

41

Time Measurement

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Although we have no control over its passage, we can measure time with more resolution and less uncertainty than any other physical quantity. The base unit of time, the second (s), is one of the seven base units of the International System of Units (SI) and can be measured so accurately that numerous other units, including the meter and ampere, depend upon its definition.

Time measurements can be divided into two general categories: *time interval* measurements and *time synchronization* measurements. Time interval measurements determine the duration or elapsed time between two events. Time standards typically produce 1 pulse per second (pps) signals. The period of these signals is a standard second that serves as a time interval reference. Many engineering and scientific applications require the measurement of time intervals much shorter than 1 s, such as *milliseconds* (ms, 10^{-3} s), *microseconds* (μ s, 10^{-6} s), *nanoseconds* (ns, 10^{-9} s), *picoseconds* (ps, 10^{-12} s), and *femtoseconds* (fs, 10^{-15} s). Thus, the instrumentation used to measure time intervals always requires subsecond resolution.

Time synchronization measurements determine the time offset between the test signal and the Coordinated Universal Time (UTC) second. The reference for these measurements is typically a 1 pps signal synchronized to UTC. If the 1 pps signal is labeled or time tagged, it can be used to synchronize time-of-day clocks and can also be used to record when an event happened. *Time tags* typically include the year, month, day, hour, minute, second, and often the fractional part of a second. When we ask the everyday question, “What time is it?” we are asking for a current time tag. By comparing and aligning time tags, we can ensure that events are *synchronized* or scheduled to occur at the same time.

Both types of time measurements are referenced to the frequency of a *periodic event* that repeats at a constant rate. For example, this periodic event could be the swings of a pendulum. We could agree to establish a base unit of time interval by defining the second as one complete swing, or cycle,

of the pendulum. Now that we have defined the second, we can measure longer time intervals, such as minutes, hours, and days, by simply counting the swings of the pendulum. This process is how a *time scale* is formed. A time scale is simply an agreed upon way to order events and keep time. It is formed by measuring and establishing a base time unit (the second) and then counting elapsed seconds to establish longer time intervals. A device that measures and counts time intervals to mark the passage of time is called a *clock*. Let's continue our discussion by looking at the evolution of clocks and timekeeping.

41.1 Evolution of Clocks and Timekeeping

All clocks share several common features, including a device that continuously produces the periodic event mentioned previously. This device is called the *resonator*. In the case of a pendulum clock, the pendulum is the resonator. Of course, the resonator needs an energy source, such as a mainspring or motor, so it can run continuously. Taken together, the energy source and the resonator form an *oscillator* that runs at a rate called the *resonance frequency*. Another part of the clock counts the oscillations and converts them to time units. And finally, the clock must display or record the results [1].

The frequency uncertainty of a clock's resonator is directly related to the timing uncertainty of the clock, as shown in Table 41.1.

Throughout history, clockmakers have searched for better oscillators that would allow them to build more accurate clocks. As early as 3500 BC, time was kept by observing the movement of an object's shadow between sunrise and sunset. This simple clock is called a *sundial*, and the resonance frequency is the apparent motion of the sun. Later, water clocks, hourglasses, and calibrated candles allowed dividing the day into smaller units of time or hours. Mechanical clocks first appeared in the early fourteenth century. Early models used a verge and foliot mechanism for an oscillator and had an uncertainty of about 15 min/day ($\cong 1 \times 10^{-2}$). However, mechanical clocks did not display minutes until near the end of the sixteenth century.

A timekeeping breakthrough occurred with the invention of the *pendulum clock*, a technology that dominated timekeeping for several hundred years and established the second as a usable unit of time interval. In the early 1580s, Galileo Galilei observed that a given pendulum took the same amount of time to swing completely through a wide arc as it did a small arc. Galileo wanted to apply this natural periodicity to time measurement and had begun work on a mechanism to keep the pendulum in motion in 1641, a year prior to his death. In 1656, the Dutch scientist Christiaan Huygens invented an escapement that kept the pendulum swinging. The uncertainty of Huygens's clock was less than 1 min/day ($\cong 7 \times 10^{-4}$) and later reduced to about 10 s/day ($\cong 1 \times 10^{-4}$). The first pendulum clocks were weight driven, but later versions were powered by springs. Huygens is often credited with inventing the spring and balance wheel assembly still found in some of today's mechanical wristwatches.

TABLE 41.1 Relationship of Frequency Uncertainty to Timing Uncertainty

Frequency Uncertainty	Measurement Period	Timing Uncertainty
$\pm 1.00 \times 10^{-3}$	1 s	± 1 ms
$\pm 1.00 \times 10^{-6}$	1 s	± 1 μ s
$\pm 1.00 \times 10^{-9}$	1 s	± 1 ns
$\pm 2.78 \times 10^{-7}$	1 h	± 1 ms
$\pm 2.78 \times 10^{-10}$	1 h	± 1 μ s
$\pm 2.78 \times 10^{-13}$	1 h	± 1 ns
$\pm 1.16 \times 10^{-8}$	1 day	± 1 ms
$\pm 1.16 \times 10^{-11}$	1 day	± 1 μ s
$\pm 1.16 \times 10^{-14}$	1 day	± 1 ns

Major advances in timekeeping accuracy resulted from the work of John Harrison, who built and designed a series of clocks in the 1720s that kept time to within fractions of a second per day (parts in 10^6). His performance was not improved upon until the twentieth century. Harrison dedicated most of his life to solving the British navy's problem of determining longitude, by attempting to duplicate the accuracy of his land clocks at sea. He built a series of clocks (now known as H1 through H5) in the period from 1730 to about 1770. He achieved his goal with the construction of H4, a clock much smaller than its predecessors, about the size of a large pocket watch. H4 used a spring and balance wheel escapement and kept time within fractions of a second per day during several sea voyages in the 1760s.

The practical performance limit of pendulum clocks was reached in 1921, when W. H. Shortt demonstrated a clock with two pendulums, one a slave and the other a master. The slave pendulum moved the clock's hands and freed the master pendulum of tasks that would disturb its regularity. The pendulums used a battery as their power supply. The Shortt clock kept time within a few seconds per year ($\cong 1 \times 10^{-7}$) and was once used as a primary standard for time interval in the United States [1–3].

Quartz crystal oscillators, based on the phenomenon of piezoelectricity discovered by P. Curie in 1880, worked better than pendulums, resonating at a nearly constant frequency when an electric current was applied. Credit for developing the first quartz oscillator is generally given to Walter Cady, who built prototypes shortly after World War I and patented a piezoelectric resonator designed as a frequency standard in 1923. Joseph W. Horton and Warren A. Morrison of Bell Laboratories built the first clock based on a quartz crystal oscillator in 1927. By the late 1930s, quartz oscillators began to replace pendulums as the standard for time interval measurements.

Billions of quartz oscillators are now manufactured annually. They are found in nearly every type of electronic circuit, including many devices that display time such as clocks, watches, cell phones, radios, and computers. Even so, quartz oscillators are not an ideal timekeeping source. Their resonance frequency depends on the size and shape of the crystal, and no two crystals are exactly alike or produce exactly the same frequency. Their frequency is also sensitive to changes in the environment, including temperature, pressure, and vibration. These limitations make them unsuitable for high-accuracy timekeeping and led to the development of atomic oscillators [1,4–6].

41.2 Atomic Oscillators

The practice of using resonant transitions in atoms or molecules is attractive for several reasons. For example, an unperturbed atomic transition is identical from atom to atom, so that, unlike a group of quartz oscillators, a group of atomic oscillators should all generate the same frequency. Also, unlike all electrical or mechanical resonators, atoms do not wear out or change their properties over time. These features were appreciated by Lord Kelvin, who suggested using transitions in sodium and hydrogen atoms as timekeeping oscillators in 1879. However, it wasn't until the late 1930s that technology made his idea possible, when I. I. Rabi and his colleagues at Columbia University introduced the idea of using an atomic resonance as a frequency standard.

Atomic oscillators use the quantized energy levels in atoms and molecules as the source of their resonance frequency. The laws of quantum mechanics dictate that the energies of a bound system, such as an atom, have certain discrete values. An electromagnetic field 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 electromagnetic energy. The resonance frequency (f) of an atomic oscillator is the difference between the two energy levels divided by Planck's constant (h):

$$f = \frac{E_2 - E_1}{h} \quad (41.1)$$

The basic principle of the atomic oscillator is simple: Because all atoms of a specific element are identical, they should produce exactly the same frequency when they absorb energy or release energy.

us, atomic oscillators easily surpassed the performance of all previous standards. In theory, the atom is a perfect pendulum whose oscillations can be used as a standard of frequency or counted to measure time interval.

The three major types of commercial atomic oscillators are based on rubidium, cesium, and hydrogen atoms, respectively. The least expensive and most common type is the *rubidium oscillator*, based on the 6.8347 GHz resonance of ^{87}Rb . Rubidium oscillators are well suited for applications that require a small, high-performance oscillator. The frequency uncertainty of a rubidium oscillator over a 1 day interval typically ranges from about $\pm 5 \times 10^{-9}$ to $\pm 5 \times 10^{-12}$.

The second type of atomic oscillator, the *cesium oscillator*, serves as a primary standard in many laboratories, because the resonance frequency of cesium (9.1926 GHz) is used to define the second (Section 41.3). Because the base unit of time is defined with respect to cesium resonance, the 1 pps output from a cesium oscillator serves as an internationally recognized time interval standard. Commercially available cesium beam oscillators typically have a frequency uncertainty over a 1 day interval near $\pm 1 \times 10^{-13}$, with the best units about one order of magnitude better. Even so, a cesium cannot recover time by itself and cannot be used as a synchronization reference unless it has been synchronized with another source.

Currently (2010), the world's best time interval standards are cesium fountains. These devices are large, sometimes several meters tall. They are not sold commercially but have been built by several national metrology laboratories. Cesium fountains work by laser cooling atoms to a temperature near absolute zero (less than $1 \mu\text{K}$) and then launching them vertically. The atoms make two passes (one on the way up, the second on the way down) through a microwave cavity where the atomic resonance frequency is measured. The atoms can be observed for about 1 s. This allows a cesium fountain to outperform cesium beam standards, which have a much shorter observation period, typically about 1 ms. The primary frequency and time interval standard in the United States is a cesium fountain called NIST-F1 (Figure 41.1) that can realize the second with an uncertainty of about 3×10^{-16} .

A third type of atomic oscillator, the *hydrogen maser*, is based on the 1.42 GHz resonance frequency of the hydrogen atom. Hydrogen masers typically are more stable than cesium oscillators for periods

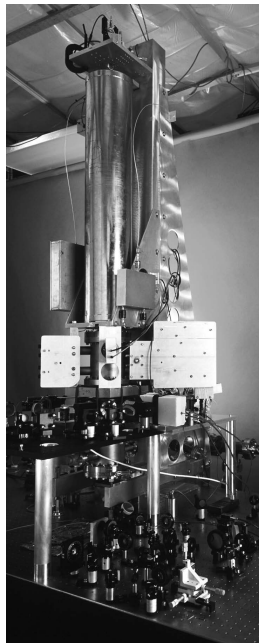


FIGURE 41.1 NIST-F1 cesium fountain.

TABLE 41.2 Evolution of Clock Design and Performance

Type of Clock	Resonator	First Appearance	Typical Time Uncertainty (1 Day)	Typical Frequency Uncertainty (1 Day)
Sundial	Apparent motion of sun	3500 BC	NA	NA
Mechanical	Verge and foliot mechanism	Fourteenth century	± 15 min	$\pm 1 \times 10^{-2}$
Pendulum	Pendulum	1656	± 10 s	$\pm 7 \times 10^{-4}$
Harrison chronometer	Pendulum	1761	± 400 ms	$\pm 4 \times 10^{-6}$
Shortt pendulum	Two pendulums, slave and master	1921	± 10 ms	$\pm 1 \times 10^{-7}$
Quartz	Quartz crystal	1927	± 100 μ s	$\pm 1 \times 10^{-9}$
Rubidium	Rubidium atomic resonance (6.834682610904 GHz)	1958	± 1 μ s	$\pm 1 \times 10^{-11}$
Cesium beam	Cesium atomic resonance (9.19263177 GHz)	1952	± 10 ns	$\pm 1 \times 10^{-13}$
Cesium fountain	Cesium atomic resonance (9.19263177 GHz)	1995	± 0.1 ns	$\pm 1 \times 10^{-15}$
Hydrogen maser	Hydrogen atomic resonance (1.420405751768 GHz)	1960	± 10 ns	$\pm 1 \times 10^{-13}$
CSACs	Cesium or rubidium atomic resonance	2001	± 10 μ s	$\pm 1 \times 10^{-10}$

shorter than about 1 month. However, they lack the accuracy of cesium standards. Few are manufactured and sold due to their high cost, which often exceeds \$200,000 [4–9].

Miniature atomic clocks, known as chip scale atomic clocks (CSACs), based on either rubidium or cesium resonance, were first reported on at NIST in 2001. At this writing (2010), these devices have been reduced to a volume of about 10 cm³, have low power consumption requirements that can be satisfied by an AA battery, and are stable enough to keep time to within about 10 μ s/day [10]. It seems likely that they will eventually be embedded in many types of commercial products.

Future atomic clocks will undoubtedly be based on the optical frequency of atoms, instead of the microwave frequencies. The resonance frequency of an optical atomic clock will be approximately 10¹⁵ Hz or about 10⁵ times higher than the cesium resonance frequency. Thus, optical clocks will operate with a much smaller unit of time, a change comparable to using the second instead of the day as the base unit of time interval and making huge reductions in uncertainty possible. Many experimental optical atomic clocks have already been successfully designed and tested, but it is difficult to predict when they will replace the existing microwave standards [6,11,12].

Table 41.2 summarizes the evolution of clock design and performance. The uncertainties listed are for modern (2010) devices and not the original prototypes. Note that the performance of time and frequency standards has improved by about 14 orders of magnitude in the past 700 years and by about 10 orders of magnitude during the past 100 years.

41.3 Definition of the Second

As noted, the uncertainty of a clock depends upon the irregularity of some type of periodic motion. This periodic motion can be measured and used to define the second, which is the base unit of time interval in the SI. Because atomic time standards were clearly superior to their predecessors, they quickly became the world reference for time interval measurements. The atomic timekeeping era formally began in 1967, when the SI second was redefined based on the resonance frequency of the cesium atom:

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.

Before the invention of atomic clocks and the acceptance of atomic time, the second was defined by using astronomical time scales. The astronomical definitions of the second were very different from the atomic definition. Instead of *multiplying* the period of a short atomic event to form a longer time interval, the early definitions of the second were based on *dividing* the period of a long astronomical event to form a shorter time interval. There was no official metrological definition of the second until the SI was formed in 1960. However, prior to that date, the second was obtained by dividing the *mean solar day* or the average period of one revolution of the Earth on its axis. The *mean solar second* was 1/86,400 of the mean solar day and served as the base unit of time interval for the Universal Time (UT) family of time scales. Several variations of UT were 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. When quartz clocks became available, astronomers noticed errors in UT0 due to polar motion, which led to the UT1 time scale.

UT1: UT1 improved upon UT0 by correcting for the shift in longitude of the observing station due to polar motion. Because the Earth's rate of rotation is not uniform, the uncertainty of UT1 can be as large as a few 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.

The *ephemeris second* was defined in 1956 and designated as the original SI second in 1960. It was defined by dividing the tropical year or the interval between the annual vernal equinoxes that 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. It also made the ephemeris second nearly impossible to realize in a laboratory and of little or no use to metrologists or engineers. Thus, its tenure was understandably short. It remained part of the SI for just 7 years before being replaced by the much more accessible atomic definition [5,6,13].

41.4 Coordinated Universal Time

Coordinated Universal Time (UTC) is an atomic time scale that is based on the SI definition of the second and that serves as the official time reference for most of the world. UTC is maintained by the Bureau International des Poids et Mesures (BIPM) in Sevres, France. As of 2010, it is computed from a weighted average of nearly 400 atomic standards located at some 70 laboratories, including the National Institute of Standards and Technology (NIST) and the US Naval Observatory (USNO). Most of these devices are cesium beam standards, but some are hydrogen masers. In addition, about ten cesium fountain standards contribute to the accuracy of UTC.

UTC is a virtual time scale, generated from computations made on past measurements, and is distributed only through a monthly BIPM publication called the *Circular T*. No physical clock generates the official UTC. To support physical measurements of time and time interval, many laboratories maintain local UTC time scales that generate real-time signals that approximate UTC as closely as possible, often within a few nanoseconds. The *Circular T* reports the time differences between UTC and these local time scales, which are generically referred to as UTC(*k*), where *k* represents the acronym for the timing laboratory. For example, NIST maintains UTC(NIST) and the USNO maintains UTC(USNO).

The BIPM derives UTC from an internal time scale called International Atomic Time (TAI). Both UTC and TAI run at the same frequency. However, UTC differs from TAI by an integer number of seconds. This difference increases when *leap seconds* occur. When necessary, leap seconds are added to the UTC time scale on either June 30 or December 31. Their purpose is to ensure that the difference between atomic time (UTC) and astronomical time (UT1) does not exceed 0.9 s. Time codes (Section 41.5) contain a *DUT1 correction* or the current value of UT1 minus UTC. By applying this correction to UTC, users who need astronomical time can obtain UT1.

Leap seconds have been added to UTC when necessary since 1972. From 1972 to 2008, UT1 has lost (on average) more than 600 ms/year with respect to UTC; thus, 24 leap seconds were added during the 36 year interval. This means that atomic seconds are shorter than astronomical seconds and that UTC runs faster than UT1. There are two reasons for this. The first and most important reason is the definition of the atomic second. The atomic second was originally defined with respect to the ephemeris second and was shorter than the mean solar second from the beginning. The second reason is that the Earth's rotational rate is gradually slowing down and the astronomical second is gradually getting longer. When a positive leap second is added to UTC, the sequence of events is

23 h 59 m 59 s

23 h 59 m 60 s

0 h 0 m 0 s

The insertion of the leap second creates a minute that is 61 s long. This “stops” UTC for 1 s, so that UT1 can catch up [5,6,13]. Some timekeeping laboratories and other organizations have found the leap second to be cumbersome to implement and support, and there is currently an International Telecommunications Union (ITU) proposal to eliminate the leap second and instead make a larger time correction, such as a leap hour, when one is eventually needed. However, leap seconds are still in effect at this writing (2010), and the issue remains unresolved.

41.5 Time Interval Measurements

A common, but not particularly accurate, way to measure time interval is to use an oscilloscope. Oscilloscopes allow us to view the pulse waveforms, making it possible to select the start and end points that define a time interval, a major advantage when dealing with odd-shaped or noisy waveforms. Sometimes one pulse is displayed, while a different pulse is used to trigger the oscilloscope. Another method is to display both time pulses on a dual-trace oscilloscope. Triggering can be achieved from either of the two displayed pulses or from a third external pulse. The divisions along the horizontal axis of an oscilloscope are in units of time, and many oscilloscopes have a delta-time function (Δt) that will measure and display the time interval between two cursors that can be moved along the horizontal axis. The oscilloscope display in [Figure 41.2](#) shows a 358 ns time interval between two cursors that are aligned with the rising edge of two 1 pps signals.

Time interval measurements made with oscilloscopes are limited by a lack of resolution and range. Oscilloscope range varies, and some models can scale from 50 ps to 10 s per time division. However, the resolution of the time interval measurement is proportional to the length of the interval. If the time pulses are 10 ms apart, for instance, the best oscilloscopes can resolve the interval to only about 1 μ s. However, if the pulses are only 100 μ s apart, the resolution is 10 ns. In both cases, the relative uncertainty is 1×10^{-4} .

A time interval counter (TIC) is usually the best instrument for measuring all but the shortest time intervals. Universal counters can measure time interval (along with other quantities such as frequency and period), and dedicated TICs are also available. A TIC measures the time interval between a start pulse and a stop pulse. The start pulse gates the TIC (starts it counting), and a stop pulse stops the counting. While the gate is open ([Figure 41.3](#)), the counter counts zero crossings from time base oscillator cycles, and the resolution of the simplest TICs is equal to the period of these cycles (e.g., 100 ns for a 10 MHz time base). However, many TICs use interpolation or digital processing schemes to divide the period into smaller parts. For example, dividing 100 ns by 5000 allows 20 ps resolution, a feat achieved

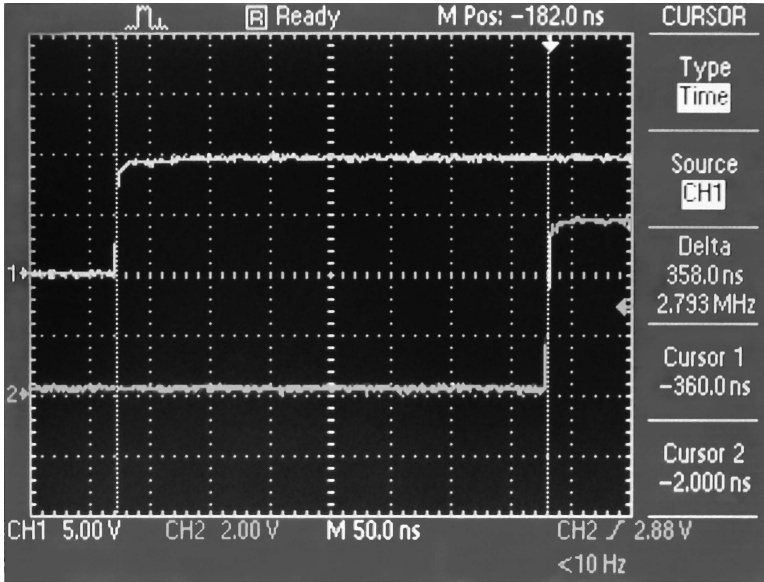


FIGURE 41.2 Measuring time interval with an oscilloscope.

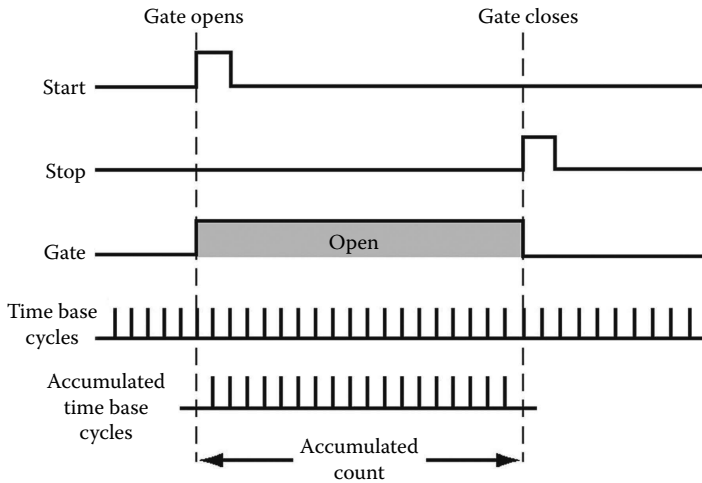


FIGURE 41.3 Gate and counting function of TIC.

by some universal counters, and some dedicated TICs achieve 1 ps resolution. These resolutions allow TICs to reach measurement uncertainties of 2×10^{-11} or less over a 1 s interval, often averaging down to parts in 10^{15} or 10^{16} after a few hours.

The uncertainty of TIC measurements can be limited, however, by resolution, trigger errors, or time base errors. A TIC generally has some ambiguity in its least significant digit of resolution. However, this count ambiguity often averages out when multiple readings are taken and is usually a problem only with single measurements. Trigger errors are a more significant problem. They occur when the counter does not trigger at the expected voltage level on the input signal and can be caused by incorrect trigger settings or by input signals that are noisy, too large, or too small. It is imperative to make sure that the TIC is triggering at the proper point on both the start and stop waveforms (if necessary, view the waveforms on an oscilloscope). Time base errors are generally not a problem when measuring short time intervals.

For example, consider a typical counter with 1 ns resolution and a time base stability of 1×10^{-8} . When a 1 ms interval is measured, the time base uncertainty is $10^{-3} \text{ s}/10^8 = 10^{-11} \text{ s}$ or 10 ps. This is much smaller than the uncertainty contributed by the counter's resolution. Even so, the best oscillator available should be used as the counter's external time base, because time base errors can be significant when long time intervals are measured.

A TIC can also measure medium and long time intervals if it has the necessary range. For example, a TIC that counts 100 ns periods with a 32 bit counter will overflow after $2^{32} \times 100 \text{ ns}$ or about 429 s. However, many TICs keep track of counter overflows, and some have the ability to measure intervals of about 1 day in time interval mode. If the TIC range is insufficient, most universal counters have a totalize mode that simply counts cycles from an external frequency source. Some commercial counters can count up to 10^{15} cycles. The period of the external gate frequency determines the resolution of this type of measurement. For example, if 1 μs resolution is desired, use a 1 MHz gate frequency. In this case, the time interval range would be $10^{15}/10^6 = 10^9 \text{ s}$ or nearly 32 years.

The most common time interval measurements are probably made with stopwatches and similar low-cost timing devices. These devices are used to measure time intervals ranging from several seconds to many hours, and although the measurement uncertainties are high, stopwatches still must be periodically calibrated. These calibrations are typically performed by manually triggering the stopwatch while listening to an audio time signal or viewing a synchronized time display. The legally required uncertainty for stopwatch calibrations is often 1 or 2 parts in 10^4 , a requirement limited mostly by human reaction time, which is often 10–100 times worse than the uncertainty of the oscillator inside the stopwatch.

Other stopwatch calibration methods reduce or eliminate the problem of human reaction time. One method utilizes a universal counter in the totalize mode described earlier. The counter is gated with a signal from a calibrated signal generator. The gate frequency should have a period at least one order of magnitude smaller than the resolution of the stopwatch. For example, if the stopwatch has 10 ms resolution, use a 1 kHz frequency (1 ms period). The operator then starts and stops the totalize counter by rapidly pressing the start–stop button of the stopwatch against the start–stop button on the counter. The readings from both instruments are recorded, and the equation $\Delta t/T$ is used to get the result, where Δt is the difference between the counter and stopwatch displays and T is the length of the measurement run. For example, if $\Delta t = 100 \text{ ms}$ and $T = 1 \text{ h}$, the uncertainty is roughly 2.8×10^{-5} , which exceeds the legal requirement.

A second method involves measuring the frequency offset of the oscillator inside the stopwatch, which is usually a 32,768 Hz quartz oscillator. For example, if the stopwatch time base oscillator has a 1 Hz frequency offset, the dimensionless frequency offset ($1/32,768 = 3 \times 10^{-5}$) translates to a time offset of about 110 ms in 1 h or near the value for Δt in the previous example. Commercially available instruments with acoustic or inductive sensors can detect the oscillator frequency and automate this measurement [14].

41.6 Time Synchronization Measurements

Many applications require multiple clocks to be *synchronized* or set to the same time. Using the time interval measurement methods described in Section 41.5, a clock can be synchronized by comparing it to a UTC reference and adjusting the time offset until it is as near zero as possible. *Time transfer* is the practice of transferring the time from a reference clock at one location and using it to measure or synchronize a clock at another location.

The reference signals used for time transfer generally need to provide two things: an on-time marker (OTM) and a time code. The OTM is typically a 1 pps signal that is synchronized to the start of the UTC second. The time code provides time-of-day information including the UTC hour, minute, and second, as well as the month, day, and year. These reference signals usually originate from a UTC time scale maintained by a national timekeeping laboratory.

Time can be transferred through many different mediums, including coaxial cables, optical fibers, radio signals, telephone lines, and computer networks. Before discussing the available radio and Internet time transfer signals, the methods used to transfer time [15] are examined.

41.6.1 Time Transfer Methods

As noted, time transfer methods are used to synchronize or compare a local clock to a reference clock. The single largest contributor to time transfer uncertainty is *path delay* or the delay introduced as the signal travels from its source to its destination. To illustrate the path delay problem, consider a reference time signal broadcast by radio. To synchronize a remote clock at a receiving site to the reference time, we need to calculate how long it took for the signal to travel from the transmitter to our receiver. Radio signals travel at the speed of light at about $3.3 \mu\text{s}/\text{km}$. Therefore, if the receiver is 1000 km from the transmitter, the time will be 3.3 ms late when we receive it. We can compensate for this path delay by making a 3.3 ms adjustment to the remote clock. This practice is called *calibrating the path*.

In the example earlier, we are assuming that the signal travelled the shortest path between the transmitter and receiver, which are not always true. Many factors limit how well the path can be calibrated, and our knowledge of the received time will always be limited by our knowledge of the path delay. However, many innovative ways have been developed to compensate for path delay. The various time transfer methods can be divided into five general categories:

1. *One-way method (user calibrates path)*: This is the simplest type of time transfer, a one-way system where the user is responsible for calibrating the path (if required). The signal from the transmitter to the receiver is delayed τ_{ab} by the medium (Figure 41.4). To obtain the best results, the user must estimate τ_{ab} and calibrate the path by compensating for the delay. In many cases, however, the time is already accurate enough to meet the user's requirements, so the delay through the medium is simply ignored.
2. *One-way method (self-calibrating path)*: This method is a variation of the simple one-way method shown in Figure 41.4. However, the time transfer system (and not the user) is responsible for estimating and removing the τ_{ab} delay.

One of two techniques is commonly used to reduce τ_{ab} . The first technique is to simply estimate τ_{ab} and to send the time out early. For example, if we estimate that τ_{ab} will be at least 20 ms for all users, we can transmit the OTM 20 ms before the arrival of the UTC second and reduce the uncertainty for all users.

A more sophisticated technique is to compute τ_{ab} and apply a correction. This can be done if the coordinates of both the transmitter and receiver are known. If the transmitter is stationary, a constant can be used for the transmitter position. If the transmitter is moving (e.g., a satellite), it must broadcast its coordinates in addition to broadcasting a time signal. The receiver's coordinates must either be computed by the receiver (in the case of satellite navigation systems) or input by the user. Then, the receiver firmware can compute the distance between the transmitter and receiver and compensate for the path delay by correcting for τ_{ab} . The uncertainty of this method is still limited by position errors for either the transmitter or receiver and by variations in the transmission speed of the signal along the path.

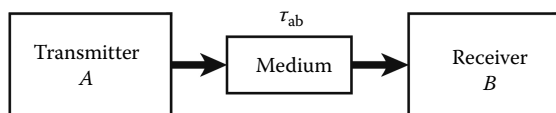


FIGURE 41.4 One-way time transfer.

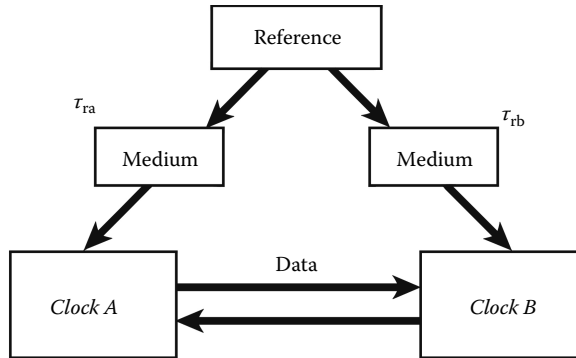


FIGURE 41.5 Common-view time transfer.

3. *Common-view method:* The common-view method involves a reference transmitter (R) and two receivers (A and B). The transmitter is in “common view” to both receivers. Both receivers compare the simultaneously received signal to their local clock and record the data (Figure 41.5). Receiver A receives the signal over the path τ_{ra} and compares the reference to its local clock ($R - \text{Clock } A$). Receiver B receives the signal over the path τ_{rb} and records ($R - \text{Clock } B$). The difference between the two measurements is an estimate of the difference between the two clocks. Errors from the two paths (τ_{ra} and τ_{rb}) that are common to the reference cancel out, eliminating much of the uncertainty caused by path delay. The result of the measurement is $(\text{Clock } A - \text{Clock } B) - (\tau_{ra} - \tau_{rb})$.

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

4. *Two-way method:* The two-way method requires two users to both transmit and receive timing signals through the same medium at the same time (Figure 41.6). This differs from the passive common-view method where timing signals are only received and not transmitted. Sites A and B simultaneously exchange time signals through the same medium and compare the received signals with their own clocks. Site A records $A - (B + \tau_{ba})$ and site B records $B - (A + \tau_{ab})$, where τ_{ba} is the path delay from B to A and τ_{ab} is the path delay from A to B . The difference between the two clocks is $(A - B)/2 + (\tau_{ba} - \tau_{ab})/2$. If the path is reciprocal ($\tau_{ab} = \tau_{ba}$), then the difference is simply $(A - B)/2$.

When properly implemented, the two-way method outperforms all other time transfer methods and has many potential applications. It can, however, be complex to implement. When wireless mediums are used, it can require a substantial amount of equipment, as well as government licensing so that users are allowed to transmit. Like the common-view method, the two-way method requires measurement data to be transferred. However, because users have the ability to transmit, it is possible to send data through the same medium as the time signals.

5. *Loop-back method:* A variation of the two-way method, the loop-back method also requires the receiver to send information back to the timing source. For example, an OTM is sent from the transmitter (A) to the receiver (B) over the path τ_{ab} . The receiver (B) then sends the OTM back to

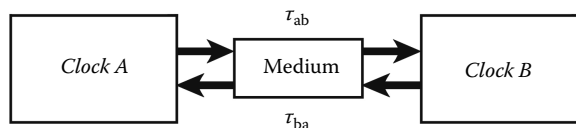


FIGURE 41.6 Two-way time transfer.

the transmitter (A) over the path τ_{ba} . The one-way path delay is assumed to be half of the measured round trip delay or $(\tau_{ab} + \tau_{ba})/2$. The transmitter calibrates the path by sending another OTM that has now been advanced by the estimated one-way delay. The method usually works well but is less accurate than the two-way method because the OTM transmissions are not simultaneous, and it is not known whether the path delay is the same in both directions. The loop-back method is not practical to use through a wireless medium and is typically applied to telephone or network connections where it can be implemented entirely in software.

41.6.2 Time Codes

A *time code* is a message containing time-of-day information that allows the user to synchronize a clock. ITU guidelines state that all time codes should distribute the UTC hour, minute, and second, as well as a DUT1 correction.

Time codes are broadcast in a number of different formats (including binary, binary coded decimal [BCD], and ASCII). There is very little standardization of broadcast time codes, but standards for redistributing time codes within a facility were first developed by the Inter-Range Instrumentation Group (IRIG) in 1956 and are still used by today's equipment manufacturers. IRIG defined numerous time code formats, but the most common is probably IRIG-B. These standardized time codes make it possible for manufacturers to build compatible equipment. For example, a satellite receiver with an IRIG-B output can drive a time-of-day display that accepts an IRIG-B input. Or it can provide a timing reference to a computer that can read IRIG-B.

The IRIG time code formats are serial, width-modulated codes that can be used in either dc level shift or amplitude-modulated (AM) form. For example, IRIG-B has a 1 s frame period and can be transmitted as either a dc level shift modulation envelope or a modulated 1000 Hz carrier. Time-of-day data (days, hours, minutes, and seconds) in BCD or straight binary format is included within the frame. Simple IRIG-B decoders retrieve just the encoded data and provide 1 s resolution. Other decoders count carrier cycles and provide resolution equal to the period of the 1000 Hz cycle (1 ms). More advanced decoders phase lock an oscillator to the time code and provide resolution limited only by the signal-to-noise ratio of the time code (typically $\pm 2 \mu\text{s}$).

41.7 Radio Time Transfer

Several types of receivers and signals are used to transfer time by radio. The cost of a time transfer receiver can vary widely, from less than \$10 for a simple radio-controlled clock that synchronizes once per day and keeps time within 1 s of UTC to \$20,000 or more for a receiver that adjusts a rubidium oscillator with satellite signals and keeps time within nanoseconds of UTC. When selecting a time transfer receiver, make sure that the signal can be received at your location, that the uncertainty is low enough to meet your requirements, and that the appropriate type of antenna can be mounted. The following sections summarize the various signals used for radio time transfer.

41.7.1 HF Time Signal Stations

High-frequency (HF) or *shortwave* radio signals are used for time transfer at moderate performance levels. These stations are useful because they provide worldwide coverage under optimal receiving conditions, they can be heard with any shortwave receiver, and they provide audio time announcements that can serve as a "talking clock." The audio signals are also widely used by metrologists as a time interval reference for stopwatch and timer calibrations. The practical limit of time transfer uncertainty with HF stations is about 1 ms. This is because the signals often travel by *sky wave* and the path length varies, making it difficult to accurately determine the path delay.

TABLE 41.3 HF Time Signal Station List

Call Sign	Location	Frequencies (MHz)	Controlling Agency
WWV	Fort Collins, Colorado, United States	2.5, 5, 10, 15, 20	NIST
WWVH	Kauai, Hawaii, United States	2.5, 5, 10, 15	NIST
BPM	Lintong, China	2.5, 5, 10, 15	National Time Service Center (NTSC)
CHU	Ottawa, Canada	3.33, 7.85, 14.67	National Research Council (NRC)
HLA	Taejon, Korea	5	Korea Research Institute of Standards and Science (KRISS)

Table 41.3 provides a list of HF time signal stations that are referenced to UTC as of 2010. Only a few stations remain, as many have been turned off in recent years. This is probably because far more accurate time signals can now be easily obtained from satellites and because low accuracy time (within 1 s) can now be easily obtained from the Internet or from inexpensive low-frequency (LF) radio-controlled clocks.

The best known HF time signal stations are WWV and WWVH, both operated by NIST. WWV is located near Fort Collins, CO, and WWVH is on the island of Kauai, HI. Both stations broadcast continuously on 2.5, 5, 10, and 15 MHz, with WWV also available on 20 MHz. All frequencies carry the same audio broadcast, which includes short pulses transmitted every second that sound similar to the ticking of a clock. At the start of each minute, a voice announces the current UTC hour and minute. WWV uses a male voice to announce the time, and WWVH uses a female voice. The voice announcement is followed by a long audio pulse of 800 ms in duration. In addition to the audio, a time code is sent on a 100 Hz subcarrier at a 1 bit per second (bps) rate.

41.7.2 LF Time Signal Stations

LF signals are seldom used for high-accuracy time transfer, but they have a major advantage over HF and satellite signals—they can be easily received indoors without an external antenna. This makes LF time signal stations the ideal synchronization source for radio-controlled clocks and wristwatches. Signals from NIST radio station WWVB synchronize an estimated total of more than 50 million radio-controlled clocks in the United States daily as of 2010, with many millions of new clocks being sold each year.

Several countries operate LF time signal stations at frequencies ranging from 40 to 77.5 kHz (Table 41.4). These stations do not provide voice announcements but do provide an OTM and a time code.

NIST radio station WWVB, which covers most of North America, has a format similar, but not identical, to that of the other stations listed in Table 41.4. WWVB requires a full minute to send its

TABLE 41.4 LF Time Signal Station List

Call Sign	Location	Frequencies (kHz)	Controlling Agency
WWVB	Fort Collins, Colorado, United States	60	NIST
BPC	Lintong, China	68.5	NTSC
DCF77	Mainingen, Germany	77.5	Physikalisch-Technische Bundesanstalt (PTB)
JJY	Japan	40, 60	National Institute of Information and Communications Technology (NICT)
MSF	Rugby, United Kingdom	60	National Physical Laboratory (NPL)
RBUS	Moscow, Russia	66.67	Institute of Metrology for Time and Space (IMVP)

time code in BCD format. Bits are sent at a rate of 1 bps by shifting the power of the carrier. The carrier power is reduced 17 dB at the start of each second, and the first carrier cycle after the power drop serves as the OTM. If full power is restored after 200 ms, it represents a binary 0. If full power is restored after 500 ms, it represents a binary 1. Reference markers and position identifiers are sent by restoring full power after 800 ms. The WWVB time code provides year, day, hour, minute, and second information, a DUT1 correction, and information about daylight saving time, leap years, and leap seconds.

Calibrating the path is easier with LF signals than HF signals, because part of the LF signal is *ground wave* and follows the curvature of the Earth. However, due to uncertainties in the estimate of path delay and because it is difficult to determine the correct OTM to within better than a few cycles of the carrier, the practical limit for timing uncertainty with WWVB and similar stations is about 0.1 ms or roughly 1000 times larger than the timing uncertainty of GPS, as explained in the next section.

41.7.3 Global Positioning System

The Global Positioning System (GPS) is a global navigation satellite system (GNSS) developed and operated by the US Department of Defense (US DoD). GPS was designed as a positioning and navigation system but has become the main system used to distribute high-accuracy time signals worldwide. The GPS constellation includes as many as 32 satellites in semi-synchronous orbit at a height of 20,200 km. The orbital period is 11 h and 58 min, which means that each satellite passes over a given location on Earth 4 min earlier than it did on the previous day. By processing GPS signals, even a low-cost handheld receiver can determine its position on Earth with an uncertainty of a few meters.

The GPS satellites carry atomic clocks that are steered from US DoD ground stations to agree with UTC(USNO), which is normally well within 20 ns of UTC. GPS time must be accurate in order for the system to meet its specifications for positioning and navigation. To illustrate this, consider that the satellites receive clock corrections from Earth-based control stations once during each orbit or about once every 12 h. The maximum acceptable contribution from the satellite clocks to the positioning uncertainty is considered to be about 1 m. Since light travels at about 3×10^8 m/s, the 1 m requirement means that the time error between clock corrections must be less than about 3.3 ns.

All GPS satellites broadcast on the *L1* (1.57542 GHz) and *L2* (1.2276 GHz) carrier frequencies, with satellites launched after May 2010 also utilizing the *L5* carrier at 1.17645 GHz. The satellites are identified by a unique spread-spectrum waveform, called a pseudorandom noise (PRN) code, which it transmits on each carrier. There are two types of PRN codes. The first type is a coarse acquisition (*C/A*) code with a chip rate of 1.023 megabits/s. The second type is a precision (*P*) code with a chip rate of 10.230 megabits/s. The *C/A* code is broadcast on *L1*, and the *P* code is broadcast on both *L1* and *L2*. A 50 bit/s data message is also broadcast on both carriers [16–18]. Dual-frequency timing receivers have become more common as of 2010, but most timing devices receive only *L1*. Nearly all GPS timing receivers can simultaneously track at least eight satellites.

41.7.4 One-Way Time Transfer Using GPS

GPS receivers transfer time from the satellites to the receiver clock through a series of range measurements. The range measurements used to calculate position are derived by measuring the time required for the signals to travel from each satellite to the receiver. After the receiver position (x, y, z) is solved for, the solution is stored. Then, by using the travel time of the signal and the exact time when the signal left the satellite, time from the satellite clocks can be transferred to the receiver clock.

is time difference between the satellite and receiver clocks, when multiplied by the speed of light, produces not the true geometric range but rather the pseudorange. The equation for the pseudorange observable is

$$p = \rho + c \times (dt - dT) + d_{\text{ion}} + d_{\text{trop}} + r_n \quad (41.2)$$

where

p is the pseudorange

c is the speed of light

ρ is the geometric range to the satellite

dt and dT are the time offsets of the satellite and receiver clocks with respect to GPS time

d_{ion} is the delay through the ionosphere

d_{trop} is the delay through the troposphere

r_n is the effects of receiver and antenna noise, including multipath

Estimates of d_{ion} and d_{trop} are obtained from the GPS broadcast.

The receiver produces a local time estimate for each satellite by using the pseudorange data to compensate for propagation delay and by applying satellite clock corrections received from the broadcast.

The receiver then combines the satellite time estimates, by simple averaging or another statistical technique, and uses this information to synchronize a 1 pps timing signal. Two additional corrections, one large and one small, are also necessary to convert GPS time to UTC(USNO). GPS time differs from UTC(USNO) by the number of leap seconds that have occurred since the origination of the GPS time scale (January 6, 1980). It also differs from UTC(USNO) by a small number of nanoseconds that continuously change. Both corrections are included in data messages broadcast by the satellites and are automatically applied by the receiver firmware. Thus, both the time-of-day and the OTM obtained from a GPS timing receiver are referenced to UTC(USNO).

Several factors limit the uncertainty of GPS time synchronization, including receiver and antenna cable delays, antenna coordinate errors, ionospheric and tropospheric delay effects noted earlier, multipath reflections, and environmental effects. Even when all of these factors are ignored, the uncertainty of the time produced by a GPS receiver will likely be less than 1 μs with respect to UTC. By calibrating the receiver and accounting for the factors listed earlier, it is usually easy to reduce this uncertainty to within ± 100 ns, with ± 20 ns being the practical limit.

41.7.5 Common-View Time Transfer Using GPS

Unlike the one-way method, the common-view GPS (CVGPS) method does not use GPS time as the reference source. Instead, GPS is simply a vehicle used to transfer time from one site to another. The CVGPS method compares two clocks at different locations to each other by simultaneously comparing them both to GPS signals that are in “common view.” The comparison results are recorded and exchanged, and the difference between the two comparisons is the time difference between the two clocks. Because GPS is available worldwide, the CVGPS method can potentially be used to compare any two clocks on Earth to each other or to synchronize a given clock on Earth to any other clock.

The CVGPS method involves one or more GPS satellites (S) and two receiving sites (A and B), each containing a GPS receiver and a local clock (Figure 41.7). The satellites transmit signals that are received at both A and B , and both sites compare the received signals to their local clock. Thus, the measurement at site A compares GPS signals, S , received over the path d_{SA} to the local clock, $\text{Clock } A - S$. Site B receives GPS signals over the path d_{SB} and measures $\text{Clock } B - S$.

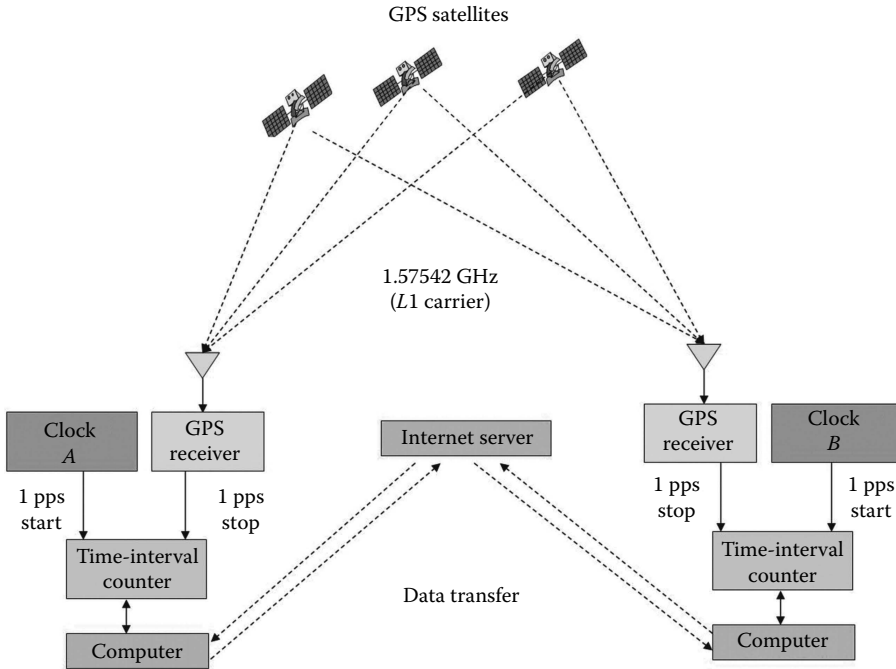


FIGURE 41.7 C/A code CVGPS using the L1 carrier.

The difference between the two measurements is an estimate of *Clock A* – *Clock B*. Delays that are common to both paths d_{SA} and d_{SB} cancel even if they are unknown, but uncorrected delay differences between the two paths add uncertainty to the measurement result. Thus, the basic equation for a CVGPS measurement is

$$(Clock\ A - S) - (Clock\ B - S) = (Clock\ A - Clock\ B) + (e_{SA} - e_{SB}) \tag{41.3}$$

e components that make up the $(e_{SA} - e_{SB})$ error term include delay differences between the two sites caused by ionospheric and tropospheric delays, multipath signal reflections, environmental conditions, and errors in the GPS antenna coordinates. These factors can be measured or estimated and applied as a correction to the measurement, or they can be accounted for in the uncertainty analysis. It is also necessary to calibrate the GPS receivers used at both sites and account for the local delays in the receiver, antenna, and antenna cable.

Figure 41.7 is a simplified diagram that illustrates C/A code common view using the L1 carrier, but there are several other variations of the CVGPS measurement technique that can provide lower measurement uncertainties. The uncertainty depends upon the type and quality of the GPS equipment in use and the technique used. For example, the differential ionospheric delay can be nearly eliminated by receiving both the L1 and L2 carrier frequencies. The quality of equipment also makes a difference; some GPS receivers are less sensitive to environmental changes than others, and some antennas are more effective than others at mitigating multipath. The most sophisticated techniques and equipment compare the local clock to the GPS carrier, rather than to the C/A code, and can reduce the time uncertainty to a few nanoseconds or less, but the incremental performance gains obtained from the additional cost and effort are relatively small. Even when inexpensive GPS hardware (L1 band only) and simple processing techniques are used, the measurement uncertainty of the CVGPS technique is often within ± 15 ns, with ± 5 ns being the practical limit for the most advanced techniques.

TABLE 41.5 Satellite Systems Used for Time Transfer

System	Controlling Region	Type of System	Completion Date	Number of Satellites
Compass	China	GNSS	2015	30
EGNOS	European Union	Augmentation, geostationary orbit	Completed	3
GPS	United States	GNSS	Completed	32
Galileo	European Union	GNSS	2015	30
GLONASS	Soviet Union	GNSS	Completed	24
QZSS	Japan	Augmentation, highly elliptical orbit	2013	3
WAAS	United States	Augmentation, geostationary orbit	Completed	2

41.7.6 Other Satellite Systems Used for Time Measurements

Several other GNSS and augmentation systems can be used as a reference for time measurements. Receivers for these systems are not yet available in some cases as of 2010, but performance should eventually be comparable to GPS in both one-way and common-view modes. In many cases, the systems were designed to interoperate with each other and thus share the same or similar frequency bands as GPS, with carrier frequencies ranging from about 1.1 to 1.6 GHz. Table 41.5 summarizes the various systems, including GPS.

41.7.7 Two-Way Satellite Time Transfer via Geostationary Satellites

The two-way satellite time transfer (TWSTT) method (Figure 41.8) requires more equipment and effort than the passive GPS methods, because users are required to both transmit and receive time signals. Signals are transmitted and received from two Earth stations through the transponder on a geostationary satellite. Each Earth station contains a local clock, a spread-spectrum satellite modem, a dish antenna, a TIC, and transmitting and receiving equipment. The carrier frequency used for the radio link is typically in the K_u band.

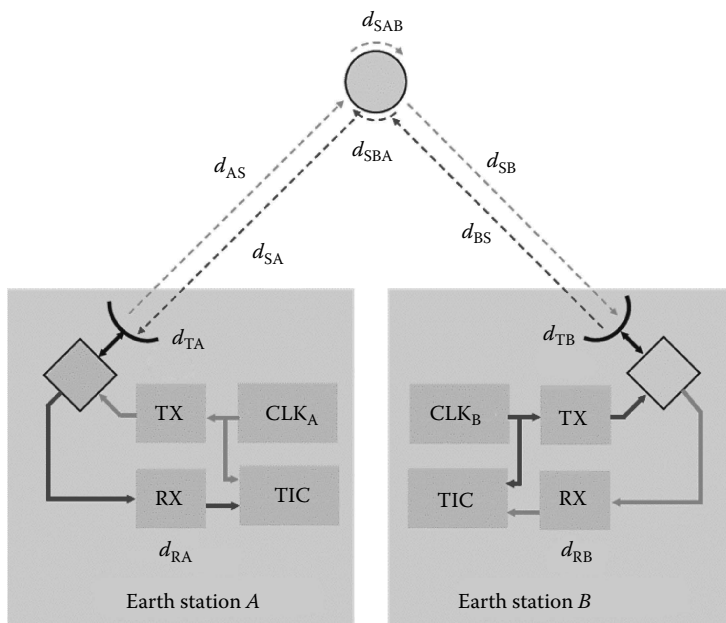


FIGURE 41.8 Two-way satellite time transfer.

TABLE 41.6 Performance of Radio Time Transfer Signals

Method	Time Uncertainty with Little or No Effort Made to Calibrate Path or Equipment	Practical Uncertainty Limit	Items Needed to Reach Uncertainty Limit
HF (WWV)	<30 ms	±1 ms	Good path delay estimate, radio propagation model
LF radio (WWVB)	<15 ms	±0.1 ms	Good path delay estimate, ability to determine the correct OTM to within a few cycles of the carrier
GPS (one way)	<1 μs	±20 ns	Calibrated receiver with antenna surveyed to within 1 m
GPS (common-view code)	±50 ns	±15 ns	Calibrated receivers at both sites with antennas surveyed to within 1 m and antennas designed to mitigate multipath
GPS (common-view carrier)	±10 ns	±5 ns	Calibrated receivers at both sites that accept the local clock input and that produce results with carrier phase observables
TWSTT	±10 ns	±1 ns	Calibrated satellite terminals at both Earth stations, good environmental control

TABLE 41.7 Suppliers of Time Standards and Measurement Equipment

Company	Website	Rubidium Oscillators	Cesium Oscillators	GPS Timing Receivers	TICs
Agilent	agilent.com				X
Accubeat	accubeat.com	X		X	
Arbiter	arbiter.com			X	
Berkeley Nucleonics	berkeleynucleonics.com				X
Brandywine	brandywinecomm.com	X		X	X
Brilliant	b-i-inc.com				X
DICOM	dicom.cz			X	
EndRun	endruntechnologies.com			X	
FEI-Zyfer	fei-zyfer.com			X	
Fluke	fluke.com	X		X	X
Frequency Electronics	frequelec.com	X	X		
FURUNO	furunogps.com			X	
Geotest	geotestinc.com				X
JAVAD	javad.com			X	
Meinberg	meinberg.de			X	
Oscilloquartz	oscilloquartz.com	X	X	X	X
Precision Test Systems	ptstest.com	X		X	X
Spectracom	spectracomcorp.com	X		X	X
Stanford Research	thinksrs.com	X			X
Symmetricom	symmetricom.com	X	X	X	X
Timetech	timetech.de			X	X
TRAK	trak.com			X	
Trimble	trimble.com			X	

Earth stations A and B simultaneously exchange time signals by transmitting a unique PRN code and receiving the PRN code sent by the other station. Each station compares the received time signal to its local clock. Station A records $TIC_A = CLK_A - (CLK_B + \tau_{ba})$, where CLK_A is the time from the local clock, CLK_B is the time from the remote clock, and τ_{ba} includes all of the terms that make up the path delay from B to A , including delays in the transmitting modem, the satellite uplink, the satellite transponder, the satellite downlink, and the receiving modem. Station B records $TIC_B = CLK_B - (CLK_A + \tau_{ab})$, where τ_{ba} includes all of the terms that make up the path link from B to A .

the two stations then exchange their results and compute their time difference:

$$A - B = \frac{TIC_A - TIC_B}{2} - \frac{\tau_{ba} - \tau_{ab}}{2}. \quad (41.4)$$

If the paths were reciprocal ($\tau_{ab} = \tau_{ba}$), then the difference would simply be $(TIC_A - TIC_B)/2$. The paths will never be completely reciprocal in practice, but most of the significant differences in the path delay do cancel. When properly implemented, the two-way satellite method outperforms all other satellite time transfer methods. The uncertainty can often be reduced to ± 1 ns [12].

Table 41.6 summarizes the various radio time transfer methods. Table 41.7 provides a list of companies that manufacture and sell atomic oscillators, GPS timing receivers, and TICs.

41.8 Internet and Network Time Transfer

The synchronization of computer clocks is a very common time transfer application. Computers connected to the Internet can synchronize their clocks quickly and easily because Network Time Protocol (NTP) [19] client software is often included with the operating system. NTP is a hierarchical clock system, where each level of the hierarchy is termed a stratum. Synchronization flows from primary servers at the lowest stratum to secondary servers at progressively higher strata. Servers referenced to national time standards are designated as Stratum-1. As of 2010, NIST maintains about half of the approximately 50 Stratum-1 NTP servers located in the United States that are accessible to the general public (see ntp.org for a current list). The demand for these servers is high, and the NIST servers handle several billion NTP requests per day.

Client computers (which can also be servers to computers at higher strata) issue time requests to an NTP server via TCP/IP port 123. They receive a data packet that contains a UTC time code and other time stamps that indicate when the request was made, when it arrived, and when the packet was sent. This information is used to calibrate the path, to synchronize the client's clock, and to steer the client's clock between synchronizations. The performance of NTP depends upon the client hardware and software and network conditions and varies widely, but uncertainties of less than a millisecond have been demonstrated under optimal conditions. A typical computer, running the Microsoft Windows operating system on the public Internet, can usually keep time within 1 or 2 s of UTC with one NTP synchronization request per week.

The Precision Time Protocol (PTP) can obtain much lower uncertainties than NTP, often less than 1 μ s, but is generally not suited for the public Internet. Defined by the IEEE-1588 standard, PTP is primarily intended for local area networks where path delays can be better measured and estimated.

The grandmaster clock is the time reference for all other clocks in a PTP system. The other clocks are designated as ordinary clocks, which have a single PTP port, and boundary clocks, which have multiple network connections and can bridge synchronization from one network segment to another.

Time transfer methods normally associated with satellites, such as the two-way and loop-back methods, are also applicable to private or dedicated networks. In fact, experiments using optical fibers as the time transfer medium over short distances have demonstrated much lower uncertainties than any of the satellite-based methods [20]. However, there are technical and financial obstacles that make it difficult to implement these techniques over long distances. For example, it is not easy to maintain the symmetry

of the path delay in very long fibers, and it is hard to justify the cost of an optical fiber network that is dedicated to time transfer. Even so, it seems likely that optical fiber networks will play a large role in future state-of-the-art time transfer experiments.

41.9 Future Developments

Optical atomic clocks will eventually replace cesium fountain clocks as the world's most accurate time standards, and the SI second will eventually be redefined, with the new definition based on an optical atomic transition, rather than a microwave transition. When this occurs, the uncertainty of the physical realization of the SI second is likely to improve by at least two orders of magnitude.

As clocks continue to improve, time transfer systems will in turn have to lower their measurement uncertainties in order to improve the performance of UTC. The future of time transfer should involve continued enhancements to satellite systems and measurement techniques, an increased reliance on signals sent over optical fibers, and perhaps the use of technologies yet to be developed.

Time-of-day clocks that are synchronized to within 1 s of UTC will become more common and should eventually become the norm rather than the exception. Many technologies could contribute to this trend, including LF radio signals, satellite signals, mobile phone signals, Internet time codes, and CSACs.

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