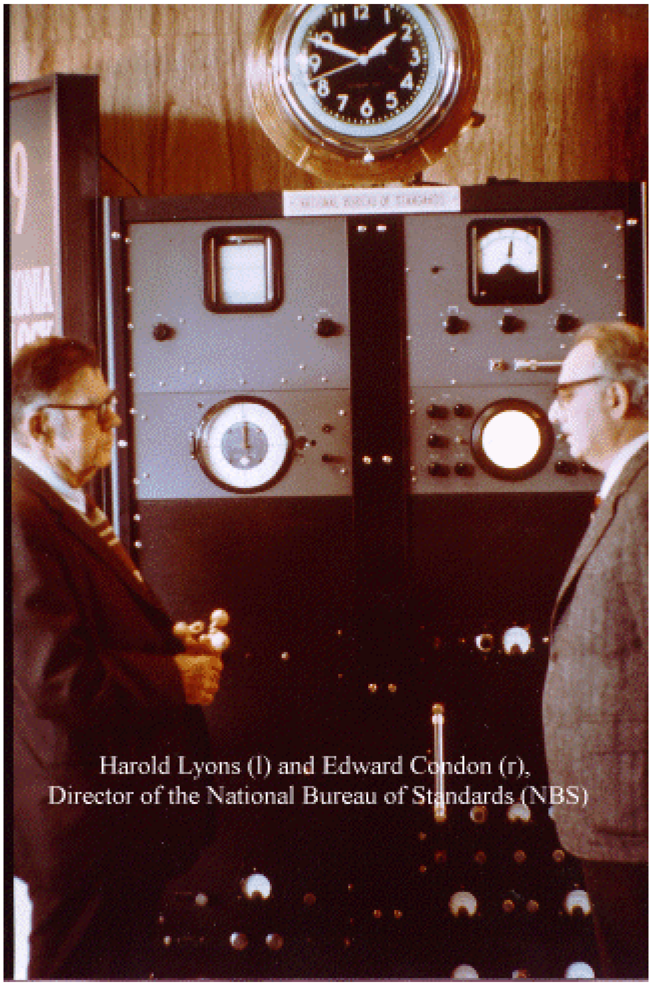
A clock referenced to an atomic oscillator. In the truest sense, only clocks with an internal atomic oscillator qualify as atomic clocks. However, the term is sometimes used to refer to radio clocks that receive a signal referenced to an atomic oscillator at a remote location.

Atomic Oscillator

An oscillator that uses the quantized energy levels in atoms and molecules as the source of its resonance. The laws of quantum mechanics dictate that the energies of a bound 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*) of an atomic oscillator is the difference between the two energy levels divided by Planck's constant (*h*):

$$f = \frac{E_2 - E_1}{h}$$

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 first atomic oscillator was developed at NIST (then NBS) in 1949, and is shown in the photo below. Its resonance frequency was derived from an absorption line in the ammonia molecule. The national frequency standards developed by NIST derive their resonance frequency from the cesium atom, and use cesium beam or cesium fountain technology. NIST researchers have used several other atoms to build experimental atomic oscillators, including mercury and calcium. Rubidium oscillators are the lowest priced and most common atomic oscillators, but cesium beam and hydrogen maser atomic oscillators are also sold commercially.



Harold Lyons (l) and Edward Condon (r), Director of the National Bureau of Standards (NBS)

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 based on the transitions of the cesium atom.

Automated Computer Time Service (ACTS)

A telephone service operated by the NIST Time and Frequency Division 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. For detailed information about the service, visit the ACTS home page.

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 analog television (TV) broadcast video signal has bandwidth of 6 MHz, some 2,000 times as wide as the telephone signal. 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. Since a person with average hearing can hear tones down to 20 or 30 Hz, an audio zero beat can resolve frequency within 2 or 3 parts in 10^6 at 10 MHz.

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 data from about 50 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 true 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. For more information, visit the BIPM web site.

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Time and Frequency from A to Z: C to Ce

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 cesium oscillator, the received signal can be used to calibrate other frequency sources. The table belows 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
LORAN-C	100 kHz
WWV	2.5, 5, 10, 15, 20 MHz
WWVH	2.5, 5, 10, 15 MHz
Global Positioning System (GPS)	1575.42 MHz, 1227.6 MHz

Carrier Phase Measurements

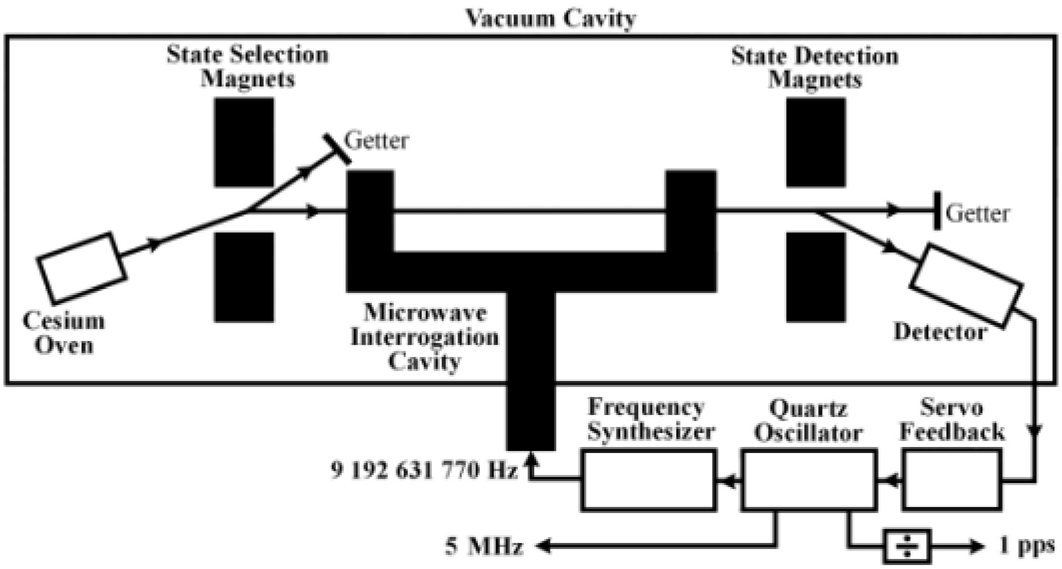
A type of calibration that uses the carrier frequency of a radio transmission as a measurement reference. Carrier phase measurements have been made for many years using low frequency radio signals from WWVB or LORAN-C. However, the carrier phase measurements with the smallest uncertainties are made using GPS satellite signals. For more information, visit the GPS carrier-phase measurement page.

Cesium Beam Oscillator

Cesium oscillators are 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.

Commercially available oscillators use cesium beam technology. Inside a cesium oscillator, ^{133}Cs atoms are heated to a gas 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 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. 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 figure.



The Q of a commercial cesium standard is a few parts in 10^8. The beam tube is typically < 0.5 m in length, and the atoms travel at velocities of > 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. Stability ($\sigma_y\tau$, at $\tau = 1$ s) is typically 5 x 10^{-12}, and reaches a noise floor near 1 x 10^{-14} at about one day, extending out to weeks or months. The frequency offset is typically near 1 x 10^{-12} after a warm-up period of 30 minutes.

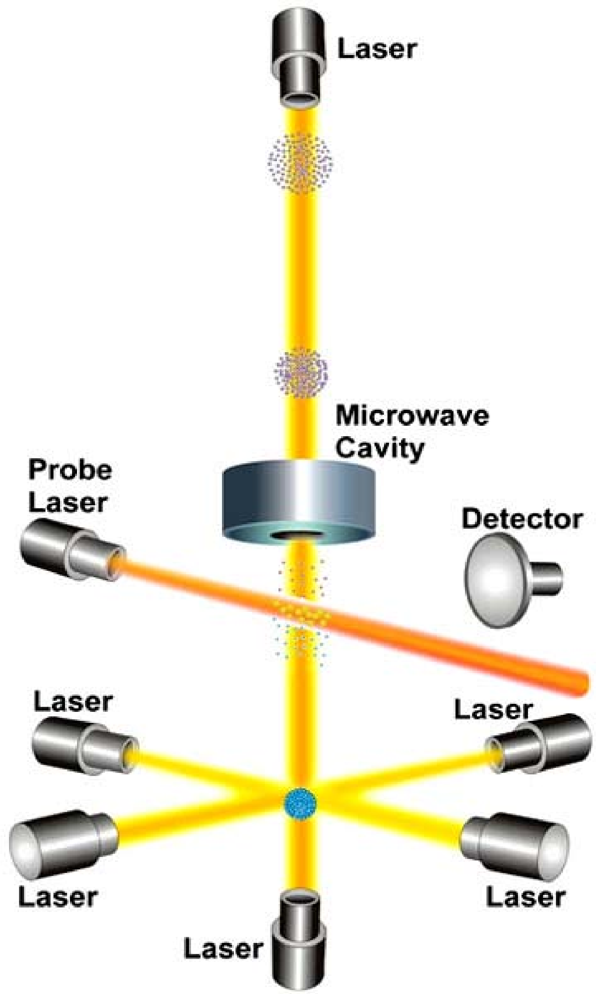
Cesium Fountain Oscillator

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-F1 serves as the primary standard of time and frequency for the United States.

A cesium fountain works by releasing a gas of cesium atoms into a vacuum chamber. 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 thousandths of a degree above absolute zero. This reduces their thermal velocity to a few centimeters per second.

Two vertical lasers 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 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 to the ground. 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-F1 is estimated at $< 2 \times 10^{-15}$.

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Characterization

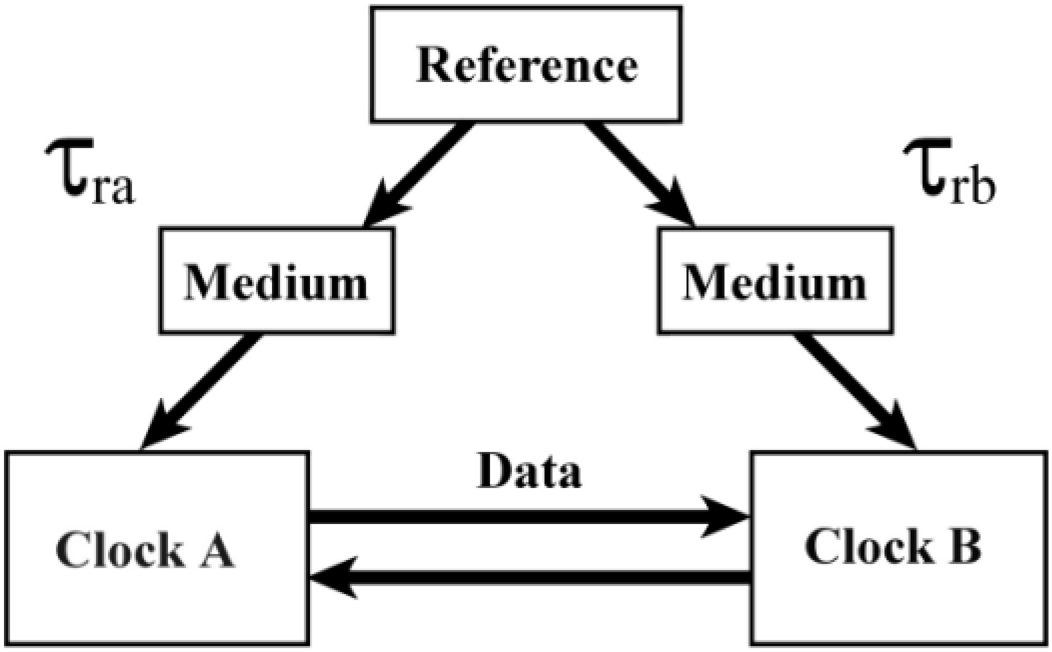
An extended test of the performance characteristics of a clock or oscillator. A characterization is more involved than a calibration. The device under test is usually measured for a long period of time (days or weeks) and sometimes a series of measurements is made under different environmental conditions.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

Clock

A device that generates periodic, accurately spaced signals used for timing 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.

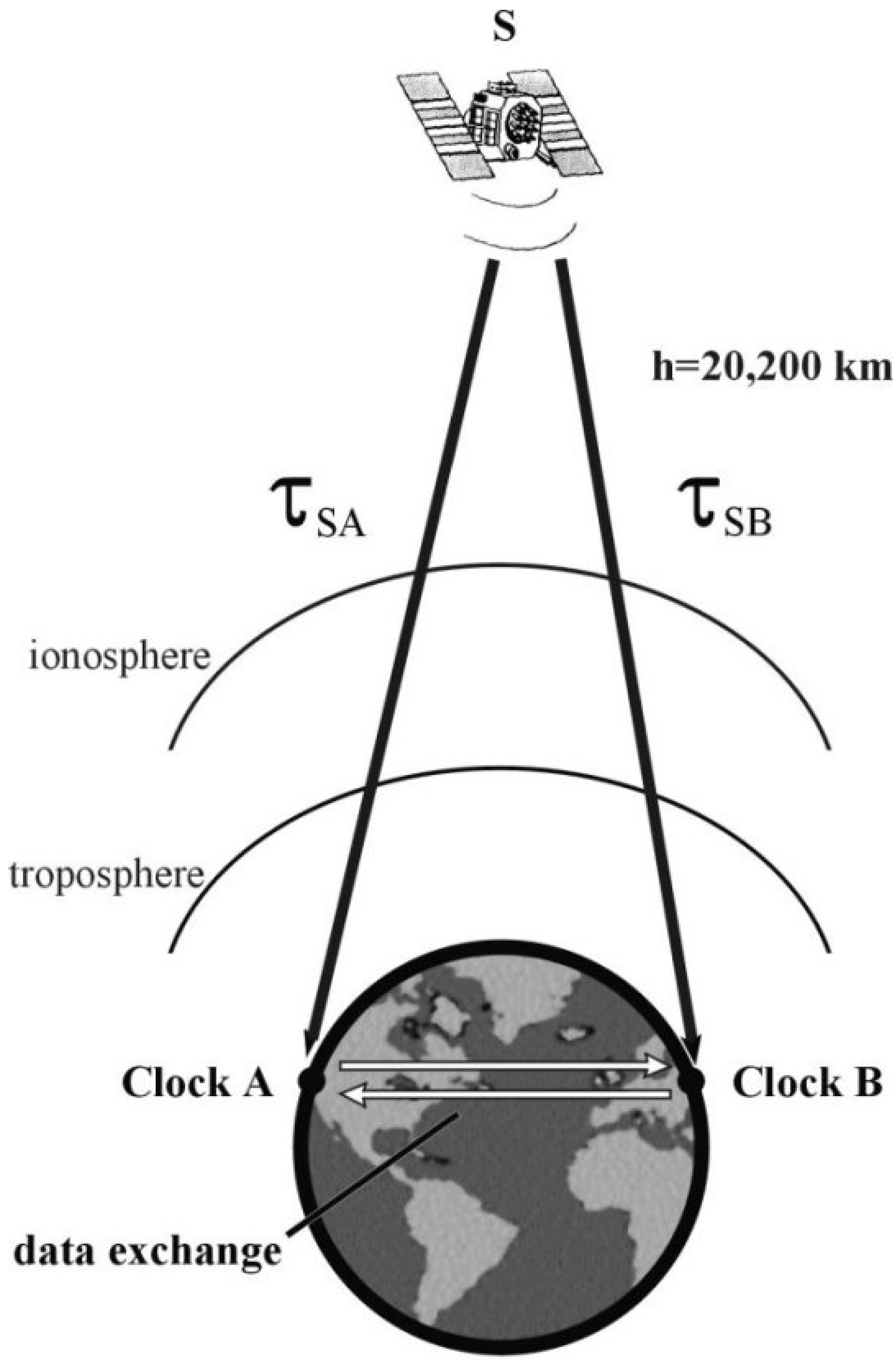
Common-View

A measurement technique used to compare two clocks or oscillators at remote locations. The common-view method involves a single 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 figure.



Common-view directly compares two time and frequency standards. 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}).

Common-view measurements were made for many years using land based transmitters as the reference. However, nearly all current common-view measurements use a GPS satellite as the reference transmitter, as illustrated below. This enables 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 time keeping 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 200 atomic time and frequency standards located at about 50 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 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 of slightly less than once per year, beginning in 1972.

Keep in mind that the BIPM maintains TAI and UTC as “paper” time scales. The major metrology 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). You can think of UTC as the ultimate standard for time-of-day, time interval, and frequency. 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 to the period of the carrier frequency, or to a multiple of the period. For example, if a WWVB receiver changes its signal tracking point during a measurement, a phase shift equivalent 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 a weak or noisy signal.

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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. Daylight Saving Time begins for most of the United States at 2 a.m. on the first Sunday of April. Time reverts to standard time at 2 a.m. on the last Sunday of October. In the European Union, it starts at 1 am the last Sunday in March, and ends the last Sunday in October.

Daylight Saving Time, for the U.S. and its territories, is not observed in Hawaii, American Samoa, Guam, Puerto Rico, the Virgin Islands, the Eastern Time Zone portion of the State of Indiana, and the state of Arizona (not the Navajo Indian Reservation, which does observe). For more information, visit the exhibit on daylight saving time.

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 that elapses between the end of one measurement and the start of the next measurement. This time interval is generally only called dead time 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 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 continuosly steered (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 steered 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.

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Drift (frequency)

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

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, GOES, and ACTS, and can be added to UTC to obtain UT1. The current DUT1 correction is available here.

Ensemble

A group of oscillators whose outputs are averaged to create a time scale. Typically, the relative value of each oscillator is weighted, so that the best oscillators contribute the most to the average. NIST uses an ensemble of oscillators to produce UTC(NIST).

Ephemeris Time (ET)

An obsolete time scale based on the ephemeris second, which served as 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.

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Time and Frequency from A to Z: F

Femtosecond (fs)

One trillionth of a second (10^{-12} 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*. Since 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 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. Since accuracy is related to the offset from an ideal value, frequency accuracy is usually stated in terms of the frequency offset.

Frequency Counter

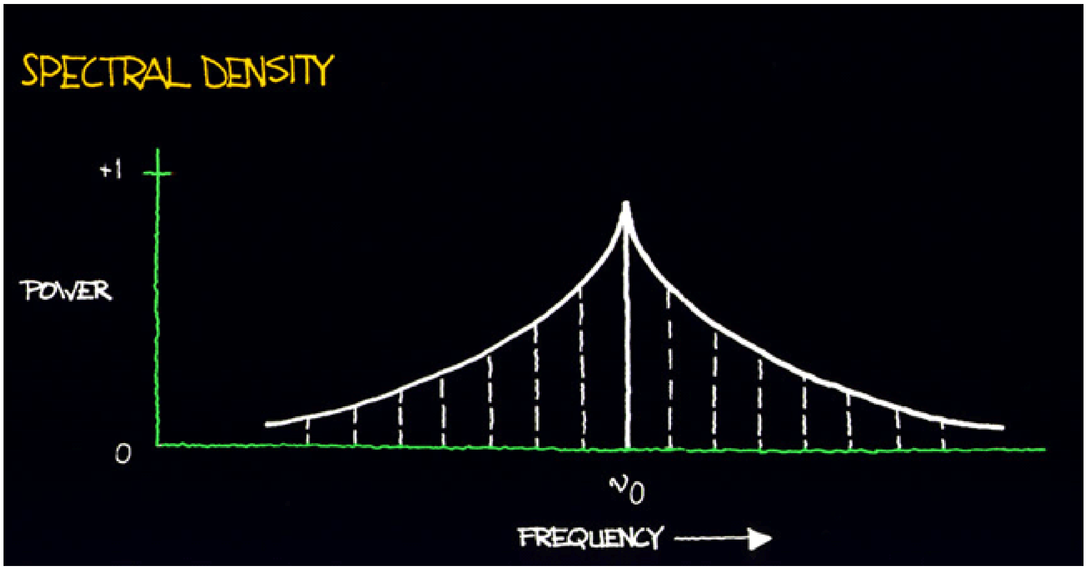
An electronic instrument or circuit that displays the frequency of an incoming signal. The frequency is determined by comparing the signal to the counter's time base oscillator. Some frequency counters (often called "universal counters") measure other parameters in addition to frequency, such as time interval and period.

Frequency Divider

An electronic instrument or circuit that converts an incoming signal to a lower frequency by removing cycles or pulses from the signal. For example, a circuit that divides by 1000 could accept a 1 MHz signal as an input, and produce a 1 kHz signal as an output. Dividers are commonly used to convert the standard output of a frequency standard (often 5 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 is often used to analyze signals in the frequency domain. It does so 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. The total power (or voltage) measured by a spectrum analyzer depends on the bandwidth used.



Frequency Drift

An undesired progressive change in frequency with time. Frequency drift can be caused by component aging and environmental changes. Frequency drift may be in either direction and is not necessarily linear.

Frequency Mixer

An electronic instrument or circuit that accepts two input frequencies, and produces a frequency (called the beat frequency or difference frequency) equal to the difference of the two inputs. Frequency mixers are commonly employed in frequency measurement 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.

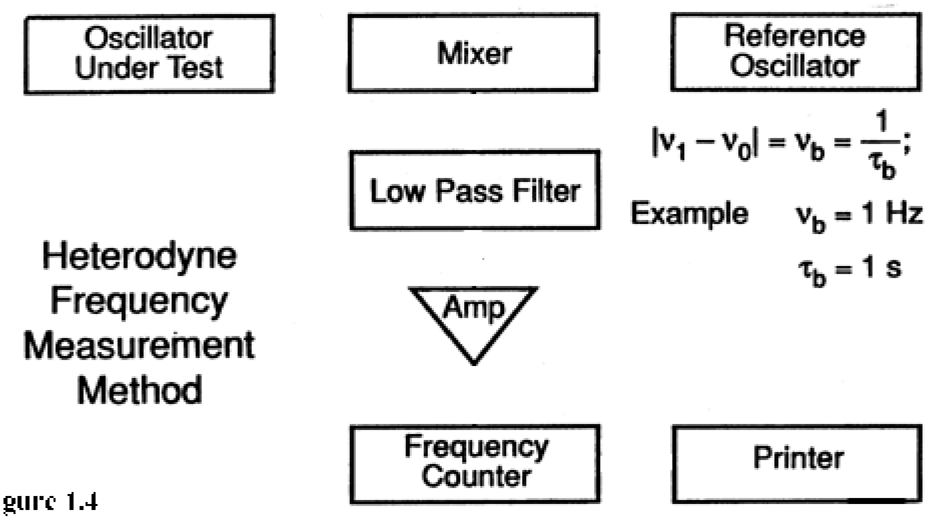


Figure 1.4

Frequency Multiplier

An electronic instrument or circuit that converts an incoming signal to a higher frequency by adding 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 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:

$$f(offset) = \frac{f_{measured} - f_{nominal}}{f_{nominal}}$$

where $f_{measured}$ is the reading from the frequency counter, and $f_{nominal}$ 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 a oscilloscope or a time interval counter. If at least two time interval measurements are made, we can estimate frequency offset as follows:

$$f(offset) = \frac{-\Delta t}{T}$$

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

Frequency offset values are usually expressed as dimensionless numbers such as 1×10^{-10}, since the quantities being measured are typically quite 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:

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

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 graphic below shows two oscillating sine waves: one stable, the other unstable.

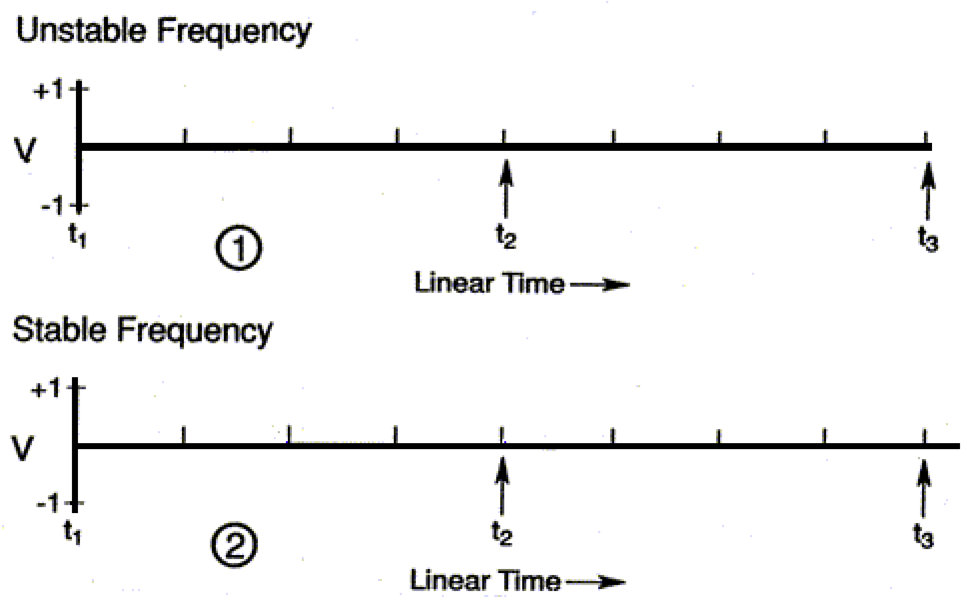


Figure 1.3

Frequency Standard

An oscillator (usually an atomic oscillator) that is used as a reference source for frequency measurements. The current frequency standard for the United States is a cesium fountain oscillator named NIST-F1.

Frequency Synthesizer

A 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.

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Gigahertz (GHz)

One billion cycles per second (10^9 Hz).

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 position with an uncertainty of < 10 m.

The GPS satellites broadcast on two carrier frequencies: L1 at 1575.42 MHz, and L2 at 1227.6 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. If a clear sky view is available, the signals can be received nearly anywhere on earth.

The primary purpose of GPS is to serve as a radionavigation system, but it has also become perhaps the dominant system for the distribution of time and frequency. Each satellite carries either rubidium or cesium oscillators, or a combination of both. The on-board oscillators provide the reference for both the carrier and code broadcasts. They are steered from USDOD ground stations and are referenced to Coordinated Universal Time (UTC) maintained by the United States Naval Observatory (USNO). By mutual agreement UTC(USNO) and UTC(NIST) are maintained within 100 ns of each other, and the difference between the two time scales is $< 1 \times 10^{-13}$.

There are several types of time and frequency measurements that involve GPS, including one-way, common-view, and carrier-phase measurements. To view one-way GPS data received at Boulder and compared to UTC(NIST), please visit the GPS data archive.

GLONASS

The Global Navigation Satellite System operated by the Soviet Federation as a space-based navigation system. GLONASS is similar in some ways to GPS, and is sometimes used as a reference or common-view source for time and frequency measurements. The GLONASS satellites use two frequency bands: 1602.5625 to 1615.5 MHz and 1240 to 1260 MHz. The satellites carry on-board cesium oscillators.

GOES

An acronym for the Geostationary Operational Environmental Satellites operated by the National Oceanic and Atmospheric Agency (NOAA). Although no longer widely used, two GOES satellites (GOES/East and GOES/West) broadcast a time code referenced to UTC (NIST). GOES/East is located at 75 west longitude and broadcasts on a carrier frequency of 468.825 MHz. GOES/West is located at 135 west longitude and broadcasts at a frequency of 468.8375 MHz.

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 sometimes incorrectly used by the general public as a synonym for UTC.

Groundwave

In radio transmission, a 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, LF signals tend to be a better time and frequency reference than high frequency (HF) signals, which are often dominated by skywave.

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Hertz

The standard unit of frequency, equivalent to one event, or cycle per second.

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 also used to increase the of some time and frequency measurement systems, by converting the incoming signal from the device under test to a lower frequency.

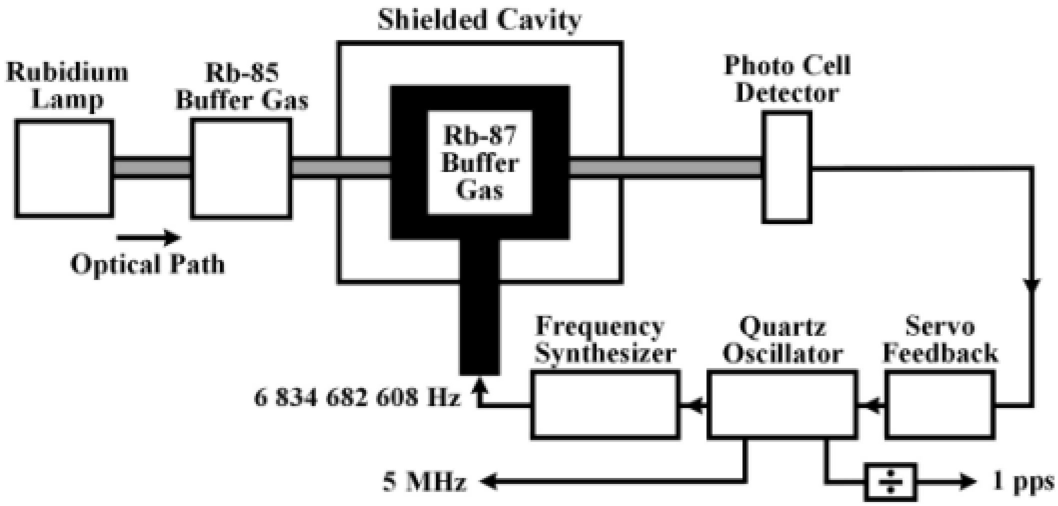
High Frequency (HF)

The part 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 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 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 a commercial cesium standard. As a result, the short-term stability is better than a cesium standard for periods out to a few days - typically < 1×10^{-12} $(\sigma_y\tau$, at $\tau = 1$ s) and reaching a noise floor of appoximately 1×10^{-15} after about 1 hour. However, when measured for more than a few days or weeks, a hydrogen maser might fall below a cesium oscillator's performance. The stability decreases because of changes in the cavity's resonance frequency over time.

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International Atomic Time (TAI)

A time scale maintained internally by the 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 increases when leap seconds occur.

International Date Line

The line on the Earth, 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 is located exactly halfway around the world from the prime meridian (0° longitude) that passes near Greenwich, England. The International Date Line passes through an area covered mainly by empty ocean. 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 several formats defined by the Daytime, Time, and NTP protocols. The ITS handles hundreds of millions of timing requests every day. For more information, visit the ITS home page.

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, since the second is defined 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 atomic oscillators which should eventually replace today's frequency standards. For more information, visit the Ion Storage Group web site.

IRIG Time Codes

The time codes originally developed by the Inter-Range Instrumentation Group (IRIG), now used in government, military and commercial fields. There are many formats and several modulation schemes, but they are typically amplitude modulated on an audio sine wave carrier. The most common version 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.

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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 like telecommunications, the term jitter is seldom used in time and frequency metrology, since terms such as phase noise are more descriptive.

Julian Day

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.

- **Julian Date (JD):** The Julian Day number followed by the fraction of the day elapsed since the preceding noon (1200 UT). {*Example:* The date 1900 January (1) 0.5 day UT corresponds to JD = 2 415 020}.
- **Julian Day Number (JDN):** The number of a specific day from a continuous day count having an initial origin of 1200 UT on 1 January 4713 BC, the start of Julian day zero. {*Example*: The day extending from 1900 January (1) 0.5 day UT to 1900 January 1.5 days UT has the number 2 415 020}.
- **Modified Julian Day (MJD):** Equal to the Julian day. Shifted so its origin occurs at midnight on 17 November 1858. The MJD differs from the Julian date by exactly 2 400 000.5 days.

Kilohertz (kHz)

One thousand cycles per second (10^3 Hz).

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Laser Cooling

A technique that uses infrared laser beams to slow down the motion of atoms and cool them to temperatures a few thousandths of a degree above absolute zero. This technique is used to improve the performance of NIST-F1 and other standards, since it increase the interrogation and observation time of the atoms. For more information, visit the Ion Storage Group web site.

Leap Day

The day added to a leap year to make it have 366 days. Leap days occur 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, and they occur at a rate of slightly less than one per year, on average. So far, all leap seconds have been added 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 have a negative leap second in the foreseeable future. For more information and a table of leap seconds, visit the NIST Time Scale Data Archive.

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 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, like the year 2000. 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 only considered as leap years if they are evenly divisible by 400. Therefore, 1700, 1800, 1900 were not leap years, and 2100 will not be a leap year. But 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 widely used as a standard for frequency calibrations. It is also possible to synchronize a LORAN-C receiver so that it produces an on-time UTC pulse. However, the broadcast does not contain a time code, so time-of-day cannot be recovered using LORAN-C. NIST continuosly monitors the broadcasts from three LORAN-C stations and publishes the results in the LORAN-C data archive.

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, and the 100 kHz LORAN-C signals.

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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 statistical test used to measure 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)

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 D/A conversion to a tuning port in the circuit. The stability of a MCXO is generally better than a TCXO, but worse than an OCXO.

Mean Solar Time

An astronomical time scale based on the average length of the day, called the mean solar day. The length of an average day was used to correct for irregularities in the Earth's rotation that would show up in a true solar time scale. For example, in a true solar time scale (apparent solar time), noon would be the instant when the Sun reaches its highest point in the sky. However, the irregular rate of the Earth's rotation causes the Sun to be at its highest point at a different time each day, varying over the course of a year to being 14.2 minutes ahead of noon to 16.3 minutes behind it. Thus, the length of an average day was used to create a more uniform system of timekeeping.

Microsecond

One millionth of a second (10^{-6} s).

Millisecond (ms)

One thousandth of a second (10^{-3} s).

Modified Allan Deviation (MDEV)

A modified version of the Allan deviation statistic, which can distinguish between white and flicker phase noise. This makes it more suitable for short-term stability estimates than the normal Allan Deviation.

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Nanosecond (ns)

One billionth of a second (10^{-9} s).

Network Time Protocol (NTP)

A standard protocol used to send a time code over the Internet. The Network Time Protocol (NTP) was created at the University of Delaware, and is defined by the RFC-1305 document. The 64-bit time code contains the time in UTC seconds since January 1, 1900 with a resolution of 200 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 the 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.

Octave

The interval between two frequencies with 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

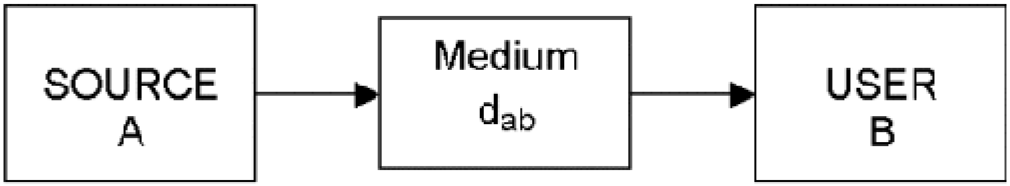
OCXO

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.

Since the environment is carefully controlled, OCXOs have excellent short-term stability. A typical OCXO might be stable $(\sigma_y\tau, \text{ at } \tau = 1\ s)$ to 1 x 10^{-12}. The limitations in short-term stability are mainly due to noise from electronic components in the oscillator circuits. Long term stability is 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 source, A, simply sends a time signal to the user, B, through a transmission medium.



The delay, d, 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. For a more detailed description, please visit the One-Way GPS Time Transfer page.

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 laser-cooled ions and neutral atoms. These standards have a much higher resonance frequency than atomic oscillators based on microwave transitions, a much higher Q, and potentially a much higher stability. Although optical frequency standards are currently used for experimental purposes only, the research being conducted in this area could lead to the next generation of atomic oscillators. For information about current research, visit the NIST Optical Frequency Group web site.

Oscillator

An electronic device used to generate a signal. The oscillation is based on a periodic event that repeats at a constant rate. The device that produces 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 exists (both mechanical and electronic), 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.

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Passive Frequency Standard

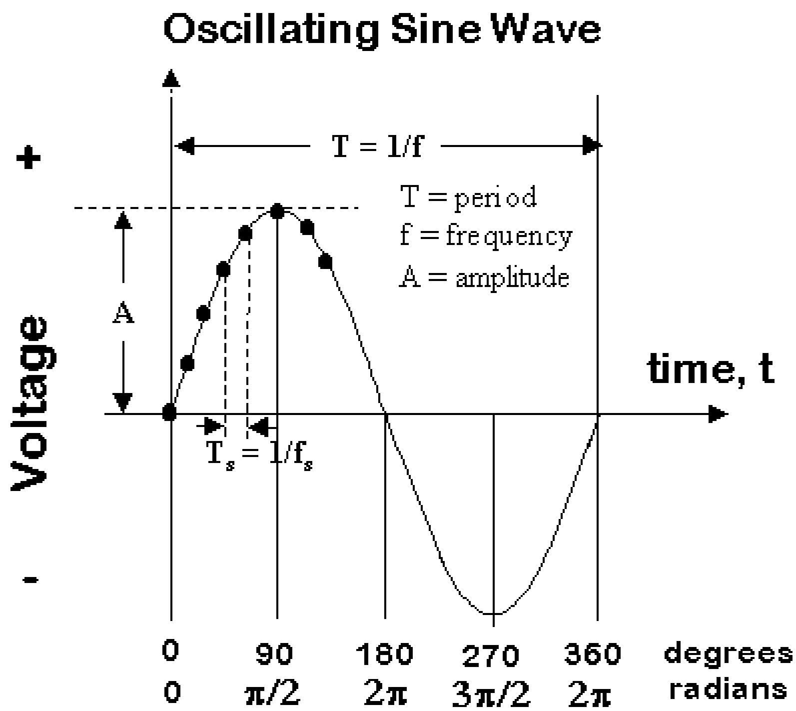
An atomic oscillator whose output signal is derived from a oscillator frequency locked to the atomic resonance frequency, instead of being directly derived from the atomic resonance. Unlike active frequency standards, the cavity where the atomic transitions take place does not sustain self-oscillation. 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 (about 3.3 microseconds/km), we can calibrate the path by estimating the path delay as 3.3 ms, and applying a 3.3 ms correction to our measurement. The more sophisticated time transfer systems are self-calibrating, and automatically correct for path delay. Path delay is not important to frequency transfer systems, since on-time pulses are not required. However, variations in path delay do limit the frequency uncertainty.

Period

The reciprocal of a frequency, T = 1/f. The period of a waveform is the time occupied by one complete cycle of the wave. The relationship between period, frequency, and for a sine wave is illustrated in the graphic below. In time and frequency metrology knowing the period of a frequency is necessary, since it helps to identify cycle slips.



Phase

The position of a point in time (instant) on a waveform cycle. A complete cycle is defined as 360° of phase as shown in the graphic above. The graphic also shows how phase is sometimes expressed in radions, where one radian of phase equals approximately 57.3 degrees. Phase can also be an expression of relative displacement between 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 degrees. 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 degrees, they are said to be in phase quadrature. When two waves differ in phase by 180 degrees (-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 one degree 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 one degree of phase is:

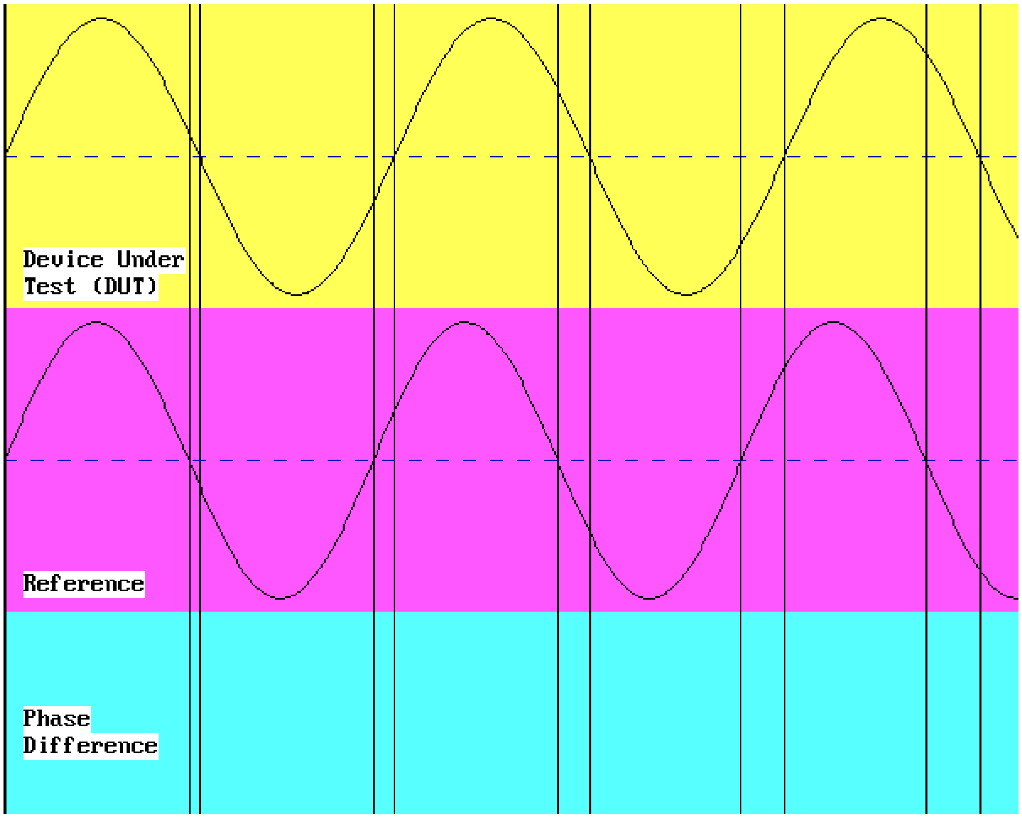
$$\mathbf{t_{deg} = 1 / (360f)}$$

Therefore, a one degree phase shift on a 5 MHz signal represents 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 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. The top sine wave is the test frequency, and the bottom sine wave 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. Vertical lines have been drawn through the points where each sine wave passes through zero. The bottom of the figure shows bars whose width represents the phase difference between the signals. In this case the phase difference is increasing, indicating that the test signal is lower in frequency than the reference.



Phase Locked Loop (PLL)

An electronic circuit with a voltage- or current-driven oscillator that is constantly adjusted to match in phase (and thus lock on) the frequency of an input signal. A PLL has many applications in time and frequency. It can be used to generate a signal, modulate or demodulate a signal, reconstitute a signal with less noise, or multiply or divide a frequency.

A typical PLL consists of a voltage-controlled oscillator (VCO) that is tuned using a varactor. The VCO is initially tuned to a frequency close to the desired frequency. A circuit called a phase comparator causes the VCO to seek and lock onto a reference frequency. This works by means of a feedback scheme. If the VCO frequency departs from the reference frequency, the phase comparator produces an error voltage that is applied to the varactor, bringing the VCO back into agreement with the reference frequency.

Phase Noise

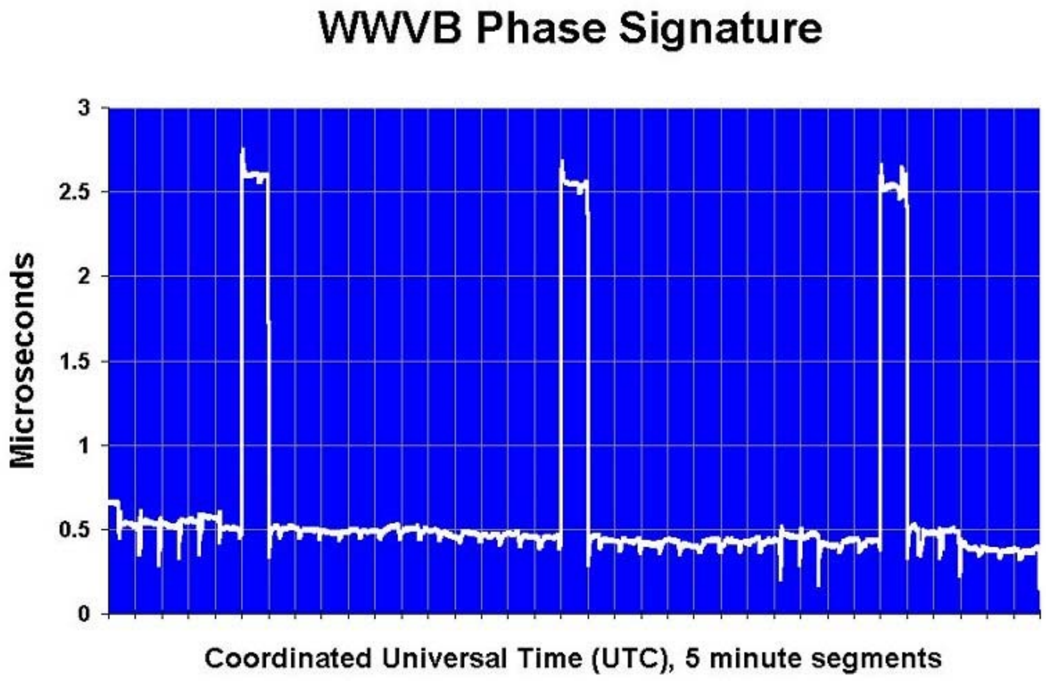
The unit used to describe phase noise is dBc/Hz (dB below the carrier per Hz of bandwidth). Reporting phase noise measurement results must include the bandwidth and the carrier frequency.

Phase Shift

The change in phase of a periodic signal with respect to a reference.

Phase Signature

An intentional phase shift in a signal used to identify that signal. For example, WWVB identifies itself by advancing the phase of its carrier frequency 45° at 10 minutes after the hour and returning to normal phase at 15 minutes after the hour. This signature can be seen on a phase plot as a approximate 2 microsecond step, as shown in the figure below.



Picosecond (ps)

One billionth of a second (10^{-9} s).

Precision

The term precision is somewhat ambiguous, and 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. Therefore, stating the precision of a measurement is often analagous to stating the uncertainty. Precision is also sometimes to 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 analagous to repeatability, reproducibility, or even stability. Precision is also sometimes used as a measure of a computer's ability to 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.

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, NIST-F1 is recognized as a primary standard for time and frequency. In time and frequency, the term primary standard is sometimes used to refer to any cesium oscillator, since the second is defined based on cesium. It is also commonly used, at least in a local sense, to refer to the best standard available at a given laboratory or facility.

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Quality Factor, Q

An inherent characteristic of an oscillator that influences its stability. The Q of an oscillator is 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}

Quartz Oscillator

The most common source of time and frequency signals. An estimated two billion (2×10^9) quartz oscillators are manufactured annually. Most are small devices built for wristwatches, clocks, and electronic circuits. However, they 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 can be made of either natural or synthetic quartz, but all modern devices use synthetic quartz. The crystal strains (expands or contracts) when a 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. 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 MHz.

Environmental changes due to temperature, humidity, pressure, and vibration can change the resonance frequency of a quartz crystal, but there are several designs that reduce these environmental effects, including the TCXO, MCXO, and OCXO. These designs (particulary 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 accuracy and stability.

Radio Clock

A clock that automatically synchronizes to a signal received by radio. The most common radio clocks receive signals from NIST radio station WWVB.

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 cavity inside an active atomic frequency standard where the atoms are directed. The cavity is part of an electric circuit tuned to the same resonance frequency as the radiation emitted by the atoms. The radiation energy built up by the atoms causes the cavity to oscillate. Named after Norman Ramsey, who was awarded the Noble Prize in 1989.

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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 could 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 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 usually possible to obtain more resolution by averaging.

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.

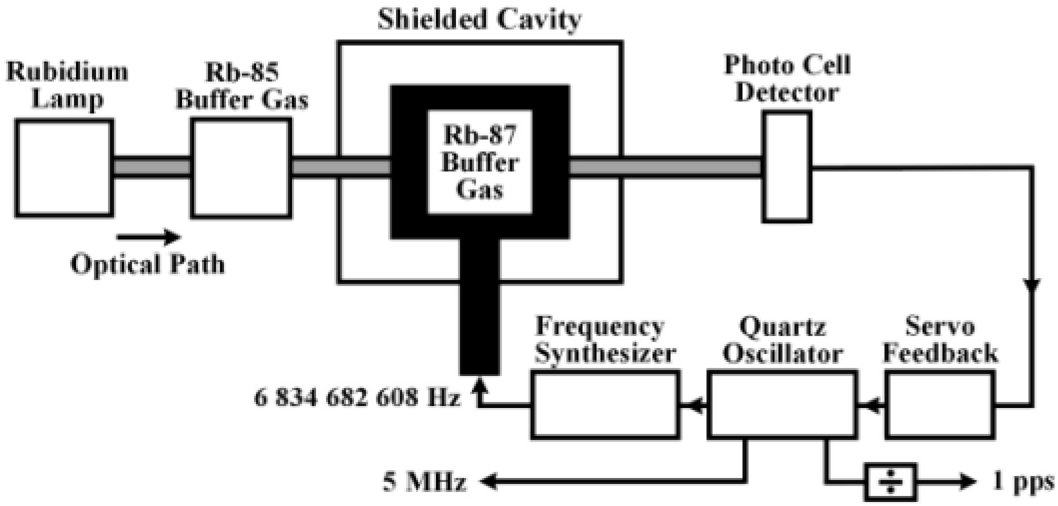
Oscillator Type	Resonance Frequency (Hz)
Pendulum	1
Quartz Wristwatch	32 768
Hydrogen Maser	1 420 405 752
Rubidium	6 834 682 608
Cesium	9 192 631 770

Resonance Width

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

Rubidium Oscillator

The lowest priced members of the atomic oscillator family, rubidium oscillators operate at 6,834,682,608 Hz, the resonance frequency of the rubidium atom (^{87}Rb), and use the rubidium frequency to control the frequency of a quartz oscillator. A microwave signal derived from the quartz oscillator is applied to the ^{87}Rb vapor within a cell, forcing the atoms into a particular energy state. An optical beam is then pumped into the cell and is absorbed by the atoms as it forces them into a separate energy state. 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 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 figure.



Rubidium oscillators continue to get 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. The shifts in the resonance frequency are due mainly to collisions of the rubidium atoms with other gas molecules. These shifts limit the long-term stability. Stability ($\sigma_y\tau$, at $\tau = 1$ s) is typically 1×10^{-11}, and about 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.

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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.

Short-Term Stability

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

Sidereal time

A time scale, of interest mainly to astronomers, based on the hour angle of the vernal equinox, the ascending node of the ecliptic on the celestial equator. Sidereal time differs from solar time, because the reference point provides a measure of the rotation of the Earth with respect to the stars, rather than the Sun.

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, they are not as suitable for time and frequency measurements as groundwave or satellite signals.

Solar Day

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

Solar Time

An astronomical time scale based on the Earth's rotational rate with respect to the sun. In a true solar time scale (apparent solar time), noon would be the instant when the Sun reaches its highest point in the sky. However, the irregular rate of the Earth's rotation causes the Sun to be at its highest point at a different time each day, so mean solar time (based on the length of an average day) is more useful for uniform timekeeping than apparent solar time.

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Stability

A inherent characteristic of an oscillator that determines how well it can produce the same frequency over a given time interval. It 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. The graphic below illustrates this by displaying two oscillating signals that are of the same frequency between t1 and t2. However, it’s clear that signal 1 is unstable and fluctuating in frequency between t2 and t3.

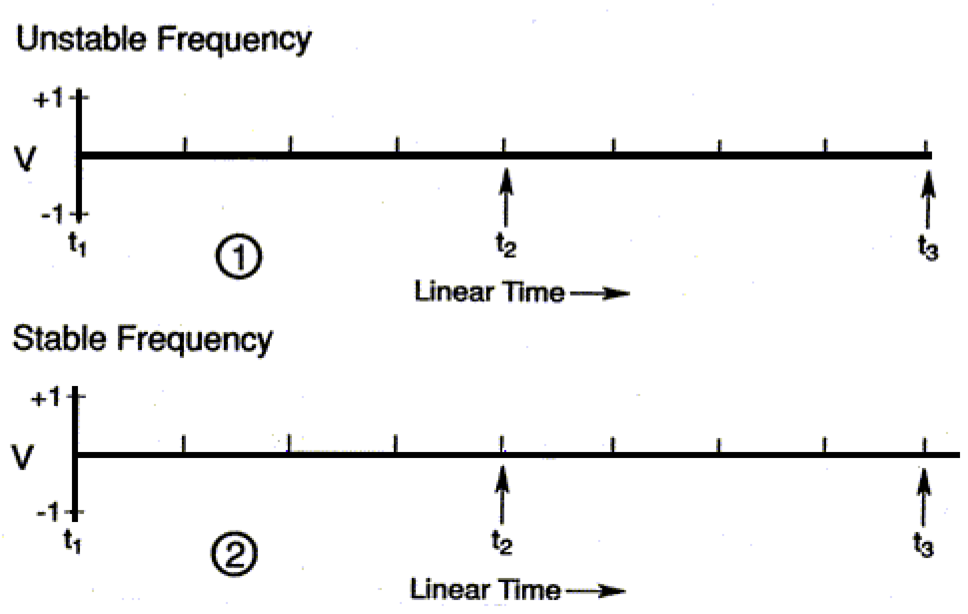

Figure 1.3

The stability of an oscillator is usually specified using 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 number 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 stopwatches 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 course compared to a time interval counter, with 10 millisecond resolution being typical.

Stratum clocks

A clock in a telecommunications system or network that is assigned a number that its quality and its position in the timing hierarchy. The highest quality clocks, called stratum 1, have a frequency offset of 1×10^{-11} or less, which means that they can keep time to within about one microsecond per day. The formal specifications are given in the ANSI standards T1.101-1999 and T1.105.09-1997. 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.

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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.

Terrahertz (THz)

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.

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Time

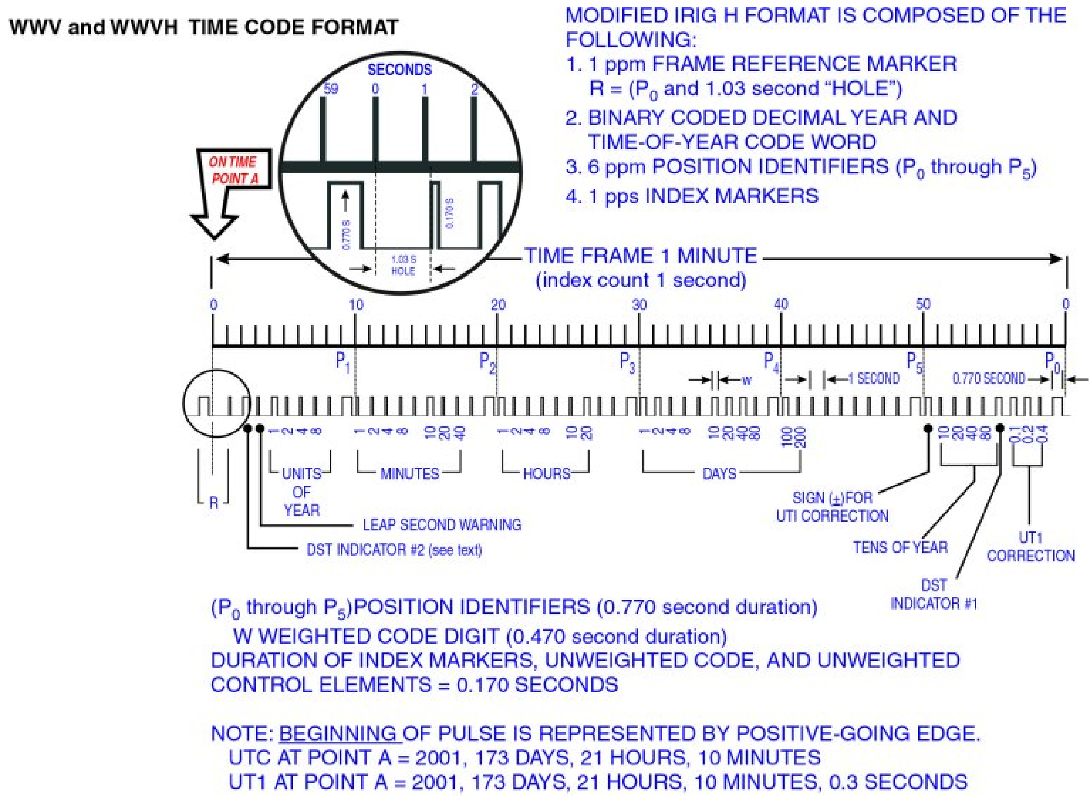
The designation of an instant on a selected time scale, used in the context of time of day; the interval between two events or the duration of an event, used in the context of time interval.

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 day, and year; and advance warning of daylight saving time and leap seconds. NIST time codes can be obtained from the WWV, WWVH, WWVB, GOES, ACTS, and Internet Time Services. The format of the WWV/WWVH time code is shown in the graphic below.



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

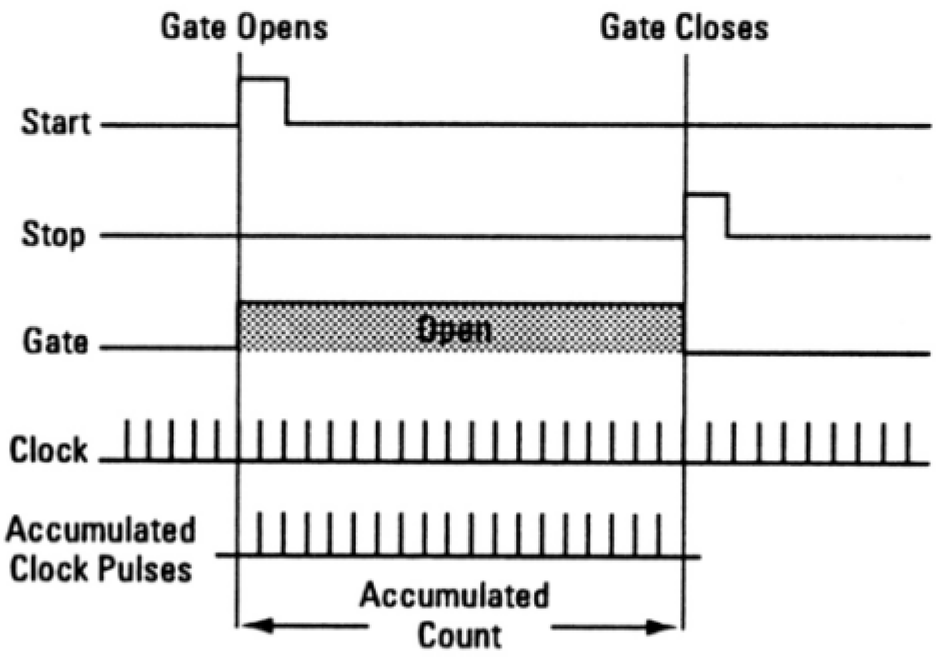
The elapsed time between two events. In time and frequency metrology, time interval is usually measured in small fractions of a second, such as milliseconds, microseconds, or nanoseconds. Course measurements of time interval can be made with a stop watch. Higher resolution time interval measurements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

TIC's differ in specification and design details, but they all contain several basic parts known as the time base, the main gate, and the counting assembly. The time base evenly spaced pulses used to measure time interval. The time base is usually an internal quartz oscillator that can often be phase locked to an external reference. It must be stable because time base errors will directly affect the measurements. The main gate controls the time at which the count begins and ends. Pulses passing through the gate are routed to the counting assembly where they are displayed on the TIC's front panel or read by computer. The counter can then be reset (or armed) to begin another measurement. The stop and start inputs are usually provided with level controls that set the amplitude limit (or trigger level) at which the counter responds to input signals. If the trigger levels are set improperly, a TIC might stop or start when it detects noise or other unwanted signals and produce invalid measurements.

The graphic below illustrates how a TIC measures the interval between two signals. The TIC begins measuring a time interval when the start signal reaches its trigger level and stops measuring when the stop signal reaches its trigger level. The time interval between the start and stop signals is measured by counting cycles from the time base. The measurements produced by a TIC are in time units such as microseconds or nanoseconds. These measurements assign a time value to the phase difference between the reference and the test signal.



The most important specification of a TIC is resolution. In traditional TIC designs, 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 traditional TIC designs count whole time base cycles to measure time interval and cannot resolve time intervals smaller than the period of one cycle. 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, a more common way to increase resolution is to detect parts of a time base cycle through interpolation and not be limited by the number of whole cycles. Interpolation has made 1 ns TICs commonplace, and even 20 picosecond TICs are available.

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.
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 work by using 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 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 in the United States. and Canada in the 1880's by the railroads to standardize time keeping. 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. Some countries use a local time that may differ 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 below 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

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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 result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties.

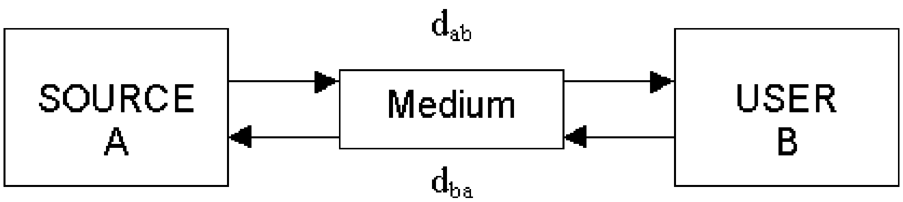
For general information about traceability, visit the NIST Traceability web site. For information specific to time and frequency metrology, visit the NIST Frequency Measurement Service page.

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 graphic below.



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 communications satellite. In this case data must be exchanged in both directions so that the two data sets can be differenced. For more information, visit the NIST Two Way Transfer web page.

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Uncertainty

Parameter, associated with the result of a measurement, that characterizes the dispersion of values that could reasonably be attributed to the measurand. By convention, two standard deviations are normally used for uncertainty numbers.

United States Naval Observatory (USNO)

Established in 1830, the USNO is one 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 kept (by mutual agreement) within 100 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 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 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.

Wavelength

The distance between identical points in the adjacent cycles of a waveform. 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

$$\mathbf{w = 300/f}$$

and conversely

$$\mathbf{f = 300/w}$$

The table shows the frequency and wavelength ranges for the frequency bands in the radio spectrum.

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
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	1 m to 10 cm
SHF	Super High	3 to 30 GHz	10 to 1 cm
EHF	Extremely	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, and its spectrum looks flat on a spectrum analyzer display. It has 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 24 hours per day, 7 days per week to millions of listeners worldwide on carrier frequencies of 2.5, 5, 10, 15, and 20 MHz. Please visit the WWV web pages for a complete description of the station.

WWVB

The NIST radio station located on the same site as WWV near Ft. Collins, Colorado. WWVB broadcasts on a carrier frequency of 60 kHz. The WWVB broadcasts are used by millions of people throughout North America to synchronize consumer electronic products like wall clocks, clock radios, and wristwatches. In addition, WWVB is used for high level applications such as network time synchronization and frequency calibrations. Please visit the WWVB web pages for a complete description of the station.

WWVH

The NIST radio station located on the Island of Kauai, Hawaii. WWVH broadcasts time and frequency information 24 hours per day, 7 days per week to listeners worldwide on carrier frequencies of 2.5, 5, 10, and 15 MHz. Please visit the WWVH web pages for a complete description of the station.

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XO

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

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 generally 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 navigation 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. 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 .

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Unlike the glossaries produced by standards committees, *Time and Frequency: From A to Z* is not intended to be an official glossary of time and frequency terminology. Instead, this glossary was created as an educational tool. Like all technical fields, time and frequency has its own terminology and jargon, including terms that are seldom used outside the field, and terms that might have different meanings in other fields. Our goal was to produce a glossary of the most common terms in the time and frequency literature, and to provide the reader with a basic understanding of what those terms mean. Readers new to the field of time and frequency should find this glossary useful when reading papers such as those found in the NIST Time and Frequency Publication Database.

The definitions in this glossary were created by reviewing and combining material from a number of different sources, with the intent of producing definitions that were complete, technically correct, and readable. We anticipate that this glossary will evolve, and we plan to continue to make changes to make the glossary more useful. Please email your comments, corrections, and suggestions to Michael Lombardi at lombardi@boulder.nist.gov.

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