Michael A. Lombardi. "Time Measurement."

Time Measurement

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Time measurements can be divided into two general categories. The first category is *time-of-day* measurements. Time-of-day is labeled with a unique expression containing the year, month, day, hour, minute, second, etc., down to the smallest unit of measurement that we choose. When we ask the everyday question, "What time is it?", we are asking for a time-of-day measurement.

The second type of time measurement (and the one more commonly referred to by metrologists) is a *time interval* measurement. A time interval measurement requires measuring the interval that elapses between two events. Time interval is one of the four basic standards of measurement (the others are length, mass, and temperature). Of these four basic standards, time interval can be measured with the most resolution and the least amount of uncertainty.

Timekeeping involves both types of measurements. First, we must find a *periodic event* that repeats at a constant rate. For example, the pendulum in a clock may swing back and forth at a rate of once per second. Once we know that the pendulum swings back and forth every second, we can establish the second as our basic unit of time interval. We can then develop a system of timekeeping, or a *time scale.* A time scale is an unambiguous way to order events. It is created by measuring a small time unit (like the second) and then counting the number of elapsed seconds to establish longer time intervals, like minutes, hours, and days. The device that does the counting is called a *clock.*

There are many types of periodic events that can form the basis for many types of clocks. Let's continue our discussion by looking at the evolution of clocks and timekeeping.

TABLE 18.1 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 μs
$\pm 1.00 \times 10^{-9}$	1 s	±1 ns
$\pm 2.78 \times 10^{-7}$	1 h	±1 ms
$\pm 2.78 \times 10^{-10}$	1 h	±1 μs
$\pm 2.78 \times 10^{-13}$	1 h	±1 ns
$\pm 1.16 \times 10^{-8}$	1 day	±1 ms
$\pm 1.16 \times 10^{-11}$	1 day	±1 μs
$\pm 1.16 \times 10^{-14}$	1 day	±1 ns

18.1 The Evolution of Clocks and Timekeeping

All clocks share several common features. Each clock has a device that produces the periodic event mentioned previously. This device is called the *resonator*. In the case of the pendulum clock, the pendulum is the resonator. Of course, the resonator needs an energy source, a mainspring or motor, for example, before it can move back and forth. Taken together, the energy source and the resonator form an *oscillator*. Another part of the clock counts the "swings" of the oscillator and converts them to time units like hours, minutes, and seconds, or smaller units like milliseconds (ms), microseconds (μs), and nanoseconds (ns). And finally, part of the clock must display or record the results.

The frequency uncertainty of a clock's resonator relates directly to the timing uncertainty of the clock. This relationship is shown in Table 18.1.

Throughout history, clock designers have searched for more stable frequency sources to use as a resonator. As early as 3500 B.C., 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, waterclocks, hourglasses, and calibrated candles allowed dividing the day into smaller units of time. In the early 14th century, mechanical clocks began to appear. Early models used a *verge and foliet mechanism* for a resonator and had an uncertainty of about 15 min/day ($\cong 1 \times 10^{-2}$). A major breakthrough occurred in 1656, when the Dutch scientist Christiaan Huygens built the first *pendulum clock*. The pendulum, a mechanism with a "natural" period of oscillation, had been studied by Galileo Galilei as early as 1582, but Huygens was the first to invent 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 ($\cong 1 \times 10^{-4}$). Huygens later developed the spring and balance wheel assembly still found in some of today's wristwatches.

Pendulum technology continued to improve until the 20th century. By 1761, John Harrison had built a marine chronometer using a spring and balance wheel escapement. One of Harrison's clocks gained only 54 s during a 5-month voyage to Jamaica, or about 1/3 s/day ($\cong 4 \times 10^{-6}$). The practical performance limit of mechanical 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 mechanical tasks that would disturb its regularity. The Shortt clock had an uncertainty of just a few seconds per year ($\cong 1 \times 10^{-7}$) and became the reference used by laboratories [1,2].

In 1927, Joseph W. Horton and Warren A. Marrison of Bell Laboratories built the first clock based on a quartz crystal oscillator. By the 1940s, quartz clocks had replaced the Shortt pendulum as primary laboratory standards. Quartz clocks work because of the piezoelectric property of quartz crystals. When an electric current is applied to a quartz crystal, it resonates at a constant frequency. With no gears or escapements to disturb their resonance frequency, quartz clocks can easily outperform pendulum clocks. Uncertainties of ±100 μs/day ($\cong 1 \times 10^{-9}$) are possible, and quartz oscillators are used extensively in wristwatches, wall and desk clocks, and electronic circuits [2–4].

The resonance frequency of quartz relies upon a mechanical vibration that is a function of the size and shape of the quartz crystal. No two crystals can be precisely alike or produce exactly the same frequency. Quartz oscillators are also sensitive to environmental parameters like temperature, humidity, pressure, and vibration [5]. These shortcomings make quartz clocks inadequate for many applications, and led to the development of atomic oscillators.

18.2 Atomic Oscillators

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):

$$f = \frac{E_2 - E_1}{h} \tag{18.1}$$

Time is kept by observing and counting the frequencies at which electromagnetic energy is emitted or absorbed by the atoms. In essence, the atom serves as a pendulum whose oscillations are counted to mark the passage of time [3].

There are three major types of atomic oscillators. The least expensive and most common type is the *rubidium oscillator*, based on the 6.835 GHz resonance of $^{Rb}87$. Rubidium oscillators range in price from about $2000 to $8000. They are well-suited for applications that require a small, high-performance oscillator with an extremely fast warm-up time. The frequency uncertainty of a rubidium oscillator ranges from about $\pm 5 \times 10^{-10}$ to $\pm 5 \times 10^{-12}$.

The second type of atomic oscillator, the *cesium beam*, serves as the primary reference for most precision timing services. As will be seen in Section 18.3, the resonance frequency of cesium (9.1926 GHz) is used to define the SI second. The primary frequency standard in the United States is a cesium oscillator called NIST-7 with a frequency uncertainty of about $\pm 5 \times 10^{-15}$. Commercially available cesium oscillators differ in quality, but their frequency uncertainty should be at least $\pm 5 \times 10^{-12}$. The price of a cesium oscillator is high, ranging from about $30,000 to $80,000.

A third type of atomic oscillator, the *hydrogen maser*, is based on the 1.42 GHz resonance frequency of the hydrogen atom. Although the performance of hydrogen masers is superior to cesium in some ways, they are not widely used due to their high cost. Few are built, and most are owned by national standards laboratories. The price of a hydrogen maser often exceeds $200,000 [2,3,6].

Table 18.2 summarizes the evolution of clock design and performance.

18.3 Time Scales and the SI Definition of the Second

As observed, the uncertainty of all clocks depends upon the irregularity of some type of periodic motion. By quantifying this periodic motion, one can define the second, which is the basic unit of time interval in the International System of Units (SI). Since atomic time standards are so clearly superior to their predecessors, they are used to define the SI second. Since 1971, the cesium atom has been used to define the 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.

International Atomic Time (TAI) is an atomic time scale that conforms as closely as possible to the SI definition of the second. TAI is maintained by the Bureau International des Poids et Measures (BIPM) in Sevres, France. As of 1996, it is created by averaging data obtained from about 250 laboratory and commercial atomic standards located at more than 40 different laboratories. Most of these standards are

TABLE 18.2 The Evolution of Clock Design and Performance

Type of Clock	Resonator	Date [Ref.]	Typical Timing Uncertainty (24 h)	Typical Frequency Uncertainty (24 h)
Sundial	Apparent motion of sun	3500 B.C.	NA	NA
Verge escapement	Verge and foliet mechanism	14th 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 crystal	Quartz crystal	1927 [4]	±100 μs	$\pm 1 \times 10^{-9}$
Rubidium gas cell	Rubidium atomic resonance (6834.682608 MHz)	1958 [7]	±1 μs	$\pm 1 \times 10^{-11}$
Cesium beam	Cesium atomic resonance (9192.63177 MHz)	1952 [8]	±10 ns	$\pm 1 \times 10^{-13}$
Hydrogen maser	Hydrogen atomic resonance (1420.405752 MHz)	1960 [9]	±10 ns	$\pm 1 \times 10^{-13}$

based on cesium, although the number of contributing hydrogen masers is increasing. The National Institute of Standards and Technology (NIST) and the United States Naval Observatory (USNO) are among the many laboratories that contribute to TAI.

Before the acceptance of atomic time scales, astronomical time scales were used. These time scales are based on the *mean solar day*, or one revolution of the Earth on its axis. Until 1956, the *mean solar second* served as the SI second. 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 ms 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* served as the SI second from 1956 to 1971. The ephemeris second was a fraction of the tropical year, or the interval between the annual vernal equinoxes 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 primarily used by astronomers as the time-independent variable for planetary ephemerides. In 1984, ET was replaced by *Terrestial Time* (TT), which is equal to TAI + 32.184 s. The uncertainty of TT is ±10 μs [10, 11].

18.4 Coordinated Universal Time (UTC)

Since January 1, 1972, all national laboratories and broadcast time services distribute Coordinated Universal Time (UTC), which differs from TAI by an integer number of seconds. The difference between UTC and TAI increases when *leap seconds* are inserted in UTC. When necessary, leap seconds are added to the UTC time scale on either June 30 or December 31. Their purpose is to keep atomic time (UTC) within ±0.9 s of astronomical time (UT1). Many time services broadcast a *DUT*1 *correction*, or the current value of UT1 minus UTC. By applying this correction to UTC, one can obtain UT1.

Leap seconds occur slightly less than once per year because UT1 is currently changing by about 800 ms per year with respect to UTC. The first leap second was introduced on June 30, 1972. So far, all leap seconds have been positive, which indicates that the mean solar second (defined by the Earth's rotation) is longer than the atomic second (defined by cesium). UTC is running faster than UT1 for two reasons. The first, and most important reason, is that the definition of the atomic second caused it to be slightly shorter than the mean solar second. The second reason is that the speed of the Earth's rotation is generally decreasing. When a positive leap second is added to UTC, the sequence of events is:

$$23\text{ h }59\text{ m }59\text{ s}$$
$$23\text{ h }59\text{ m }60\text{ s}$$
$$0\text{ h }0\text{ m }0\text{ s}$$

The insertion of the leap second creates a minute that is 61 s long. This effectively "stops" the UTC time scale for 1 s, so that UT1 has a chance to catch up. Unless a dramatic, unforeseen change in the Earth's rotation rate takes place, future leap seconds will continue to be positive [10, 11].

18.5 Introduction to Time Transfer

Many applications require different clocks at different locations to be set to the same time (*synchronization*), or to run at the same rate (*syntonization*). A common application is to transfer time from one location and synchronize a clock at another location. This requires a 1 pulse per second (pps) output referenced to UTC. Once we have an on-time pulse, we know the arrival time of each second and can syntonize a local clock by making it run at the same rate. However, we still must know the *time-of-day* before we can synchronize the clock. For example, is it 12:31:38 or 12:31:48? To get the time-of-day, we need a *time code* referenced to UTC. A time code provides the UTC hour, minute, and second, and often provides date information like month, day, and year.

To summarize, synchronization requires two things: an on-time pulse and a time code. Many *time transfer signals* meet both requirements. These signals originate from a UTC clock referenced to one or more cesium oscillators. The time signal from this clock is then distributed (or transferred) to users.

Time can be transferred through many different mediums, including coaxial cables, optical fibers, radio signals (at numerous places in the spectrum), telephone lines, and computer networks. Before discussing the available time transfer signals, the methods used to transfer time are examined.

Time Transfer Methods

The single largest contributor to time transfer uncertainty is *path delay*, or the delay introduced as the signal travels from the transmitter (source) to the receiver (destination). To illustrate the path delay problem, consider a time signal broadcast from a radio station. Assume that the time signal is nearly perfect at its source, with an uncertainty of ±100 ns of UTC. If a receiving site is set up 1000 km away, we need to calculate how long it takes for the signal to get to the site. Radio signals travel at the speed of light ($\cong 3.3\ \mu s\ km^{-1}$). Therefore, by the time the signal gets to the site, it is already 3.3 ms late. We can compensate for this path delay by making a 3.3 ms adjustment to the clock. This is called *calibrating the path.*

There is always a limit to how well we can calibrate a path. For example, to find the path length, we need coordinates for both the receiver and transmitter, and software to calculate the delay. Even then, we are assuming that the signal took the shortest path between the transmitter and receiver. Of course, this is not true. Radio signals can bounce between the Earth and ionosphere, and travel much further than the distance between antennae. A good path delay estimate requires knowledge of the variables that influence radio propagation: the time of year, the time of day, the position of the sun, the solar index, etc. Even then, path delay estimates are so inexact that it might be difficult to recover time with ±1 ms uncertainty (10,000 times worse than the transmitted time) [12, 13].

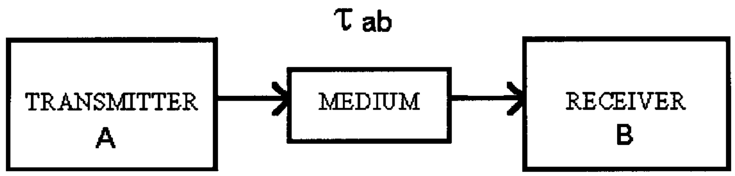

FIGURE 18.1 One-way time transfer.

Designers of time transfer systems have developed many innovative ways to deal with the problem of path delay. The more sophisticated methods have a *self-calibrating path* that automatically compensates for path delay. The various time transfer systems can be divided into five general categories:

1. *One-way method* (*user calibrates path*): This is the simplest and most common kind of time transfer system, a one-way system where the user is responsible for calibrating the path (if required). As illustrated in Figure 18.1, the signal from the transmitter to the receiver is delayed τ_{ab} by the medium. To obtain the best results, the user must estimate τ_{ab} and calibrate the path by compensating for the delay.

   Often, the user of a one-way system only requires timing uncertainty of ±1 s, so no effort is made to calibrate the path. For example, the user of a high-frequency (HF) broadcast can synchronize a clock at the 1 s level without worrying about the effect of path delay.
2. *One-way method* (*self-calibrating path*): This method is a variation of the simple one-way method shown in Figure 18.1. 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 the size of τ_{ab}. The first technique is to make a rough estimate of τ_{ab} and to send the time out early by this amount. For example, if it is known that τ_{ab} will be at least 20 ms for all users, we can send out the time 20 ms early. This advancement of the timing signal will reduce the uncertainty for all users. For users where τ_{ab} is ≅20 ms, it will remove nearly all of the uncertainty caused by path delay.

   A more sophisticated technique is to compute τ_{ab} in software. A correction for τ_{ab} can be computed and applied 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 (a satellite, for example) it must broadcast its coordinates in addition to broadcasting a time signal. The receiver's coordinates must be computed by the receiver (in the case of radionavigation systems), or input by the user. Then, a software-controlled receiver can compute the distance between the transmitter and receiver and compensate for the path delay by correcting for τ_{ab}. Even if this method is used, uncertainty is still introduced by position errors for either the transmitter or receiver and by variations in the transmission speed along the path.

   Both techniques can be illustrated using the GOES satellite time service (discussed later) as an example. Because the GOES satellites are in geostationary orbit, it takes about 245 ms to 275 ms for a signal to travel from Earth to the satellite, and back to a random user on Earth. To compensate for this delay, the time kept by the station clock on Earth is advanced by 260 ms. This removes most of τ_{ab}. The timing uncertainty for a given user on Earth should now be ±15 ms. The satellite also sends its coordinates along with the timing information. If a microprocessor-controlled receiver is used, and if the coordinates of the receiver are known, the receiver can make an even better estimate of τ_{ab}, typically within ±100 μs.
3. *Common-view method*: The common-view method involves a single 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 18.2). 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. Errors from the two paths (τ_{ra} and τ_{rb}) that are

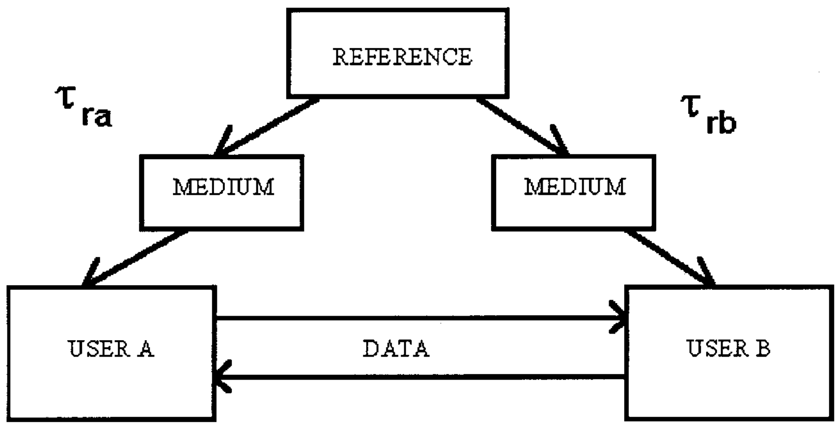

FIGURE 18.2 Common-view time transfer.

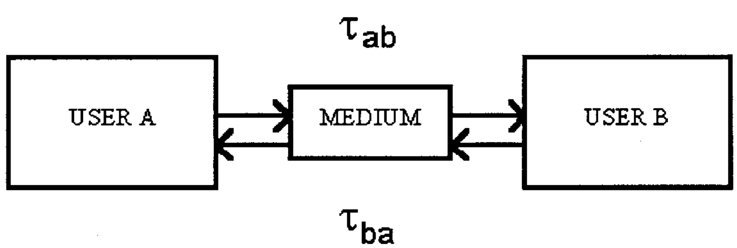

FIGURE 18.3 Two-way time transfer.

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) – ($\tau_{ra} - \tau_{rb}$).

Keep in mind that the common-view technique does not synchronize clocks in *real time*. The data must be exchanged with another user, and the results might not be known until long after the measurements are completed.

4. *Two-way method*: The two-way method requires two users to both transmit and receive through the same medium at the same time (Figure 18.3). 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 + τ_{ba}) and site B records B – (A + τ_{ab}), where τ_{ba} is the path delay from A to B, and τ_{ab} is the path delay from A to B. The difference between these two sets of readings produces 2(A – B) – ($\tau_{ba} - \tau_{ab}$). If the path is reciprocal ($\tau_{ab} = \tau_{ba}$), then the difference, A – B, is known perfectly because the path between A and B has been measured. When properly implemented using a satellite or fiber optic links, the two-way method outperforms all other time transfer methods and is capable of ±1 ns uncertainty.

   Two-way time transfer has many potential applications in telecommunications networks. However, when a wireless medium is used, there are some restrictions that limit its usefulness. It might require expensive equipment and government licensing so that users can transmit. And like the common-view method, the two-way method requires users to exchange data. However, because users can transmit, it is possible to include the data with the timing information and to compute the results in real time.
5. *Loop-back method*: Like the two-way method, the loop-back method requires the receiver to send information back to the transmitter. For example, a time signal is sent from the transmitter (A)

to the receiver (B) over the path τ_{ab}. The receiver (B) then echoes or reflects the signal back to the transmitter (A) over the path τ_{ba}. The transmitter then adds the two path delays ($\tau_{ab} + \tau_{ba}$) to obtain the round-trip delay, and divides this number by 2 to estimate the one-way path delay. The transmitter then advances the time signal by the estimated one-way delay.

Several factors contribute uncertainty to the loop-back method. One is that it is not always known if the signal from A to B traveled the same path as the signal from B to A. In other words, we cannot assume a *reciprocal* path. Even if we have a reciprocal path, we are not using the same path at the same time. First, the transmitter sent data to the receiver, then the receiver sent data back to the transmitter. In the interval between data transmissions, the path may have changed, and these changes contribute to the uncertainty.

The loop-back method might not be practical through a wireless medium because returning information to the transmitter requires a radio transmitter, a broadcast license, etc. When the medium is a telephone or network connection, however, it is possible to implement the loop-back method entirely in software.

Time Codes

A *time code* is a message containing time-of-day information, that allows the user to set a clock to the correct time-of-day. International Telecommunications Union (ITU) guidelines state that all time codes should distribute the UTC hour, minute, and second, as well as a DUT1 correction [14].

Time codes are broadcast in a number of different formats (including binary, binary coded decimal [BCD], and ASCII) and there is very little standardization. However, standards do exist for redistributing time codes within a facility. These standard time codes were first created by the Inter-Range Instrumentation Group (IRIG) in 1956 and are still widely used by equipment manufacturers today. IRIG defined a number of time codes, but the most common is probably IRIG-B. The IRIG codes make it possible for manufacturers to build compatible equipment. For example, a satellite receiver with an IRIG-B output can drive a large time-of-day display that accepts an IRIG-B input. Or, it can provide a timing reference to a network server 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 as a modulated 1000 Hz carrier. BCD and straight binary time data (days, hours, minutes, seconds) is included within the 1 s frame. Simple IRIG-B decoders retrieve just the encoded data and provide 1 s resolution. Other decoders count carrier cycles and provide timing 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 time code signal-to-noise ratio (typically $\pm$ 2 μs).

18.6 Radio Time Transfer Signals

Many types of receivers receive time codes transmitted by radio. The costs vary widely, from less than $500 to $15,000 or more. Radio clocks come in several different forms. Some are standalone (or rack mount) devices with a digital time display. These often have a computer interface like RS-232 or IEEE-488. Others are available as cards that plug directly into a computer's bus. When selecting a radio clock, make sure that the signal is usable in the area and that the appropriate type of antenna can be mounted.

When reviewing radio time signals, please remember that the stated uncertainty values refer to the raw signal. Additional delays are introduced before the signal is processed by the receiver and used to synchronize a clock. For example, there is cable delay between the antenna and receiver. There are equipment delays introduced by hardware, and processing delays introduced by software. If unknown, these delays can cause *synchronization errors*. Depending on the application, synchronization errors may or may not be important. However, they must be measured and accounted for when performing an uncertainty analysis of a timing system.

HF Radio Signals (including WWV and WWVH)

High-frequency (HF) or *shortwave* radio broadcasts are commonly used for time transfer at moderate performance levels. These stations are popular for several reasons: they provide worldwide coverage, they work with low-cost receivers, and they provide an audio announcement that lets you "listen" to the time.

To use an HF time signal, you need a shortwave radio. Many types of shortwave radios are available, ranging from simple portables that cost less than $100 to communication-type receivers costing many thousands of dollars. A few companies manufacture dedicated HF timing receivers that automatically find the best signal to use by scanning several different frequencies. Some of them have a built-in computer interface (usually RS-232) so you can use them to set a computer clock.

There are many HF time and frequency stations located around the world, including the NIST-operated stations, WWV and WWVH. WWV is near Fort Collins, CO, and WWVH is on the island of Kauai, HI. Both stations broadcast continuous time and frequency signals on 2.5, 5, 10, and 15 MHz. WWV also broadcasts on 20 MHz. All frequencies carry the same program, and at least one frequency should be usable at all times. The stations can also be heard by telephone: dial (303) 499-7111 for WWV and (808) 335-4363 for WWVH.

The audio portion of the WWV/WWVH broadcast includes seconds pulses or ticks produced by a double-sideband, 100% modulated signal on each RF carrier. The first pulse of every hour is an 800 ms pulse of 1500 Hz. The first pulse of every minute is an 800 ms pulse of 1000 Hz at WWV and 1200 Hz at WWVH. The remaining seconds pulses are brief audio bursts (5 ms pulses of 1000 Hz at WWV and 1200 Hz at WWVH) that sound like the ticking of a clock. All pulses occur at the beginning of each second. The 29th and 59th seconds pulses are omitted. Each tick is preceded by 10 ms of silence and followed by 25 ms of silence to avoid interference from other time stations and to make it easier to hear the tick. 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.

In addition to audio, a time code is also sent on a 100 Hz subcarrier. The time code is a modified version of IRIG-H and is sent once per minute in BCD format, at a 1 bit per second (bps) rate. Within 1 min, enough bits are sent to express the minute, hour, and day of year, the DUT1 correction, and a Daylight Saving Time (DST) indicator. The coded time information refers to the time at the start of the 1-min frame.

WWV and WWVH are best suited for synchronization at the 1 s (or fraction of a second) level. The actual uncertainty depends on the user's distance from the transmitter, but should be less than 30 ms. Although ± 1 ms uncertainty is possible with a well-calibrated path, there are other signals available that are easier to use and more reliable at the 1 ms level [15].

LF Radio Signals (including WWVB and LORAN-C)

Before the development of satellite signals, low-frequency (LF) signals were the method of choice for time transfer. While the use of LF signals has diminished, they still have one major advantage — they can often be received indoors without an external antenna. This makes them ideal for many consumer electronic applications.

Many countries have time services in the LF band from 30 kHz to 300 kHz, as well as in the VLF (very low frequency) band from 3 kHz to 30 kHz. These signals lack the bandwidth needed to provide voice announcements, but often provide an on-time pulse and/or a time code. As with HF signals, the user must calibrate the path to get the best results. However, because part of the LF signal is *groundwave* and follows the curvature of the Earth, a good path delay estimate is much easier to make. Two examples of LF signals used for time transfer are WWVB and LORAN-C. WWVB transmits a binary time code on a 60 kHz carrier. LORAN-C transmits on-time pulses at 100 kHz but has no time code.

WWVB

WWVB is an LF radio station (60 kHz) operated by NIST from the same site as WWV near Ft. Collins, CO. The signal currently covers most of North America, and a power increase (6 dB and scheduled for 1998) would increase the coverage area and improve the signal-to-noise ratio within the United States.

Although far more stable than an HF path, the WWVB path is influenced by the path length, and by daily and seasonal changes. Path length is important because part of the signal travels along the ground (*groundwave*), and another part is reflected from the ionosphere (*skywave*). The groundwave path is more stable and considerably easier to estimate than the skywave path. If the path is relatively short (less than 1000 km), then it is often possible for a receiver to continuously track the groundwave signal, because it always arrives first. If the path length increases, a mixture of groundwave and skywave will be received. And over a very long path, the groundwave could become so weak that it will only be possible to receive the skywave. In this instance, the path becomes much less stable.

Time of day is also important. During the day, the receiver might be able to distinguish between groundwave and skywave and path stability might vary by only a few microseconds. However, if some skywave is being received, *diurnal* phase shifts will occur at sunrise and sunset. For example, as the path changes from all darkness to all daylight, the ionosphere lowers. This shortens the path between the transmitter and receiver, and the path delay decreases until the entire path is in sunlight. The path delay then stabilizes until either the transmitter or receiver enters darkness. Then the ionosphere rises, increasing the path delay.

The WWVB time code is synchronized with the 60 kHz carrier and is broadcast once per minute. The time code is sent in BCD format. Bits are sent by shifting the power of the carrier. The carrier power is reduced 10 dB at the start of each second. If full power is restored 200 ms later, it represents a 0 bit. If full power is restored 500 ms later, it represents a 1 bit. Reference markers and position identifiers are sent by restoring full power 800 ms later. The time code provides year, day, hour, minute, and second information, a DUT1 correction, and information about Daylight Saving Time, leap years, and leap seconds [15].

LORAN-C

LORAN-C is a ground-based radionavigation system. Most of the system is operated by the U.S. Department of Transportation (DOT), but some stations are operated by foreign governments. The system consists of groups of stations (called chains). Each chain has one master station, and from two to five secondary stations. The stations are high power, typically 275 to 1800 kW, and broadcast on a carrier frequency of 100 kHz using a bandwidth from 90 kHz to 110 kHz.

Because there are many LORAN-C chains using the same carrier frequency, the chains transmit pulses so that individual stations can be identified. Each chain transmits a pulse group consisting of pulses from all of the individual stations. The pulse group is sent at a unique Group Repetition Interval (GRI). For example, the 7980 chain transmits pulses every 79.8 ms. By looking for pulse groups spaced at this interval, the receiver can identify the 7980 chain.

Once a specific station within the chain is identified, the pulse shape allows the receiver to locate and track a specific groundwave cycle of the carrier. Generally, a receiver within 1500 km of the transmitter can track the same groundwave cycle indefinitely, and avoid reception of the skywave. Since the receiver can distinguish between groundwave and skywave, the diurnal phase shifts are typically quite small (<500 ns). However, if the path length exceeds 1500 km, the receiver could lose lock, and "jump" to another cycle of the carrier. Each cycle jump introduces a 10 μs timing error, equal to the period of 100 kHz.

LORAN-C does not deliver a time code, but can deliver an on-time pulse referenced to UTC. This is possible because the arrival time of a pulse group coincides with the UTC second at a regular interval. This *time of coincidence* (TOC) occurs once every 4 to 16 min, depending on the chain being tracked. To get a synchronized 1 pps output, one needs a timing receiver with TOC capability and a good path delay estimate. One also needs a TOC table for the chain being tracked (available from the United States Naval Observatory). Once a LORAN-C clock is set on time, it can produce a 1 pps output with an uncertainty of ±500 ns [12, 16].

Geostationary Operational Environmental Satellite (GOES)

NIST provides a continuous time code through the GOES (Geostationary Operational Environmental Satellite) satellites. These satellites are operated by the National Oceanic and Atmospheric Administration (NOAA). The service provides coverage to the entire Western Hemisphere.

Two satellites are used to broadcast time. GOES/East at 75° West longitude broadcasts on a carrier frequency of 468.8375 MHz. GOES/West at 135° West longitude broadcasts on a carrier frequency of 468.825 MHz. The satellites are in geostationary orbit 36,000 km above the equator. The GOES master clock is synchronized to UTC(NIST) and located at NOAA's facility in Wallops Island, VA. The satellites serve as transponders that relay signals from the master clock.

The GOES time code includes the year, day-of-year, hour, minute, and second, the DUT1 correction, satellite position information, and Daylight Saving Time and leap second indicators. The time code is interlaced with messages used by NOAA to communicate with systems gathering weather data. A 50 bit message is sent every 0.5 s, but only the first 4 bits (one BCD word) contains timing information. A complete time code frame consists of 60 BCD words and takes 30 s to receive.

By using the satellite position information, GOES receiving equipment can measure and compensate for path delay if the receiver's coordinates are known. The timing uncertainty of the GOES service is ±100 μs [15].

Global Positioning System (GPS)

The Global Positioning System (GPS) is a radionavigation system developed and operated by the U.S. Department of Defense (DOD). It consists of a constellation of 24 Earth-orbiting satellites (21 primary satellites and 3 in-orbit spares). The 24 satellites orbit the Earth in six fixed planes inclined 55° from the equator. Each satellite is 20,200 km above the Earth and has an 11-h, 58-min orbital period, which means a satellite will pass over the same place on Earth 4 min earlier each day. Since the satellites continually orbit the Earth, GPS should be usable anywhere on the Earth's surface.

Each GPS satellite broadcasts 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* code (called the C/A code) with a chip rate of 1023 chips per millisecond. The second is a *precision* code (called the P code) with a chip rate of 10230 chips per millisecond. The C/A code repeats every millisecond. The P code only repeats every 267 days, but for practical reasons is reset every week. The C/A code is broadcast on L1, and the P code is broadcast on both L1 and L2

For national security reasons, the DOD started the *Selective Availability* (SA) program in 1990. SA intentionally increases the positioning and timing uncertainty of GPS by adding about 300 ns of noise to both the C/A code and the P code. The resulting signal is distributed through the *Standard Positioning Service* (SPS). The SPS is intended for worldwide use, and can be used free of charge by anyone with a GPS receiver. The *Precise Positioning Service* (PPS) is only available to users authorized by the United States military. PPS users require a special receiver that employs cryptographic logic to remove the effects of SA. Since PPS use is restricted, nearly all civilian GPS users use the SPS.

Using GPS in One-Way Mode

GPS has the best price-performance ratio of any current time transfer system. Receivers range in price from less than $500 for an OEM timing board, to $20,000 or more for the most sophisticated models. The price often depends on the quality of the receiver's timebase oscillator. Lower priced models have a low-quality timebase that must be constantly steered to follow the GPS signal. Higher priced receivers have better timebases (some have internal rubidium oscillators), and can ignore many of the GPS path variations because their oscillator allows them to coast for longer intervals.

TABLE 18.3 Timing Uncertainty of GPS in One-Way Mode

Service	Uncertainty (ns) 50th percentile	Uncertainty (ns) 1σ	Uncertainty (ns) 2σ
SPS	±115	±170	±340
PPS	±68	±100	±200

To use most receivers, you simply mount the antenna, connect the antenna to the receiver, and turn the receiver on. The antenna is often a small cone or disk (normally about 15 cm in diameter) and must be mounted outdoors where it has a clear, unobstructed view of the sky. Once the receiver is turned on, it performs a sky search to find out which satellites are currently above the horizon and visible from the antenna site. The receiver then collects two blocks of data (called the *almanac* and *ephemeris*) from the satellites it finds. Once this is done, it can compute a 3-dimensional coordinate (latitude, longitude, and altitude) as long as four satellites are in view. The receiver can then compensate for path delay, and synchronize its on-time pulse.

If the antenna has a clear view of the sky, at least four satellites should be in view at all times, and the receiver should always be able to compute its position. The simplest GPS receivers have just one channel and look at multiple satellites using a sequencing scheme that rapidly switches between satellites. More sophisticated models have parallel tracking capability and can assign a separate channel to each satellite in view. These receivers typically track from 5 to 12 satellites at once (although more than 8 will only be available in rare instances). By averaging data from multiple satellites, a receiver can remove some of the effects of SA and reduce the timing uncertainty.

GPS Performance in One-Way Mode

Most GPS timing receivers provide a 1 pps on-time pulse. GPS also broadcasts three pieces of time code information: the number of weeks since GPS time began (January 5, 1980); the current second in the current week; and the number of leap seconds since GPS time began. By using the first two pieces of information, a GPS receiver can recover GPS time. By adding the leap second information, the receiver can recover UTC. GPS time differs from UTC by the number of leap seconds that have occurred since January 5, 1980.

Most GPS receivers output UTC in the traditional time-of-day format: month, day, year, hour, minute, and second. Table 18.3 lists the UTC uncertainty specifications for both the SPS and PPS.

Since nearly all GPS receivers are limited to using the SPS, the top row in the table is of most interest. It shows there is a 50% probability that a given on-time pulse from GPS will be within ±115 ns of UTC. The 1σ uncertainty of GPS (~68% probability) is ±170 ns, and the 2σ uncertainty (95%) is ±340 ns.

To achieve the uncertainties shown in Table 18.3, one must calibrate receiver and antenna delays, and estimate synchronization errors. For this reason, some manufacturers of GPS equipment quote a timing uncertainty of ±1 μs. This specification should be easy to support, even if receiver and antenna delays are roughly estimated or ignored. Other manufacturers use averaging techniques or algorithms that attempt to "remove" SA. These manufacturers might quote an uncertainty specification of ±100 ns or less [17, 18].

Using GPS in Common-View Mode

The *common-view* mode is used to synchronize or compare time standards or time scales at two or more locations. Common-view GPS is the method used by the BIPM to collect data from laboratories who contribute to TAI.

Common-view time transfer requires a specially designed GPS receiver that can read a tracking schedule. This schedule tells the receiver when to start making measurements and which satellite to track. Another user at another location uses the same schedule and makes simultaneous measurements from

TABLE 18.4 Performance of Radio Time Transfer Signals

Radio Time Transfer Signal	Performance without Path Calibration	Typical Limit of System	Items Needed to Reach Performance Limit
HF (WWV/WWVH)	–30 ms (signal delay depends on distance from transmitter)	±1 ms	Path delay estimate, radio propagation model
GOES Satellite	±16 ms	±100 µs	Receiver that corrects for path delay
WWVB	–10 ms (signal delay depends upon distance from transmitter)	±100 µs	Path delay estimate, knowledge of equipment and antenna delays
LORAN-C	±10 µs	±500 ns	Path delay estimate, receiver that is TOC capable, TOC table, knowledge of equipment and antenna delays
GPS (one-way mode)	±340 ns	±100 ns	Commercially available GPS receiver that averages data from multiple satellites. Knowledge of equipment and antenna delays.
GPS (common-view mode)	±20 ns	±5 ns	Common-view receiver, tracking schedule, and another user or laboratory that will exchange data; knowledge of equipment and antenna delays

the same satellite. The tracking schedule must be designed so that it chooses satellites visible to both users at reasonable elevation angles.

Each site measures the difference between its local clock and the satellite. Typically, measurements are made during a satellite pass lasting for less than 15 min. The individual measurements at each site are estimates of (Clock A – GPS) and (Clock B – GPS). If these results are subtracted, the GPS clock drops out and an estimate of (Clock A – Clock B) remains. Since GPS clock errors (including SA) do not influence the results, the uncertainty of GPS common view can be as small as ±5 ns [19].

Although common view is important for international timing comparisons, it is impractical for the average user for several reasons. First, it requires exchanging data with another user. Second, common view does not provide continuous data. It only provides data during comparisons lasting for less than 15 min. And finally, common view does not work in real time; one will not know the timing uncertainty until after the data exchange.

Table 18.4 summarizes the various radio time transfer signals.

Table 18.5 lists some manufacturers of radio clocks. It includes radio clocks that use high-frequency (HF) radio signals, WWVB or other low-frequency (LF) radio signals, LORAN-C (LORAN), the Global Positioning System (GPS), and GPS common-view (GPS-CV). A wide variety of equipment is available for a wide variety of applications. Contact the manufacturer for specific details.

18.7 Computer Time Transfer Signals

One of the most common time transfer problems involves synchronizing computer clocks. Radio clocks like those described in the last section are often used for computer timekeeping. However, using a dial-up or Internet time service is often more convenient and less expensive than purchasing a radio clock [20].

Dial-Up Time Setting Services

Dial-up time services allow computers to synchronize their clocks using an ordinary telephone line. To illustrate how these services work, take a look at NIST's Automated Computer Time Service (ACTS), which went online in 1988.

TABLE 18.5 Sources of Radio Clocks

Radio Clock Manufacturer	Location	Type of Receivers Sold
Absolute Time	San Jose, CA	GPS
Arbiter	Paso Robles, CA	GPS
Allen Osborne	Westlake Village, CA	GPS, GPS-CV
Ashtech	Sunnyvale, CA	GPS
Austron	Austin, TX	LORAN, GPS, GPS-CV
Bancomm	San Jose, CA	GPS
Chrono-Log	Havertown, PA	HF, GPS
Datum	Anaheim, CA	GPS
Efratom	Irvine, CA	GPS
ESE	El Segundo, CA	GPS
Franklin Instrument	Warminster, PA	LF
Frequency and Time Systems	Beverly, MA	GPS
Garmin	Lenexa, KS	GPS
Heath	Benton Harbor, MI	HF
Hewlett-Packard	Santa Clara, CA	GPS
Macrodyne	Clifton Park, NY	GPS
Magellan	San Dimas, CA	GPS
Motorola	Northbrook, IL	GPS
Odetics	Anaheim, CA	GPS
Rockwell	Newport Beach, CA	GPS
Spectracom	East Rochester, NY	LF, GPS
Spectrum Geophysical	West Covina, CA	GPS
Stanford Research	Sunnyvale, CA	LORAN
Stanford Telecomm	Santa Clara, CA	GPS
Telecom Solutions	San Jose, CA	GPS
Tracor	Austin, TX	LF
Trak Systems	Tampa, FL	GPS
Trimble	Sunnyvale, CA	GPS
True Time	Santa Rosa, CA	HF, LF, GPS

ACTS requires a computer, a modem, and some simple software. When a computer connects to ACTS by telephone, it receives an ASCII time code. The information in this time code is used to synchronize the computer clock. ACTS is usable at modem speeds up to 9600 baud with 8 data bits, 1 stop bit, and no parity. To receive the full time code, one must connect at 1200 baud or higher. The full time code is transmitted once per second and contains more information than the 300 baud time code, which is transmitted every 2 s. Table 18.6 describes the full ACTS time code.

The last character in the time code is the on-time marker (OTM). The values enclosed in the time code refer to the arrival time of the OTM. In other words, if the time code states it is 12:45:45, it means it is 12:45:45 when the OTM arrives. To compensate for the path delay between NIST and the user, ACTS sends the OTM out 45 ms early. The 45 ms advance was chosen based on experiments conducted using 1200 baud modems. It allows 8 ms for sending the OTM at 1200 baud, 7 ms for transmission time between NIST and a typical user, and 30 ms for modem processing delay.

Advancing the OTM by 45 ms always reduces the amount of path delay. However, ACTS can calibrate the actual path by using the *loop-back* method. The loop-back method is implemented if the user's software returns the OTM to ACTS after it is received. Each time the OTM is returned, ACTS measures the round-trip path delay, and divides this quantity by 2 to get the one-way path delay. Then, after three consistent measurements, ACTS advances the OTM by the amount of the one-way path delay. For example, if the one-way path delay is 50.4 ms, ACTS sends the OTM out 50.4 ms (instead of 45 ms) early. At this point, the path is calibrated, and the OTM changes from an asterisk to a pound sign (#). If the loop-back option is used, the uncertainty of ACTS is ±5 ms [21].

TABLE 18.6 The Automated Computer Time Service (ACTS) Time Code

Code	Meaning
JJJJJ	The Modified Julian Date (MJD). The MJD is the last five digits of the Julian Date, which is a count of the number of days since January 1, 4713 B.C.
YR-MO-DA	The year, month, and day.
HH:MM:SS	Hour, minute, and second. The time is always transmitted as UTC, and an offset must be applied to obtain local time.
TT	A two-digit code that indicates whether the United States is on Standard Time (ST) or Daylight Saving Time (DST). It also indicates when ST or DST is approaching. The code is set to 00 when ST is in effect, or to 50 when DST is in effect. During the month in which a time change occurs, this number will begin deincrementing by 1 each day until the change occurs. For example, if TT is set to 5, it means the change from DST to ST will take place in 5 days.
L	A one-digit code that indicates whether a leap second will be added or subtracted at midnight on the last day of the current month. If the code is 0, no leap second will occur this month. If the code is 1, a positive leap second will be added at the end of the month. If the code is 2, a second will be deleted at the end of the month.
DUT1	The current difference between the UT1 time scale and UTC. This number can be added to UTC to obtain UT1. The correction ranges from –0.8 to 0.8 s.
msADV	A five-digit code that displays the number of milliseconds that NIST advances the time code. It defaults to 45.0 ms, but will change to reflect the actual one-way line delay if the on-time marker (OTM) is echoed back to NIST.
UTC(NIST)	A label that indicates one is receiving UTC from the National Institute of Standards and Technology (NIST).
<OTM>	A single character sent at the end of each time code. The OTM is originally an asterisk (*) and changes to a pound sign (#) if ACTS has successfully calibrated the path.

TABLE 18.7 Dial-Up Time Setting Services

Organization	Location	Telephone Number
Federal Institute of Physics and Metrology (PTB)	Germany	011-49-53-1-512038
National Research Council (NRC)	Canada	(613) 745-3900, Ottawa (416) 445-9408, Toronto
National Center for Metrology (CENAM)	Mexico	011-52-42-110505
National Institute of Standards and Technology (NIST)	Boulder, CO	(303) 494-4774
National Observatory at Rio de Janeiro (ONRJ)	Brazil	011-55-21-580-0677
Technical University of Graz (TUG)	Austria	011-433-16472366
Telecommunications Laboratory (TL)	Taiwan	011-886-3-424-5490
United States Naval Observatory (USNO)	Washington, D.C.	(202) 762-1594

Some dial-up services similar to ACTS are listed in Table 18.7. These services all transmit time codes in ASCII, but several different formats are used. Due to this lack of standardization, software that accesses multiple services must be able to interpret several different time code formats.

Network Time Setting Services

Computers connected to the Internet can be synchronized without the expense of using a dial-up service. The Internet time servers provide a higher level of standardization than the dial-up services. Several standard timing protocols are defined in a series of RFC (Request for Comments) documents. One can obtain these documents from a number of Internet sites. The four major timing protocols are the Time Protocol, the Daytime Protocol, the Network Time Protocol (NTP), and the Simple Network Time Protocol (SNTP). Table 18.8 summarizes the various protocols and their port assignments, or the port on which the time server "listens" for a request from the client [22–26].

TABLE 18.8 Internet Time Protocols

Protocol Name	Document	Format	Port Assignments
Time Protocol	RFC-868	Unformatted 32-bit binary number contains time in UTC seconds since January 1, 1900.	Port 37 tcp/ip, udp/ip
Daytime Protocol	RFC-867	Exact format not specified in standard. Only requirement is that time code is sent as ASCII characters. Often is similar to time codes sent by dial-up services like ACTS.	Port 13 tcp/ip, udp/ip
Network Time Protocol (NTP)	RFC-1305	Server responds to each query with a data packet in NTP format. The data packet includes a 64-bit timestamp containing the time in UTC seconds since January 1, 1900, with a resolution of 200 ps, and an uncertainty of 1 to 50 ms. NTP software runs continuously on the client machine as a background task that periodically gets updates from the server.	Port 123 udp/ip
Simple Network Time Protocol (SNTP)	RFC-1769	A version of NTP that does not change the specification, but simplifies some design features. It is intended for machines where the full performance of NTP is "not needed or justified."	Port 123 udp/ip

NIST operates a Network Time Service that distributes time using the Time, Daytime, and NTP formats from multiple servers [27]. Small computers (PCs) normally use the Daytime Protocol. Large computers and workstations normally use NTP, and NTP software is often included with the operating system. The Daytime Protocol time code is very similar to ACTS. Like ACTS, the Daytime Protocol time code is sent early (by 50 ms), but the server does not calibrate the path. However, the timing uncertainty should be ±50 ms at most locations.

Computer software to access the various dial-up and network time services is available for all major operating systems. One can often obtain evaluation copies (shareware) from the Internet or another on-line service.

18.8 Future Developments

Both the realization of the SI second and the performance of time transfer techniques will continue to improve. One promising development is the increased use of *cesium-fountain* standards. These devices work by laser cooling the atoms and then lofting them vertically. The resonance frequency is detected as the atoms rise and fall under the influence of gravity. Many laboratories are working on this concept, which should lead to substantial improvement over existing atomic-beam cesium standards [28]. In the longer term, a *trapped-ion* standard could lead to improvements of several orders of magnitude. This standard derives its resonance frequency from the systematic energy shifts in transitions in certain ions. The frequency uncertainty of such a device could eventually reach $\pm 1 \times 10^{-18}$ [29].

The future of time transfer should involve more and more reliance on satellite-based systems. Ground-based systems such as LORAN-C are expected to be phased out [30]. The timing uncertainty of GPS will improve if the Selective Availability (SA) program is discontinued (as expected) in the early part of the next century [31]. GLONASS, the Russian counterpart to GPS, might become more widely used [32]. And, in the near future, a time transfer service from the geostationary INMARSAT satellites could be available. This service uses technology similar to GPS, but should provide better performance.

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