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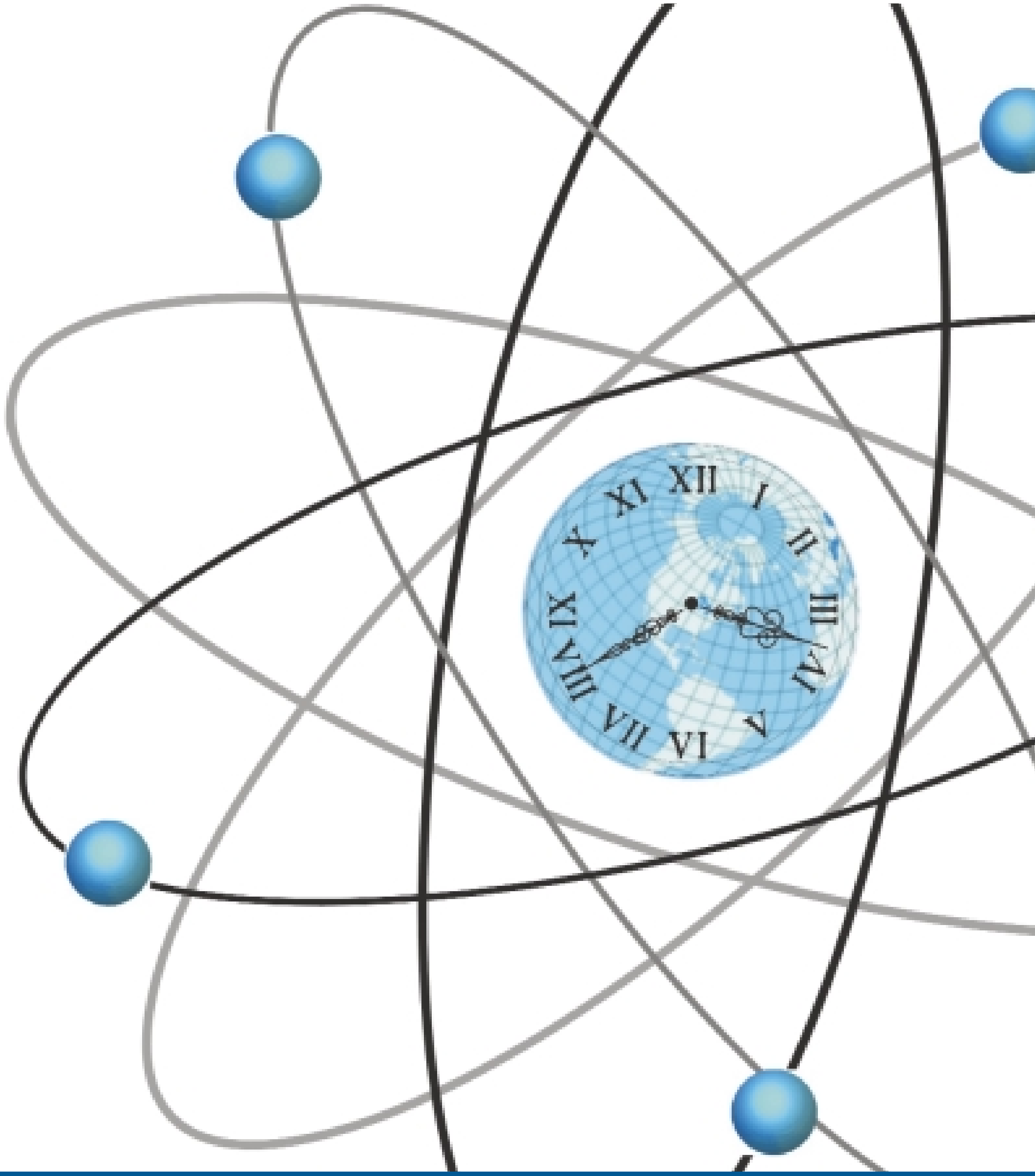
NIST Time and Frequency Services

Michael A. Lombardi



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NIST Time and Frequency Services

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Chapter 1

How NIST Provides Time and Frequency Standards for the United States

The National Institute of Standards and Technology (NIST) maintains the standards for time and frequency for most users in the United States. NIST provides a variety of services designed to deliver time and frequency signals to the people who need them. The signals are broadcast via several mediums, including high and low frequency radio, the Internet, and telephone lines. These signals are used to synchronize millions of clocks everyday, throughout the United States and around the world. This booklet is a guide to NIST Time and Frequency Services. It describes the signals and services offered by NIST, how they work, and how you can use them.

Beginning with Chapter 2, we'll take a detailed look at each of the time and frequency services that NIST provides. However, let's begin by discussing why time and frequency services are needed in the first place, and how NIST provides and controls them.

Who Needs Time and Frequency Standards?

Everybody needs time and frequency standards. If we stop and think about it, time and frequency standards are involved in one way or another in just about everything we do.

Time and frequency standards supply us with three basic types of information. The first type, *date and time-of-day*, tell us when something happened. Date and time-of-day can be used to record events, or to make sure that multiple events are *synchronized*, or happen at the same time. It's easy to think of ways we use date and time-of-day in our everyday lives. For example, we use date information to remind us when birthdays, anniversaries, and other holidays are scheduled to occur. We use time-of-day information to set our alarm clocks so we get out of bed on time. Our wristwatches and wall clocks help us get to school and work on time. And if we plan to meet a friend for dinner at 6 p.m., that's a simple example of synchronization. If our watches agree, we should both arrive at about the same time.

Date and time-of-day information have other, more sophisticated uses as well. Fighter planes flying in a high-speed formation require synchronized clocks. If one banks or turns at the wrong time, it could result in a collision and loss of life. If you are watching a network television program, the local station has to be ready to receive the network feed (usually from a satellite), at the exact instant it arrives. This requires synchronization of the station and network clocks. The instruments used to detect and measure earthquakes, called seismographs, require synchronized clocks so that data collected at various locations can be compared and combined. Stock market transactions need to be synchronized so that the buyer and seller can agree upon the same price at the same time. A time error of just a few seconds could result in a large difference in the price of a stock. The electric power companies also need time synchronization. They use synchronized clocks throughout their power grids, so they can instantly transfer power to the parts of the grid where it is needed most. They also use synchronized clocks to determine the location of short circuit faults along a transmission line.

The second type of information, *time interval*, tells us "how long" it takes for something to happen. We use time interval to state our age, or the amount of time we have been alive. Most workers are paid for the amount of time that they worked, usually measured in hours, weeks, or months. We pay for time as well—30 minutes on a parking meter, a 20 minute cab ride, a 5 minute long distance phone call, or a 30 second radio advertising spot.

The standard unit of time interval is the second (s), which is defined according to a property of the cesium atom, as we shall see shortly. However, many applications in science and technology require the measurement of intervals much shorter than one second; such as *milliseconds* (10^{-3} s), *microseconds* (10^{-6} s), *nanoseconds* (10^{-9} s), and even *picoseconds* (10^{-12} s).

The third type of information, *frequency*, is the rate at which something happens. The unit we use to measure frequency is the hertz (Hz), or the number of events per second. Many of the frequencies we depend upon are generated by fast moving electrical signals that are reproduced many thousands (kHz) or millions (MHz) of times per second, or even faster. For example, the quartz watch on your wrist keeps time by counting the frequency of a quartz crystal designed to run at a frequency of 32,768 Hz. When the crystal has oscillated 32,768 times, the watch records that one second has elapsed. Channel 7 on your television receives video at a frequency of 175.25 MHz. The station has to transmit on this frequency as accurately as possible, so that its signal does not interfere with the signals from other stations. Your television has to be able to pick out the channel 7 frequency from all the other available radio signals, so that you see the correct picture on your screen. A high speed Internet connection might use something called a T1 line, which sends data at a frequency of 1,544,000 bits per second (1.544 MHz). And the computer that you use to connect to the Internet might run at a frequency faster than 1 GHz (one billion cycles per second). All of these applications require an *oscillator* that produces a specific frequency. This oscillator should be *stable*, which means that the frequency it produces stays the same (with only minor variations) over long time intervals.

Accurate frequency is critical to today's communication networks. It shouldn't surprise you that the highest capacity networks run at the highest frequencies. In order to send data faster and faster, we need stable oscillators situated throughout a network that all produce nearly the same frequency. The process of making multiple oscillators run at the same frequency is called *syntonization*.

Of course, all three types of time and frequency information are very closely related. As we mentioned, the standard unit of time interval is the second. If we count seconds in an agreed upon fashion, we can calculate the date and the time-of-day. And if we count the number of events that occur during a second, we can measure the frequency.

It's easy to see that the world depends heavily on time and frequency information, and that we rely on many millions of clocks and oscillators to keep time and produce frequency. To keep the world running smoothly, these devices need to be periodically compared to an internationally recognized standard. This comparison might be as simple as setting our watch or alarm clock to the correct minute, or adjusting the frequency of an atomic oscillator so it keeps time within a few nanoseconds per day. The time and frequency standards maintained by NIST provide the reference for these comparisons.

NIST and the Primary Standards of Measurement

The task of maintaining the national standards for time and frequency is an important part of the work done at NIST, and it fits in perfectly with the agency's mission. NIST serves as the national measurement laboratory, or the ultimate reference point for measurements made in the United States. NIST is responsible for maintaining the seven base physical quantities at the highest possible accuracies. Time is one of the seven base quantities; the others are used in the measurement of length, light, electricity, chemical concentration, temperature, and mass. NIST distributes the standard units of measurement throughout the country in the form of measurement services and standard reference materials. By doing so, it provides measurement references to anyone

Figure 1.1. The NIST Boulder Laboratories

who needs them. If a measurement is made using a NIST reference, and if the uncertainty of the measurement is known and documented, the measurement is said to be *traceable*. Establishing *traceability* is important to many organizations, because it helps them prove that their measurements are being made correctly. In some cases, traceability is even a legal or contractual requirement.

NIST strives to develop in-house measurement capabilities that exceed the highest requirements of users in the United States. Since these requirements become more demanding every year, NIST scientists and researchers are continually developing new standards and measurement techniques to keep up with this demand. While these new standards are being developed, other NIST personnel are busy distributing the existing standards and measurement techniques, so that everyone can make traceable measurements that are nearly as good as those made inside the national laboratory.

Although most of NIST is located in Gaithersburg, Maryland, the Time and Frequency division is located in Boulder, Colorado (Figure 1.1). The time and frequency services controlled from Boulder are excellent examples of how NIST is able to distribute its standards and measurement capability to a wide variety of users throughout the United States.

Atomic Time and the Definition of the Second

We mentioned earlier that the standard unit for time interval is the second (s). Since 1967, the second has been defined as the duration of 9,192,631,770 cycles of the radiation associated with a specified transition of the *cesium atom*. Frequency (expressed in hertz) is obtained by counting events over a 1 s interval.

The second is one of the seven base units of measurement in the International System of Units (SI). These units are used to express the values of the seven physical quantities that we mentioned earlier. The seven base units were defined by international agreement and all other units of measurement can be derived from them. The International Bureau of Weights and Measures (BIPM) located near Paris, France, is responsible for ensuring that the major countries of the world use the SI units. This means that the second and the other base units are defined the same way all over the world. As a result, the timekeeping standards maintained by the major countries tend to closely agree with each other—typically to within one microsecond, and often to within a few nanoseconds.

Since the second is defined based on a property of the cesium atom, it should come as no surprise that the electronic device that produces the standard second is called a *cesium oscillator*. Cesium oscillators (and other types of atomic oscillators) are called *intrinsic standards*, because they produce frequency based on a natural phenomena, in this case a property of an atom. NIST maintains an *ensemble* of atomic oscillators in Boulder, Colorado. The outputs of these oscillators are averaged together to produce the national standard for time and frequency. Most of the oscillators in the ensemble are commercially available, but the primary standard, called NIST-F1, is a custom device that was designed and built at NIST (Figure 1.2). The *primary standard* is used to help calibrate the ensemble.

NIST-F1 became operational in late 1999, and is the latest in a long line of NIST primary time and frequency standards. NIST-F1 is a *cesium fountain* frequency standard, and has many performance advantages over the earlier *cesium beam* standards. At this writing (2001), NIST-F1 is one of the most accurate clocks in the world, and can keep time to within about 0.1 nanoseconds per day. Along with the other atomic clocks in the ensemble, NIST-F1 provides the reference for the NIST time and frequency services.

Coordinated Universal Time (UTC)

The ensemble and primary standard described above form what is known as the NIST *time scale*. This time scale produces a very stable and accurate frequency by using a weighted average of all its oscillators, with the best oscillators receiving the most weight. Small adjustments, never more than about 2 nanoseconds per day, are made to the NIST time scale to keep it in agreement with international standards. The output of the time scale is called UTC(NIST), which is short for Coordinated Universal Time kept at NIST.

You can think of UTC(NIST) as both a frequency and a time standard. It produces an extremely stable frequency that serves as the standard for the United States. It also produces the standard for time interval, by generating pulses that occur once per second. By counting these second pulses, NIST can keep time. The second pulses are added together to keep track of longer units of time interval—such as years, months, days, hours, and minutes.

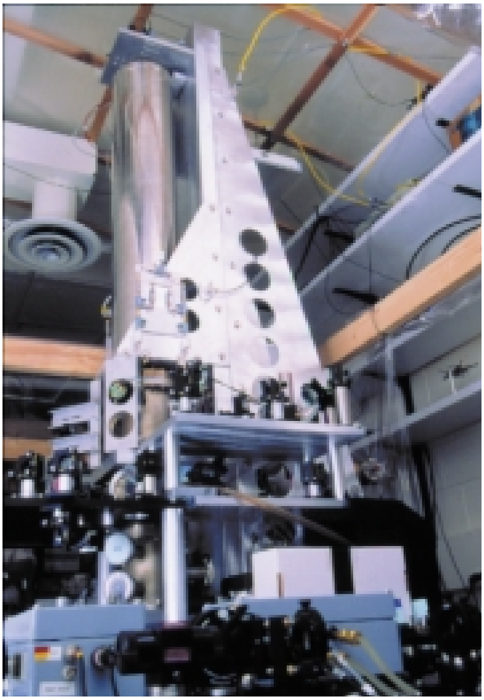


Figure 1.2. NIST-F1 Primary Standard

The UTC system of timekeeping is similar to your local time, with two major differences. Since UTC is used internationally, it ignores local conventions such as Daylight Saving Time and time zones. In other words, UTC is the same no matter where you are located on Earth. Unlike local time, which is usually based on a 12-hour clock, UTC is a 24-hour clock system. The hours are numbered from 0 to 23. The time at midnight is 0 hours, 0 minutes, and 0 seconds. The time just before the next midnight is 23 hours, 59 minutes, and 59 seconds.

To convert UTC to local time, you need to add or subtract a specific number of hours. The number of hours to add or subtract depends on the number of time zones between your location and the zero meridian that passes through Greenwich, England. When local time changes from Daylight Saving to

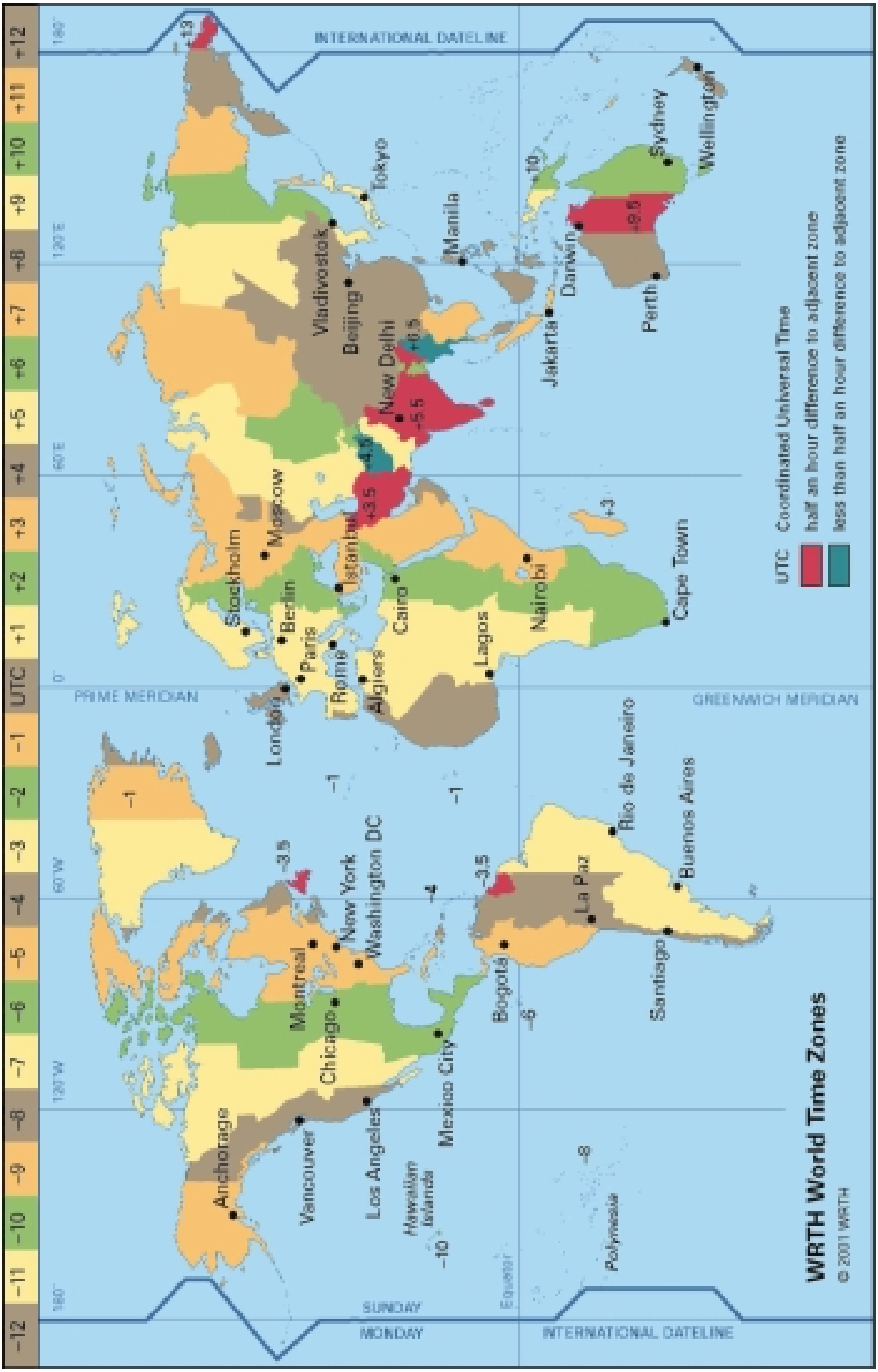


Figure 1.3. World Time Zone Map

Standard Time, or vice versa, UTC does not change. However, the difference between UTC and local time changes by 1 hour. For example, in New York City, the difference between UTC and local time is 5 hours when Standard Time is in effect, and 4 hours when Daylight Saving Time is in effect.

Most of the hardware and software products that access NIST services allow you to select your time zone and are capable of automatically converting UTC to your local time. These products also automatically correct for Daylight Saving Time. The conversion is fairly simple. The chart of world time zones in Figure 1.3 shows the number of hours to add or subtract from UTC to obtain your local standard time. If Daylight Saving Time is in effect at your location, add 1 hour to what is shown on the chart.

Leap Seconds

As we mentioned earlier, the second is defined according to the intrinsic properties of the cesium atom. This means that UTC is an *atomic time scale*, which runs at an almost perfectly constant rate. Prior to atomic time, time was kept using *astronomical time scales* that used the rotation of the Earth as their reference. When the switch to atomic time keeping occurred, it became obvious that while much was gained, some things were lost. A few people still needed time referenced to the Earth's rotation for applications such as celestial navigation, satellite observations of the Earth, and some types of surveying. These applications relied on an astronomical time scale named UT1.

For these reasons, it was agreed that UTC should never differ from UT1 by more than 0.9 s. Therefore, those who needed UT1 could just use UTC, since they could be sure that the difference between the two time scales would be less than 1 s. Keeping the two time scales in agreement requires making occasional 1 s adjustments to UTC. These adjustments are called *leap seconds*. A leap second can be positive or negative, but so far, only positive leap seconds have been needed. Leap seconds are announced by the International Earth Rotation Service and are usually inserted into the UTC time scale on June 30 or December 31, making those months 1 s longer than usual. Currently, about 4 leap seconds are required every 5 years.

All NIST services automatically add leap seconds when necessary. For the very few people who need to know UT1 with an uncertainty of less than 1 s, most NIST services also broadcast a UT1 *correction*. This correction reports the current time difference between UTC and UT1 to the nearest 0.1 s.

Traceability

Earlier, we introduced the concept of measurement traceability. Each of the NIST time and frequency services provides a way to establish traceability to NIST and to international standards. You can think of traceability as a chain that extends all the way from the definition of the SI unit to your measurement or application. Keeping the chain intact requires making a series of comparisons. Each link in the chain is continually compared to the previous link. Figure 1.4 illustrates the part of the traceability chain that extends from the SI definition of the second down to the NIST services.

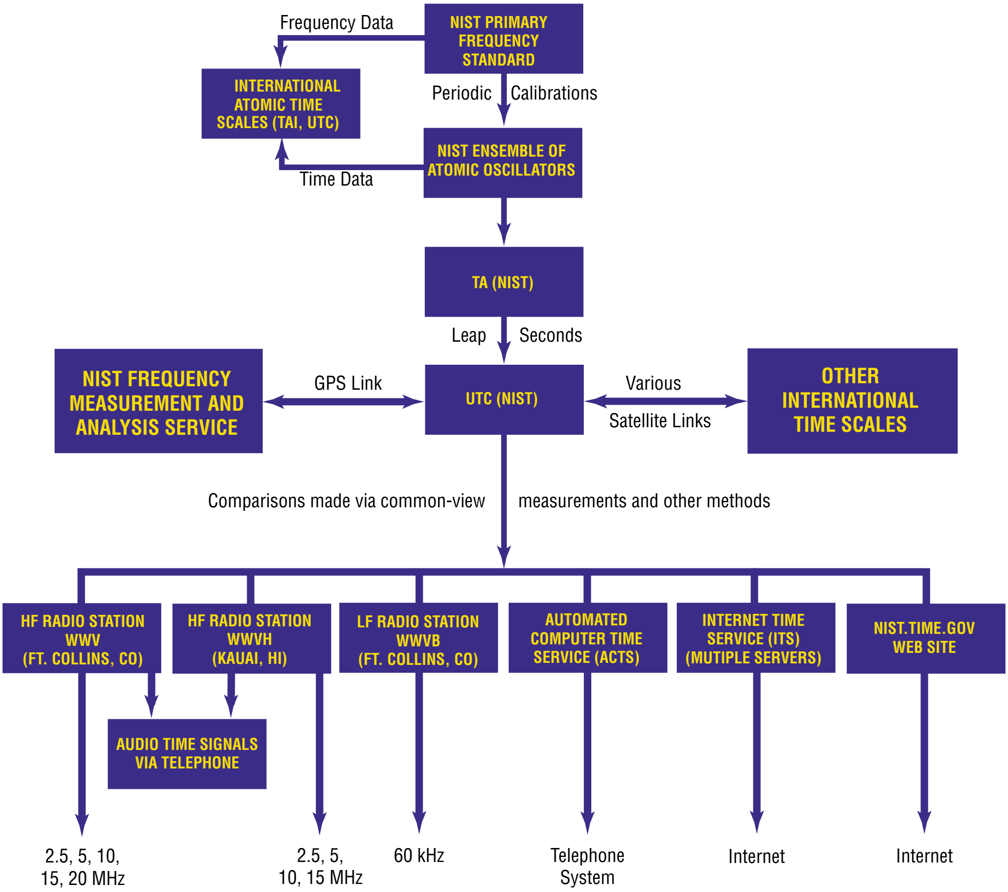


Figure 1.4. The Traceability Chain for NIST Time and Frequency Services

The traceability chain starts with a time and frequency source that is as nearly perfect as possible. For example, at the NIST laboratories it is possible to synchronize a clock to within nanoseconds or even picoseconds of UTC. However, as we transfer UTC down through the links in the chain, we add *uncertainty* to our measurement. By the time a NIST service is used to synchronize a computer clock, the time might only be within a few milliseconds of UTC, and these few milliseconds become our *measurement uncertainty* relative to UTC. This is an important concept. Whenever we talk about traceability, we also need to talk about measurement uncertainty. The typical uncertainty of each time and frequency service is discussed in the following chapters.

Let's examine Figure 1.4 to see how the traceability chain works. We mentioned that NIST compares its time and frequency standards to the time scales maintained in other countries. The comparison data are handled and processed by the BIPM, the same organization responsible for the SI units. Most international comparisons are done using a technique called *common-view*. Normally, if you wanted to compare one oscillator or clock to another, you would connect them both to the same measurement system and make a comparison. However, what if the two clocks aren't located in the same place? They might be in different buildings, different cities, or even different countries. For example, what if you want to compare a clock in the United States to one in Italy? Obviously, you can't directly compare them using the same measurement system, but you can indirectly compare them using the common-view technique.

To use the common-view technique, both oscillators are simultaneously compared to a common-view reference and measurement data are collected. The reference is usually a Global Positioning System (GPS) satellite, although other satellite and land based signals are sometimes used. The collected measurement data are then exchanged and processed to see how one oscillator compares to the other. For the purposes of illustration, let's say that the clock in the United States is measured to be 10 ns fast with respect to the satellite, and the clock in Italy is measured to be 10 ns slow with respect to the satellite. Even though we were unable to directly compare the two clocks, we now know that the United States clock was 20 ns ahead of the Italian clock at the time the common-view measurement was made.

NIST is one of about 50 laboratories that send their common-view data to the BIPM. Like NIST, most of these laboratories serve as the ultimate reference point for measurements made in their countries. The BIPM averages data from all of the contributing laboratories, and produces a time scale called International Atomic Time (TAI). When corrected for leap seconds, TAI becomes Coordinated Universal Time (UTC), or the true international time scale.

Unlike UTC(NIST) and similar time scales maintained by other laboratories, UTC is a paper time scale. About 250 oscillators contribute to UTC, but the BIPM has access only to the data, not the oscillators. Even so, the BIPM's role is very important. They publish the time offset or difference of each laboratory's version of UTC relative to the international average. For example, the BIPM publishes the time offset between UTC and UTC(NIST), which is typically less than 10 ns. The work of the BIPM makes it possible for NIST and the other laboratories to adjust their standards so that they agree as closely as possible with the rest of the world. Since every national measurement laboratory is always comparing itself to the other laboratories, you can rest assured that the units of time and frequency are defined in the same way all over the world.

The process of comparing the NIST time scale to the other standards of the world completes the first link of the traceability chain. The second link is used to control the broadcast services described in Chapters 2 through 4. These services are continuously compared to the NIST time scale, and much care is taken to keep the measurement uncertainty as small as possible. Some of the services used to synchronize computer equipment (Chapter 4) are directly connected to the NIST time scale, but most are referenced to atomic standards located outside of NIST's Boulder, Colorado, laboratory. For example, the NIST radio station sites described in Chapters 2 and 3 are located in Fort Collins, Colorado, and Kauai, Hawaii. Three cesium standards are kept at Fort Collins and

Kauai to provide the reference for each station's time code generators and transmitters. These standards are continuously compared and adjusted to agree with the Boulder time scale, using the same common-view technique used for the international comparisons. As a result, time can easily be kept within 100 ns of UTC(NIST) at each radio station.

The next link in the traceability chain connects NIST to the user. The signals broadcast by NIST must travel across a path en route to the user, and the uncertainties introduced by this link are much larger than those introduced by the previous two links. As we shall see in the following chapters, signals that travel over a low frequency (LF) radio or satellite path usually have smaller uncertainties than signals that travel over a high frequency (HF) radio path, or a telephone or Internet path.

The final link in the traceability chain occurs when you actually use the signal. Some uncertainty is always added after the signal arrives at your location. The amount of uncertainty added depends upon your application. In some cases, the amount of uncertainty added by this final link will be much larger than the combined uncertainty of all the previous links. For example, if you use a NIST signal to synchronize a computer clock (Chapter 4), the resolution of the clock is one limiting factor. If the clock displays only seconds, you won't be able to synchronize it to less than one second. Another source of uncertainty is the delay introduced by your client software or operating system, which might be larger than the total broadcast delay. If you calibrate a stop watch using an audio time signal (Chapter 3), the largest cause of uncertainty is human reaction time, which is not nearly as stable or consistent as the audio signal. In other cases, the uncertainty of the final link is very small. The best receivers and measurement systems use sophisticated electronics and software to preserve as much of the signal accuracy as possible.

As you read through the rest of this booklet, keep the traceability chain in mind. NIST maintains time and frequency standards that are as nearly perfect as possible. By providing time and frequency services, NIST makes it possible for all of us to use these standards as the reference for our own measurements.

Time and Frequency Services Offered by NIST

Table 1.1 lists the time and frequency services currently offered by NIST. It also lists the medium each service uses to deliver its time and frequency information, what you need to have in order to use the service, and some of its typical applications. The remaining chapters provide a detailed look at each service listed in the table.

For the current status of each of these services, including contact information, broadcast outage reports, and new developments, please visit the NIST Time and Frequency Division web site located at:

http://www.boulder.nist.gov/timefreq

TABLE 1.1 – TIME AND FREQUENCY SERVICES OFFERED BY NIST

NAME OF SERVICE	REQUIREMENTS	CHAPTER	TIME UNCERTAINTY	FREQUENCY UNCERTAINTY
nist.time.gov web site	Computer, Internet connection, web browser	4	< 2 s	Not applicable
Telephone time-of-day service	Telephone	3	< 30 ms	Not applicable
Automated Computer Time Service (ACTS)	Computer, analog modem, telephone line, client software	4	< 15 ms	Not applicable
Internet Time Service (ITS)	Computer, Internet connection, client software	4	< 100 ms	Not applicable
Radio Stations WWV and WWVH	HF receiver	3	1 to 20 ms	10^{-6} to 10^{-9}
Radio Station WWVB	LF receiver	2	0.1 to 15 ms	10^{-10} to 10^{-12}
Frequency Measurement Service (FMS)	Paid subscription, NIST provides equipment	5	< 20 ns	2×10^{-13}

Chapter 2

Synchronizing the Nation's Clocks: NIST Radio Station WWVB

There are literally millions of wall clocks, desk clocks, clock radios, wristwatches, and other devices that set themselves to NIST time. These *radio controlled clocks* contain tiny radio receivers tuned to NIST radio station WWVB, located near Fort Collins, Colorado. WWVB continuously broadcasts time and frequency signals at 60 kHz, in the part of the radio spectrum known as low frequency (LF). The WWVB signal includes a time code containing all of the information needed to synchronize radio controlled clocks in the United States and the surrounding areas. In addition, calibration and testing laboratories use the 60 kHz carrier frequency from WWVB as a reference for the calibration of electronic equipment and frequency standards.

History of WWVB

LF and VLF (very low frequency) broadcasts have long been used to distribute time and frequency standards. As early as 1904, the United States Naval Observatory (USNO) was broadcasting time signals from the city of Boston as an aid to navigation. This experiment and others like it made it evident that LF and VLF signals could cover a large area using a relatively small amount of power. By 1923, NIST radio station WWV (Chapter 3) had begun broadcasting standard carrier signals to the public on frequencies ranging from 75 to 2000 kHz. These signals were used to calibrate radio equipment, which became increasingly important as more and more stations became operational. Over the years, many radio navigation systems were designed using stable time and frequency signals broadcast on the LF and VLF bands. The most well known of these navigation systems is LORAN-C, which allows ships and planes to navigate by transmitting stable 100 kHz signals from multiple transmitters.

The station known today as WWVB began life as radio station KK2XEI in July 1956. The transmitter was located at Boulder, Colorado, and the radiated power was just 1.4 W. Even so, the signal was monitored at Harvard University in Massachusetts. The purpose of this experimental transmission was to show that the radio path was stable and the frequency error was small at low frequencies.

In 1962, NIST (then called the National Bureau of Standards or NBS) began building a new facility at a site north of Fort Collins, Colorado. This site became the home of WWVB and WWVL, a 20 kHz transmitter that was moved from the mountains west of Boulder.

The site was attractive for several reasons, one being its exceptionally high ground conductivity, which was due to the high alkalinity of the soil. It was also reasonably close to Boulder (about 80 km, 49.3 mi), which made it easy to staff and manage; but much farther away from the mountains. The increased distance from the mountains made it a better choice for broadcasting an omnidirectional signal.

WWVB went on the air on July 5, 1963, broadcasting a 7 kW signal on 60 kHz. WWVL began transmitting a 500 W signal on 20 kHz the following month. Although WWVL went off the air in July 1972, the WWVB signal became a permanent part of the nation's infrastructure.

A time code was added to WWVB on July 1, 1965. This made it possible for radio clocks to be designed that could decode the signal and automatically synchronize themselves. The time code format has changed only slightly since 1965; it uses a scheme known as binary coded decimal (BCD) which uses four binary digits (bits) to send one decimal number.

The radiated power of WWVB was increased to its current level of 50 kW in 1999. The power increase made the coverage area much larger, and made it easy for tiny receivers with simple antennas to receive the signal. This resulted in the introduction of many new low cost radio controlled clocks that "set themselves" to agree with NIST time.

Figure 2.1. Aerial View of WWVB/WWV Station Site

Figure 2.2. WWVB Antenna Towers

WWVB Station Description

WWVB is located on a 390 acre (158 hectare) site located near Fort Collins, Colorado. Radio station WWV (Chapter 3) shares the same location. An aerial view of the station site is shown in Figure 2.1.

WWVB uses two nearly identical antennas that were originally constructed in 1962, and refurbished in 1999. The north antenna was originally built for the now discontinued WWVL 20 kHz broadcast, and the south antenna was built for the WWVB 60 kHz broadcast. The antennas are spaced 867 m apart. Figure 2.2 shows two of the south antenna towers.

Each antenna is a top-loaded monopole consisting of four 122 m (400 ft) towers arranged in a diamond shape (Figure 2.3). A system of cables, often called a capacitance hat or top hat, is suspended between the four towers. This top hat is electrically isolated from the towers, and is electrically connected to a downlead suspended from the center of the top hat. The combination of the downlead and the top hat serves as the radiating element.

Ideally, an efficient antenna system requires a radiating element that is at least one-quarter wavelength long. However, at a low frequency such as 60 kHz, it is difficult to construct an antenna that large. The wavelength of 60 kHz is about 5000 m, so a one-quarter

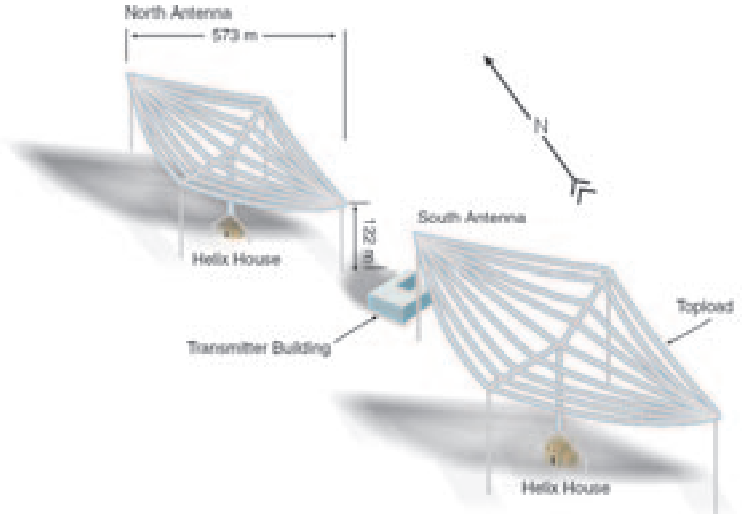


Figure 2.3. Diagram of WWVB Antenna Array

Figure 2.4. A WWVB Transmitter

wavelength antenna would be 1250 m tall, or about 10 times the height of the WWVB antenna towers. As a compromise, some of the missing length was added horizontally to the top hats of this vertical dipole, and the downlead of each antenna is terminated at its own helix house under the top hats. Each helix house contains a large inductor to cancel the capacitance of the short antenna and a variometer (variable inductor) to tune the antenna system. Energy is fed from the transmitters to the helix houses using underground cables housed in two concrete trenches. Each trench is about 435 m long.

A computer is used to automatically tune the antennas during icy and/or windy conditions. This automatic tuning provides a dynamic match between the transmitter and the antenna system. The computer looks for a phase difference between voltage and current at the transmitter. If one is detected, an error signal is sent to a three-phase motor in the helix house that rotates the rotor inside the variometer. This retunes the antenna and restores the match between the antenna and transmitter.

There are three transmitters at the WWVB site. Two are in constant operation and one serves as a standby. A photograph of one of the transmitters is shown in Figure 2.4. Each transmitter consists of two identical power amplifiers that are combined to produce the greatly amplified signal sent to the antenna. One transmitter delivers an amplified time code signal into the north antenna system, and one transmitter feeds the south antenna system. The time code is fed to a console where it passes through a control system and then is delivered to the transmitters.

Using two transmitters and two antennas allows the station to be more efficient than using a single transmitter and antenna. As we described, the length of the WWVB antennas is much less than one-quarter wavelength. And when the length of a vertical radiator is less than the wavelength, the efficiency of the antenna goes down, and some of the transmitter power is lost. In other words, if the efficiency of an antenna is less than 100%, the transmitter power is greater than the effective radiated power. The north antenna system at WWVB has an efficiency of about 57%, and the south antenna has an efficiency of about 59%. However, the combined efficiency of the north and south antennas is about 71%. As a result, each transmitter must produce only about 36 kW of power for WWVB to produce its effective radiated power of 50 kW.

On rare occasions, one of the WWVB antenna systems might require maintenance or repairs. When this happens, the power of one transmitter is temporarily increased to about 50 kW and a single transmitter and antenna are used to deliver the signal. Using this technique, the station is still able to deliver an effective radiated power of about 28 kW.

TABLE 2.1 – CHARACTERISTICS AND SERVICES OF WWVB

CHARACTERISTICS & SERVICES	NIST RADIO STATION WWVB
Date Service Began	July 1956
South Antenna Coordinates	40° 40’ 28.3” N 105° 02’ 39.5” W
North Antenna Coordinates	40° 40’ 51.3” N 105° 03’ 00.0” W
Standard Carrier Frequency	60 kHz
Power	50 kW
Standard Time Intervals	Seconds, 10 seconds, minutes
Time of Day Information	Time code frame sent every minute, BCD format

WWVB Signal Description

WWVB identifies itself by advancing its carrier phase 45° at 10 minutes after the hour and returning to normal phase at 15 minutes after the hour. If you plot WWVB phase, this results in an hourly phase shift of approximately 2.1 μs as shown in Figure 2.5.

WWVB is also identified by its unique time code. The time code is synchronized with the 60 kHz carrier and is broadcast continuously at a rate of 1 bit per second using a simple modulation scheme called *pulse width modulation*. The time code is sent in binary coded decimal (BCD) format, where four binary digits (bits) are used to represent one decimal number. The carrier power is reduced and restored to produce the time code bits. The carrier power is reduced 10 dB at the start of each second. If full power is

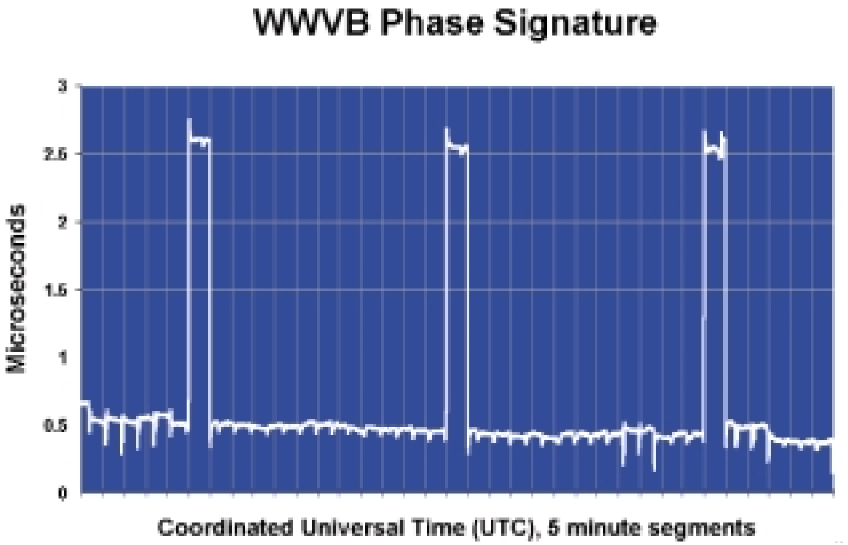


Figure 2.5. WWVB Phase Signature

restored 200 ms later, it represents a 0 bit. If full power is restored 500 ms later, it represents a 1 bit. If full power is restored 800 ms later, it represents a reference marker or a position identifier.

The binary-to-decimal weighting scheme is 8-4-2-1. The *most significant bit* is sent first. This is the reverse of the WWV/ WWVH time code described in Chapter 3. The BCD groups and the equivalent decimal numbers are shown in Table 2.2.

TABLE 2.2 - BCD WEIGHTING SCHEME USED BY WWVB TIME CODE

DECIMAL NUMBER	BIT 1 2^3	BIT 2 2^2	BIT 3 2^1	BIT 4 2^0
0	0	0	0	0
1	0	0	0	1
2	0	0	1	0
3	0	0	1	1
4	0	1	0	0
5	0	1	0	1
6	0	1	1	0
7	0	1	1	1
8	1	0	0	0
9	1	0	0	1

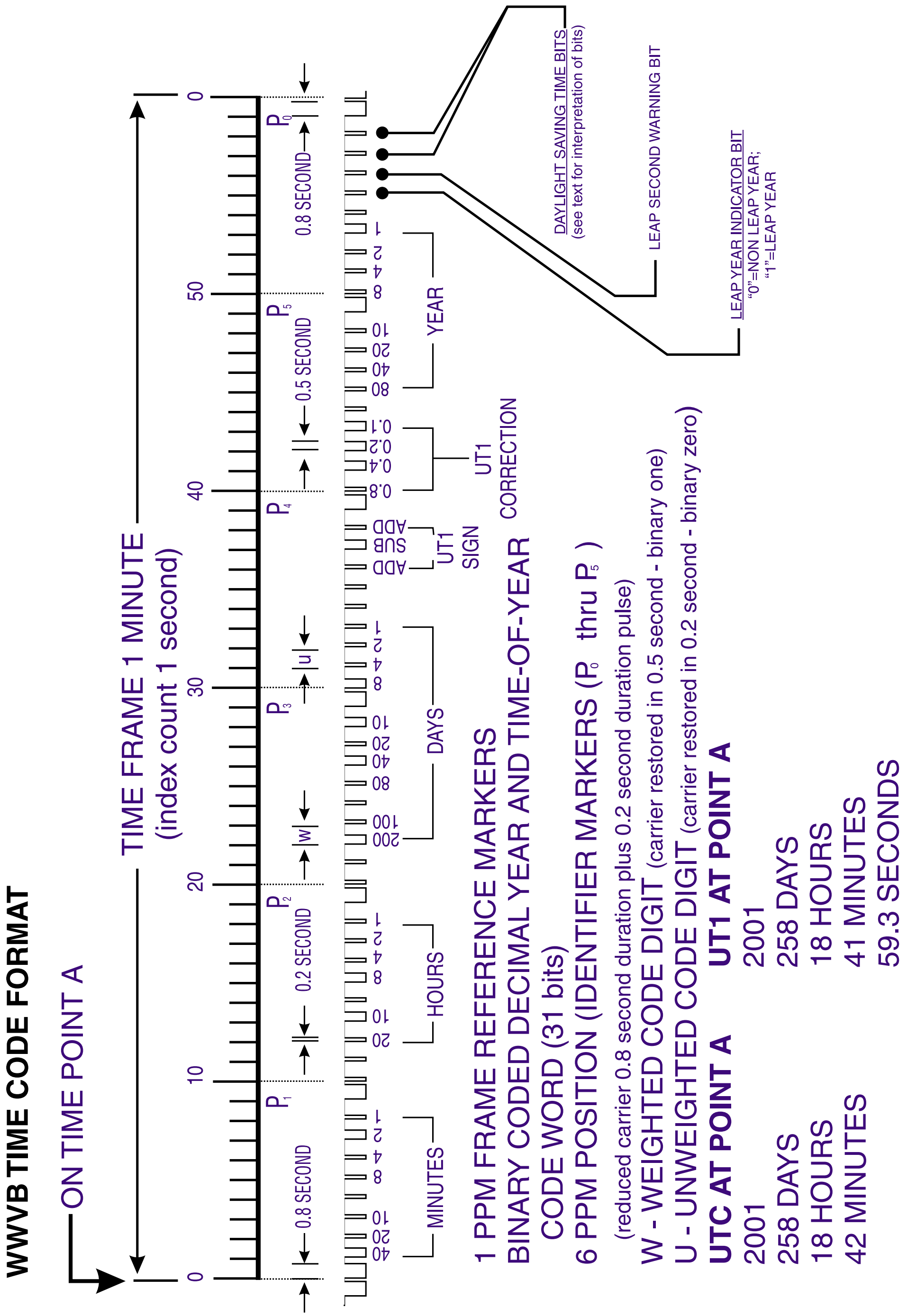


Figure 2.6. The WWVB Time Code Format

TABLE 2.3 - WWVB TIME CODE BITS

BIT NUMBER	BIT DESCRIPTION	BIT NUMBER	BIT DESCRIPTION
0	Frame Reference Bit, P_r	30	Day of Year, 8
1	Minutes, 40	31	Day of Year, 4
2	Minutes, 20	32	Day of Year, 2
3	Minutes, 10	33	Day of Year, 1
4	Reserved	34	Reserved
5	Minutes, 8	35	Reserved
6	Minutes, 4	36	UTI Sign, +
7	Minutes, 2	37	UTI Sign, -
8	Minutes, 1	38	UTI Sign, +
9	Position Marker 1, P_1	39	Position Marker 4, P_4
10	Reserved	40	UT1 Correction, 0.8 s
11	Reserved	41	UT1 Correction, 0.4 s
12	Hours, 20	42	UT1 Correction, 0.2 s
13	Hours, 10	43	UT1 Correction, 0.1 s
14	Reserved	44	Reserved
15	Hours, 8	45	Year, 80
16	Hours, 4	46	Year, 40
17	Hours, 2	47	Year, 20
18	Hours, 1	48	Year, 10
19	Position Marker 2, P_2	49	Position Marker 5, P_5
20	Reserved	50	Year, 8
21	Reserved	51	Year, 4
22	Day of Year, 200	52	Year, 2
23	Day of Year, 100	53	Year, 1
24	Reserved	54	Reserved
25	Day of Year, 80	55	Leap Year Indicator
26	Day of Year, 40	56	Leap Second Warning
27	Day of Year, 20	57	Daylight Saving Time
28	Day of Year, 10	58	Daylight Saving Time
29	Position Marker 3, P_3	59	Frame Reference Bit, P_0

WWVB requires one minute to send its time code (Figure 2.6). The time code frame contains the current minute, hour, day of year, the last two digits of the current year, the UT1 correction, leap year and leap second indicators, and information about daylight and standard time. Two BCD groups are used to express the hour (00 to 23), minute (00 to 59), and year (00 to 99); and three groups are used to express the day of year (001 to 366). The time code frame begins with a frame reference marker consisting of reference bits P_0 and P_r. The on-time reference point of the time code frame is the leading edge of the reference bit P_r. Seconds are determined by counting pulses within the frame. Position markers (P_1 through P_5) lasting for 0.8 s are transmitted every 10 s within the time code frame. The individual bits are annotated in Table 2.3.

UT1 corrections are broadcast at seconds 36 through 43. The bits transmitted at seconds 36, 37, and 38 show if UT1 is positive or negative with respect to UTC. If 1 bits are sent at seconds 36 and 38, the UT1 correction is positive. If a 1 bit is sent at second 37, the UT1 correction is negative. Bits 40, 41, 42, and 43 form a four-bit BCD group that show the magnitude of the correction in units of 0.1 s.

A *leap year* indicator is transmitted at second 55. If it is set to 1, the current year is a leap year. The bit is set to 1 during each leap year after January 1 but before February 29. It is set back to 0 on January 1 of the year following the leap year.

A *leap second* indicator is transmitted at second 56. If this bit is high, it indicates that a leap second will be added to UTC at the end of the current month. The bit is set to 1 near the start of the month in which a leap second is added. It is set to 0 immediately after the leap second insertion.

Daylight saving time (DST) and standard time (ST) information is transmitted at seconds 57 and 58. When ST is in effect, bits 57 and 58 are set to 0. When DST is in effect, bits 57 and 58 are set to 1. On the day of a change from ST to DST bit 57 changes from 0 to 1 at 0000 UTC, and bit 58 changes from 0 to 1 exactly 24 hours later. On the day of a change from DST back to ST bit 57 changes from 1 to 0 at 0000 UTC, and bit 58 changes from 1 to 0 exactly 24 hours later.

Figure 2.6 shows one frame of the time code. The six position identifiers are labeled as P0, P1, P2, P3, P4, and P5. The minutes, hours, days, year, and UT1 sets are marked by brackets; with the weighting factors printed below the bits. Wide pulses represent 1 bits and narrow pulses represent 0 bits. Unused bits are set to 0. The decoded UTC at the start of the frame is 2001, 258 days, 18 hours, and 42 minutes. Since the UT1 correction is –0.7 s, the decoded UT1 is 2001, 258 days, 18 hours, 41 minutes, 59.3 s.

WWVB Coverage Area

The propagation characteristics of LF radio waves make them well suited for time and frequency transfer. At these longer wavelengths, losses in the Earth’s surface are low. Thus, the ground wave can travel well for thousands of kilometers and moderate amounts of transmitted power can cover large portions of a hemisphere.

Figures 2.7 and 2.8 show the estimated coverage area of WWVB during the daytime and nighttime hours in the Fall season (October). The dark color indicate areas where signal levels are estimated to be 100 microvolts per meter (µV/m) or greater. Table 2.4 provides a rough estimate of the expected seasonal signal strength at six different locations.

TABLE 2.4 - ESTIMATED SEASONAL SIGNAL STRENGTH OF WWVB, µV/M

Season	UTC	Cutler, Maine	Honolulu	Mexico City	Miami	San Diego	Seattle
Winter	0000	220	3.2	180	180	180	250
Winter	0400	220	125	560	560	1000	560
Winter	0800	220	320	560	560	1000	560
Winter	1200	320	320	560	560	1000	560
Winter	1600	32	3.2	180	100	180	250
Winter	2000	32	3.2	180	100	180	250
Spring	0000	25	3.2	180	100	180	250
Spring	0400	250	32	560	180	1000	560
Spring	0800	250	400	560	180	1000	560
Spring	1200	40	400	320	100	1000	560
Spring	1600	32	3.2	180	100	180	250
Spring	2000	32	3.2	180	100	180	250
Summer	0000	32	3.2	180	100	180	250
Summer	0400	250	8	560	560	1000	560
Summer	0800	250	400	560	560	1000	560
Summer	1200	32	100	180	100	560	320
Summer	1600	32	3.2	180	100	180	250
Summer	2000	32	3.2	180	100	180	250
Fall	0000	125	3.2	180	56	180	250
Fall	0400	250	180	560	500	1000	560
Fall	0800	250	100	560	500	1000	560
Fall	1200	12	100	560	18	1000	560
Fall	1600	32	3.2	180	100	180	250
Fall	2000	32	3.2	180	100	180	250

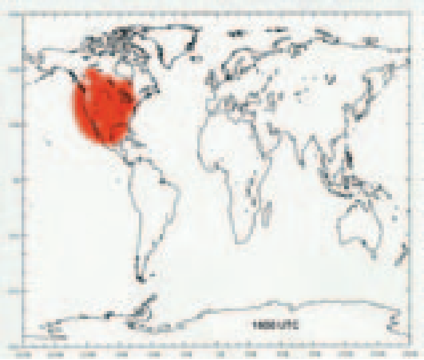


Figure 2.7. Daylight Coverage Area

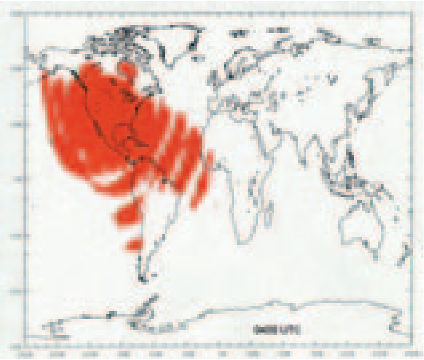


Figure 2.8. Nighttime Coverage Area

WWVB Receiving Equipment and Applications

WWVB receivers are used to control digital and analog wall clocks, desk clocks, travel alarms, clock radios, and wristwatches. New applications for WWVB receivers are found almost daily, and millions of units have been sold.

The simple WWVB receivers share several common characteristics. The receiver usually consists of a single integrated circuit that amplifies and demodulates the WWVB signal. A microprocessor (sometimes integrated into the receiver circuit) is often used to digitally process the time code and drive either an analog or digital display. On some models the microprocessor also outputs the time code to a serial interface so it can be read by a computer system.

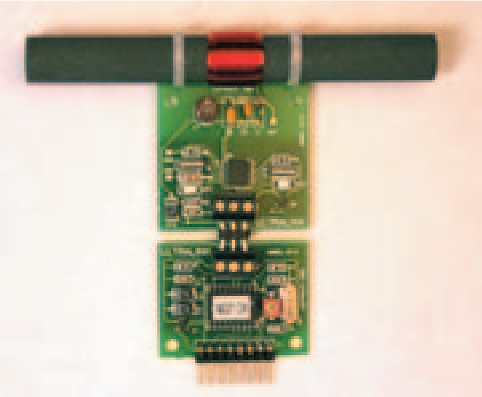


Figure 2.9. WWVB Receiver Circuit

One major advantage of WWVB is that the signal can be received using an indoor antenna. LF signals have long wavelengths and when they collide with an object, the angle of incidence is very small. This allows much of the signal to penetrate the object it strikes instead of being reflected. The 60 kHz WWVB signal has a wavelength of approximately 5000 m and can penetrate buildings and walls and easily reach indoor antennas. The antennas used are surprisingly simple. One type of antenna often used in WWVB designs is a ferrite loop, similar to those found inside an AM radio. This antenna consists of a ferrite (a grayish-black material) bar wrapped with a coil of fine wire. The length of wire and the way it is positioned and wrapped on the bar determine how well the antenna works. The goal is to make the antenna electrically resonant at either a quarter or half-wavelength of the 60 kHz carrier frequency. For the purpose of illustration, a receiver that was designed to be embedded inside another device is shown in Figure 2.9. The bar at the top of the photograph is a 4 in (10.16 cm) wide ferrite loop antenna, so you can see that the circuit board is just a few centimeters wide and contains just a few components. Obviously, the receivers and antennas used by some products, such as WWVB wristwatches, are much smaller than the one pictured here.

WWVB clocks like those you might find in a home or office are shown in Figure 2.10. These clocks not only keep accurate time, but they automatically adjust for Daylight Saving Time, leap seconds, and leap years. They work by synchronizing an inexpensive quartz oscillator to the WWVB time code. The period of synchronization varies from model to model, but many units synchronize only once every 24 hours; usually during the evening when the signal is strongest. In between synchronizations, time is kept using the quartz oscillator. Typically, the quartz oscillator can maintain frequency to within a few parts per million, so it will take at least two or three days to gain or lose a full second even if WWVB has not been received. Therefore, synchronizing once per day is usually enough to keep a clock's display on the right second. If you live within the coverage area and your WWVB clock is unable to synchronize, it usually means a source of radio interference is near the receiver. Some common culprits are computer monitors (some have a scan rate at or very close to 60 kHz), noisy AC wiring, fluorescent lamps, or nearby power lines, transformers, or radio transmitters.

Figure 2.10. WWVB Radio Controlled Clocks

More expensive WWVB receivers are used for applications that require better performance and reliability. These receivers continually track the signal, and require an outdoor antenna for best results. Figure 2.11 shows a receiver designed to distribute time to other systems, such as communications systems, computers, wall clocks, voice recorders, radio consoles, phone systems, and so on. This type of receiver includes a large digital clock

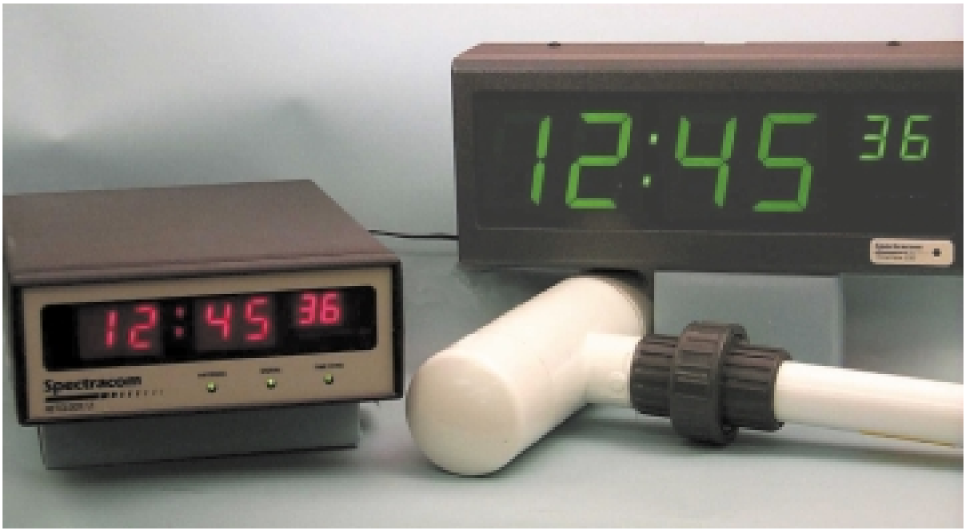


Figure 2.11. WWVB Time Distribution Receiver

display, and typically outputs a time code in several different formats. Time codes in text and binary format are output in computer readable format using standard serial interfaces such as RS-232 and RS-485. Standard time code formats like those defined by the Inter-Range Instrumentation Group (IRIG) or the National Emergency Number Association (NENA) might also be available. In addition, this type of receiver might include an on time 1 pulse per second signal that can be used as a measurement reference.

Another type of WWVB receiver is designed to work as a frequency standard that can distribute standard frequencies or be used as a reference to calibrate other oscillators. This type of device is known as a *carrier phase tracking receiver*. It disciplines a stable quartz oscillator so that it agrees with the WWVB signal and outputs standard frequencies such as 100 kHz, 1 MHz, 5 MHz, and 10 MHz. The receiver continuously compares its local oscillator to the WWVB signal and makes corrections as necessary. Some receivers designed as frequency standards ignore the time code entirely and do not output time-of-day or an on-time pulse.

WWVB Performance

NIST maintains the time and frequency standards at the WWVB site as closely as possible. The transmitted frequency of WWVB is maintained within a few parts in 10^{13} and time at the station site is kept within 100 ns of UTC(NIST).

The received performance of WWVB depends upon the quality of the received signal, the type of receiver and antenna used, and the distance between your receiving site and the transmitter. Let's look at a few examples of the type of performance you can obtain.

The majority of WWVB users use the station to get time-of-day, using low cost consumer clocks and watches such as those shown in Figure 2.10. The received time is delayed as it travels along the signal path from the transmitter to your receiver. The longer the path, the greater the delay. Like all radio signals, the WWVB signal travels at the speed of light and the longest possible delay in the continental United States is <15 ms. For most people and most applications, this small amount of delay really doesn't make any difference. For example, if the time displayed by a wall clock or wristwatch is 15 ms late, your eyes won't be able to tell.

If you need more accurate time, you might want to calibrate the path. For example, some WWVB receivers produce a 1 pulse per second (pps) signal. This signal is intended to be on time, or to coincide with the arrival of the UTC second. Receivers that produce 1 pps may have a switch or software setting that allows you to advance the on-time pulse to compensate for the path delay. You can estimate the path delay with software that computes the distance between your receiving site and WWVB (the station's coordinates are listed in Table 2.1), and then calculates the time required for a radio signal to travel that distance. Using this technique, it's possible to keep time within 0.1 ms of UTC.

If you use WWVB for frequency measurements or calibrations, there is no need to estimate or compensate for the path delay. For frequency, the important issue is *path stability*, or the changes in the path delay that occur over time. Part of the signal that leaves the WWVB transmitter travels along the ground (*groundwave*) and another part is reflected from the ionosphere (*skywave*). Groundwave reception provides better results than skywave reception. The reason is simple—the groundwave signal follows a direct route to your receiver, and therefore the path length doesn't change very much.

Since the groundwave doesn't travel as far as the skywave, it might not be possible to receive. The further you are from the transmitter, the more important it is to have a sensitive receiver and a good antenna in order to track the groundwave. If your receiving site is relatively close to the transmitter (<1000 km), the signal should be predominantly groundwave. For longer paths, a mixture of groundwave and skywave is received. And over a very long path, the groundwave might become so weak that it is only possible to receive the skywave. In this instance, the path becomes much less stable.

The characteristics of a LF path also vary at different times of day. For example, during the daylight and nighttime hours the path delay might vary by only a few hundred nanoseconds. However, if the skywave is being received, phase shifts will occur at sunrise and sunset. For instance, as the path changes from all darkness to all daylight, the ionosphere lowers and the path gets shorter. The path length then stabilizes until either the transmitter or receiver enters darkness. At this point, the ionosphere rises and the path gets longer. If the signal becomes weak and the receiver loses its tracking point on the carrier, it often has to find a new cycle of the carrier to track. Therefore, the received phase of WWVB often shifts by a multiple of 16.67 μs, or the period of the 60 kHz carrier, if the signal is weak or noisy.

WWVB receivers designed as frequency standards attempt to stay locked to the 60 kHz carrier as tightly as possible. Receivers that stay locked to the same groundwave

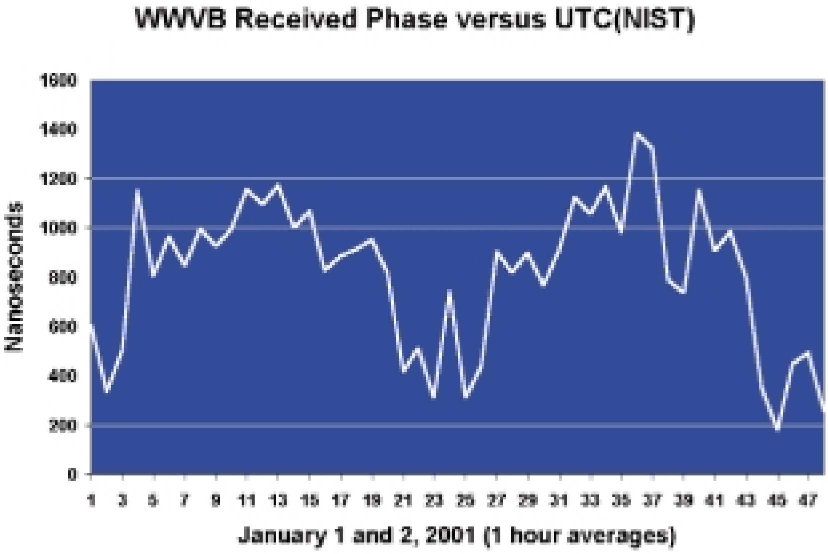


Figure 2.12. WWVB Phase as Received in Boulder, Colorado

cycle at all times can produce frequency traceable to UTC(NIST) with an uncertainty of $< 1 \times 10^{-12}$ when averaged over one or more days. The peak-to-peak variation in the phase is typically about 1 microsecond over 24 hours (Figure 2.12). If the receiver is changing cycles and/or losing lock due to a weak or noisy signal, large phase steps could be introduced and the frequency uncertainty might be 10 to 100 times larger.

The data points shown in Figure 2.12 are one-hour averages so the phase signature (Figure 2.4) has been averaged out. The phase plot shows a diurnal variation due to changes in the path length at sunrise and sunset. Each individual day looks like one "cycle" of the phase plot. This same pattern will repeat itself day after day if the receiver stays locked to the signal.

Chapter 3

Time Signals You Can Hear: NIST Radio Stations WWV and WWVH

The world's most famous time announcements undoubtedly are those broadcast by NIST radio stations WWV and WWVH. Millions of listeners are familiar with these broadcasts, where the announcer states the time in hours, minutes, and seconds "at the tone." These stations operate in the part of the radio spectrum that is properly known as HF (high frequency), but is commonly called shortwave. WWV is located just north of Fort Collins, Colorado, and WWVH is located on the island of Kauai, Hawaii. Both stations broadcast continuous time and frequency signals on 2.5, 5, 10, and 15 MHz, and WWV also broadcasts on 20 MHz. Both stations can also be heard by telephone. And as we shall see in this chapter, both stations provide much more information than just the time.

The coverage area of the two stations is essentially worldwide on 5, 10, and 15 MHz, although reception might be difficult in some areas, since standard time and frequency stations in other parts of the world use these same frequencies. Both stations send QSL cards confirming reports of long distance reception. WWV has received reports from as far away as the South Pole, and reports from Europe, Asia, and Australia are common. WWVH has received reports from as far away as South Africa, a distance of 19,300 km (12,000 miles) from Hawaii.

WWV and WWVH broadcast the same program on all frequencies, 24 hours a day. At least one of the frequencies should be usable at any given time of day. The most commonly used frequency is 10 MHz, since it is normally usable both during the day and at night. As a general rule, frequencies above 10 MHz work best in the daytime, and the lower frequencies work best at night. The 2.5 MHz broadcasts work best in the area near the stations. For example, the 2.5 MHz WWV broadcast should work well for residents of Colorado and its neighboring states, since propagation is similar to the commercial AM broadcast band.

History and Site Description of WWV

WWV has a long and storied history that dates back to the very beginning of radio broadcasting. The call letters WWV were assigned to NIST (then called the National Bureau of Standards) in October 1919. Although the call letters WWV are now synonymous with the broadcasting of time signals, it is unknown why those particular call letters were chosen or assigned. Testing of the station began from Washington, D.C. in May 1920, with the broadcast of Friday evening music concerts that lasted from 8:30 to 11 p.m. The 50 W transmissions used a wavelength of 500 m (about 600 kHz, or near the low end of today's commercial AM broadcast band), and could be heard out to about 40 km away from the station. A news release dated May 28, 1920 hinted at the significance of this event:

> *This means that music can be performed at any place, radiated into the air by means of an ordinary radio set, and received at any other place even though hundreds of miles away. The music received can be made as loud as desired by suitable operation of the receiving apparatus. Such concerts are sometimes sent out by the radio laboratory of the Bureau of Standards in connection with trials of experimental apparatus. This music can be heard by anyone in the states near the District of Columbia having a simple amateur receiving outfit. The pleasant evenings which have been experienced by persons at a number of such receiving stations suggest interesting possibilities of the future.*

Interesting possibilities, indeed! Keep in mind that KDKA of Pittsburgh, Pennsylvania, generally acknowledged as the first commercial broadcast station, did not go on the air until November 2, 1920.

On December 15, 1920 the station began assisting the Department of Agriculture in the distribution of market news to farm bureaus and agricultural organizations. A 2 kW spark transmitter and telegraphic code were used to broadcast 500 word reports, called the *Daily Market Marketgram*, on 750 kHz. The operating radius was about 300 km out of Washington. These broadcasts continued until April 15, 1921.

By December 1922, it was decided that the station's purpose would be the transmission of standard frequency signals. The first tests were conducted on January 29th and 30th of 1923, and included the broadcast of wavelengths from 200 to 545 kHz. By May of 1923, WWV was broadcasting frequencies from 75 to 2000 kHz on a weekly schedule. The accuracy of the transmitted frequency was quoted as being "better than three-tenths of one per cent." The output power of the station was 1 kW.

There were numerous changes in both the broadcast schedule, format, and frequency of WWV throughout the 1920's. In January 1931, the station was moved from Washington to the nearby city of College Park, Maryland. A 150 W transmitter operating at 5 MHz was initially used, but the power was increased back to 1 kW the following year. A new device, the *quartz oscillator*, made it possible to dramatically improve the stability of the output frequency of WWV. Quartz oscillators were first used at WWV in 1927, and by 1932 allowed the transmitted frequency to be controlled to less than 2 parts in 10^7.

The station moved again in December 1932, this time to a Department of Agriculture site near Beltsville, Maryland. By April of 1933, the station was broadcasting 30 kW on 5 MHz, and 10 and 15 MHz broadcasts (20 kW output power) were added in 1935. The 5 MHz frequency was chosen for several reasons, including "its wide coverage, its relative freedom from previously assigned stations, and its convenient integral relation with most frequency standards." The 10 and 15 MHz frequencies were chosen as *harmonics*, or multiples of 5 MHz. WWV continues to use all of these frequencies today, as well as another harmonic (20 MHz), and a sub-harmonic (2.5 MHz).

The Beltsville area was the home of WWV until December 1966 (although the location name for the broadcast was changed to Greenbelt, Maryland in 1961). During the years in Beltsville, many interesting developments took place. A fire destroyed the station in November 1940, but the standard frequency equipment was salvaged and the station returned to the air just five days later using an adjacent building. An act of Congress in July 1941 provided $230,000 for the construction of a new station, which was built 5 km south of the former site and went on the air in January 1943. The 2.5 MHz broadcasts began in February 1944 and have continued to the present day. Transmission on 20, 25, 30, and 35 MHz began in December 1946. The 30 and 35 MHz broadcasts were discontinued in January 1953 and the 25 MHz broadcast was stopped in 1977. With the exception of an almost two-year interruption in 1977 and 1978, the 20 MHz broadcasts have continued to the present day.

Much of the current broadcast format also took shape during the Beltsville years. The 440 Hz tone (A above middle C) was added to the broadcast in August 1936, at the request of several music organizations. Since 1939, 440 Hz (known to musicians as A4 or A440) has been the international standard for musical pitch. The second pulses were added in June 1937, and the geophysical alert messages began in July 1957. And as quartz oscillator technology improved, so did the frequency control of the broadcast. The transmitted frequency was routinely kept within 2 parts in 10^{10} of the national standard by 1958.

WWV's most well known feature, the announcement of time, also began during the Beltsville years. A standard time announcement in telegraphic code was added in October 1945, and voice announcements of time began on January 1, 1950. The original voice announcements were at five-minute intervals. It is interesting to note that WWV continued to broadcast local time at the transmitter site until 1967.

From 1955 to 1958, WWV played a key role in the definition of the atomic second. During this period the United States Naval Observatory (USNO) in Washington, D.C., and the National Physical Laboratory (NPL) in Teddington, United Kingdom made simultaneous common-view measurements of the signals broadcast from WWV. The USNO compared the signal to an astronomical time scale (UT2) and NPL compared the signal to the new cesium standard they had just developed. The data they collected helped the USNO and NPL equate the length of the astronomical second to the atomic second, and led to the atomic second being defined as the duration of 9,192,631,770 cycles of the cesium atom.

In 1966, WWV was moved to its current location, near Fort Collins, Colorado. The LF station WWVB had gone on the air in July 1963 near Fort Collins, and it was decided that WWV would share the same 390 acre (158 hectare) site. The new site was about 80 km from the Boulder laboratories where the national standards of time and frequency were kept. The proximity to Boulder and the use of atomic oscillators at the transmitter site would make it possible to control the transmitted frequency to within 2 parts in 10^{11}, a factor of 10 improvement. Today, the station's frequency is controlled within a few parts in 10^{13}.

At 0000 UTC on December 1, 1966 the Greenbelt, Maryland, broadcast was turned off and the new transmitter at Fort Collins was turned on. In April 1967, the station began broadcasting Greenwich Mean Time (GMT) instead of local time, and began its current format of using Coordinated Universal Time (UTC) in December 1968. The time announcements were made every minute, instead of every 5 minutes, beginning in July 1971.

On August 13, 1991 both WWV and WWVH began broadcasting voice recordings that were digitized and stored in solid state memory devices. Previous voice recordings were played back from mechanical drum recorders, which were more prone to failure. The male voice on WWV was designed to sound like Don Elliot, the station's original announcer. WWVH still uses the voice of its original announcer, Jane Barbe, although the digital storage device has made her voice sound slightly different.

Other new features and programming changes have been added to the WWV broadcast over the past decade, and the current station schedule is described in the remainder of this chapter. A photo of the station is shown in Figure 3.1.

Figure 3.1. Radio Station WWV

History and Site Description of WWVH

WWVH began operation on November 22, 1948 at Kihei on the island of Maui, in the then territory of Hawaii (Hawaii was not granted statehood until 1959). The original station broadcast a low power signal on 5, 10, and 15 MHz. As it does today, the program schedule of WWVH closely follows the format of WWV. However, voice announcements of time were not added to the WWVH broadcast until July 1964.

Figure 3.2. Radio Station WWVH

The original WWVH station site was constantly threatened by an eroding shoreline, and much of the station's equipment and property had been damaged. It was estimated that 75 feet of shoreline were lost in the period from 1949 to 1967. By 1965, the ocean was within a few meters of both the main building and the 15 MHz antenna, and it was obviously necessary to move WWVH to a new location.

Figure 3.3. Aerial View of WWVH Station Site

In July 1971, the station moved to its current location, a 30 acre (12 hectare) site near Kekaha on the Island of Kauai, Hawaii. Photographs of the entrance to WWVH and an aerial view are shown in Figures 3.2 and 3.3.

Station Specifications

WWV and WWVH radiate 10 kW on 5, 10, and 15 MHz. The radiated power is lower on the other frequencies: WWV radiates 2.5 kW on 2.5 and 20 MHz while WWVH radiates 5 kW on 2.5 MHz and does not broadcast on 20 MHz. This information is summarized in Table 3.1.

TABLE 3.1 – SPECIFICATIONS FOR WWV AND WWVH

Characteristics	WWV	WWVH
Date Service Began	March 1923	November 1948
Standard Carrier Frequencies	2.5, 5, 10, 15, & 20 MHz	2.5, 5, 10, & 15 MHz
Power	2.5 kW on 2.5 and 20 MHz, 10 kW on 5, 10, and 15 MHz	5 kW on 2.5 MHz, 10 kW on 5, 10, and 15 MHz

Antennas

The WWV antennas are half-wave vertical antennas that radiate omnidirectional patterns. Since there are five broadcast frequencies, five antennas are in use at all times. Each antenna is connected to a single transmitter using a rigid coaxial line, and the site is designed so that no two coaxial lines cross. Each antenna is mounted on a tower that is approximately one half-wavelength tall. The tallest tower, for 2.5 MHz, is about 60 m tall. The shortest tower, for 20 MHz, is about 7.5 m tall. The 10 m tall tower for the 15 MHz broadcast (with the 122 m tall WWVB towers in the background) is pictured in Figure 3.4.

Figure 3.4. 15 MHz WWV Antenna (WWVB Towers in Background)

The top half of each antenna is a quarter-wavelength radiating element. The bottom half of each antenna consists of nine quarter-wavelength wires that connect to the center of the tower and slope downwards to the ground at a 45° angle. This sloping skirt functions as the lower half of the radiating system and also guys the antenna (Figure 3.5). The WWV antenna coordinates are listed in Table 3.2.

TABLE 3.2 – WWV ANTENNA COORDINATES

Frequency (MHz)	Latitude	Longitude
2.5	40° 40’ 55.2” N	105° 02’ 31.3” W
5	40° 40’ 42.1” N	105° 02’ 24.9” W
10	40° 40’ 47.8” N	105° 02’ 25.1” W
15	40° 40’ 45.0” N	105° 02’ 24.5” W
20	40° 40’ 53.1” N	105° 02’ 28.5” W

WWV also has standby antennas that are used only if a primary transmitter or antenna fails. On 2.5, 15, and 20 MHz, these antennas are connected to the standby transmitters. The standby antenna for 15 MHz is an omnidirectional half-wave dipole. Broadband antennas serve as the standby units for 2.5 and 20 MHz. On 5 and 10 MHz, the primary and standby transmitters share the same antenna, and an automated RF switch is used to switch between transmitters if necessary.

The 2.5 MHz antenna at WWVH is nearly identical to its WWV counterpart. However, the 5, 10, and 15 MHz antennas are phased array vertical dipoles. They consist of two half-wave vertical dipoles that are separated by a quarter-wavelength and driven 90° out of phase. These antennas radiate a cardioid pattern with the maximum gain pointed toward the west. Each frequency also has a vertical monopole standby antenna connected to the standby transmitters, in the event that the primary system fails. The WWVH Antenna Coordinates are listed in Table 3.3.

TABLE 3.3 – WWVH ANTENNA COORDINATES

Frequency (MHz)	Latitude	Longitude
2.5	21° 59’ 20.9” N	159° 45’ 52.4” W
5	21° 59’ 10.8” N	159° 45’ 44.8” W
10	21° 59’ 18.2” N	159° 45’ 51.3” W
15	21° 59’ 15.3” N	159° 45’ 50.0” W

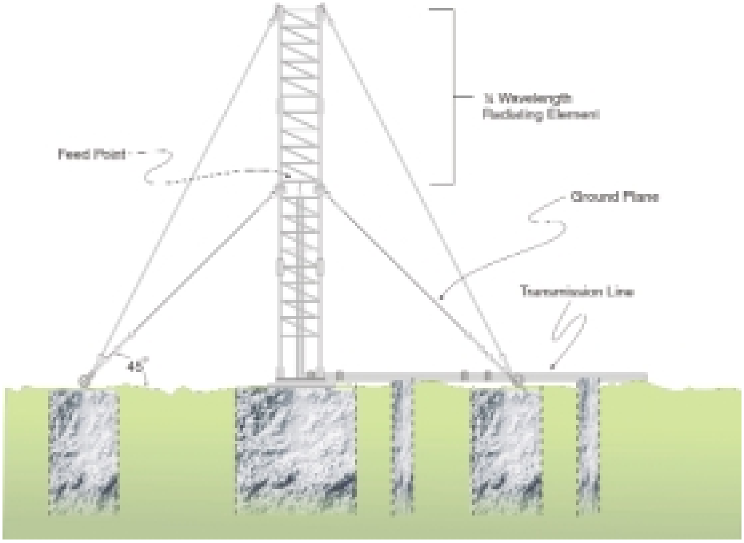


Figure 3.5. Diagram of WWV Antenna

Transmitters

The WWV transmitters consist of two types: plate modulated class C transmitters operating at 10 kW each on 5, 10 and 15 MHz, and class A transmitters operating at 2.5 kW each on 2.5 and 20 MHz. All frequencies have a standby transmitter/antenna system that will automatically begin operating within three minutes of a primary system failure.

WWVH uses class-C plate modulated transmitters on 5, 10, and 15 MHz that operate at 10 kW with 50% efficiency. The 2.5 MHz transmitter is of the class-A type and operates at 5 kW with 20% efficiency. All four frequencies have a backup transmitter/antenna system that will automatically begin transmission within three minutes after the primary system fails. All four of the backup transmitters are 5 kW class-A transmitters, identical to the primary transmitter on 2.5 MHz.

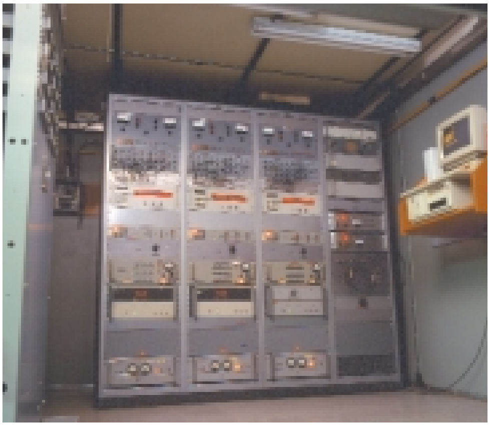


Figure 3.6. WWV Control Room

The signals broadcast by both stations use double sideband amplitude modulation. The modulation level is 50% for the steady tones, 50% for the BCD time code, 100% for the second pulses and the minute and hour markers, and 75% for the voice announcements.

The carrier frequencies and the information modulated on to the carrier are derived from cesium oscillators that are steered to agree with UTC(NIST). Figure 3.6 shows a portion of the equipment in the WWV control room, including the time code generators and cesium oscillators.

Information Transmitted

WWV and WWVH are best known for their audio time announcements, but the stations provide other information as summarized in Table 3.4.

TABLE 3.4 – INFORMATION PROVIDED BY WWV AND WWVH

SERVICE TYPE	INFORMATION PROVIDED
Standard Audio Frequencies	440, 500, & 600 Hz
Time Intervals	Seconds, 10 seconds, minutes, hours.
Time Signals: Voice	Voice announcement is made once per minute
Time Signals: Code	BCD code on 100 Hz subcarrier, 1 pulse/s
Official Announcements	Geoalerts, Marine Storm Warnings, Global Positioning System Status Reports

Figures 3.7 and 3.8 show the hourly program schedules of WWV and WWVH along with station location, radiated power, and details of the modulation.

Time Announcements

Voice announcements are made from WWV and WWVH once every minute. Since both stations can be heard in some areas, a man's voice is used on WWV, and a woman's voice is used on WWVH to avoid confusion. The WWVH announcement occurs first, at about 15 s before the minute. The WWV announcement follows at about 7.5 s before the minute. Though the announcements occur at different times, the tone markers are transmitted at the exact same time from both stations. However, they may not be received at exactly the same instant due to differences in the propagation delays from the two station sites.

Standard Time Intervals

The most frequent sounds heard on WWV and WWVH are the seconds pulses. These pulses are heard every second except on the 29th and 59th seconds of each minute. The first pulse of each hour is an 800 ms pulse of 1500 Hz. The first pulse of each minute is an 800 ms pulse of 1000 Hz at WWV and 1200 Hz at WWVH. The remaining second pulses are short audio bursts (5 ms pulses of 1000 Hz at WWV and 1200 Hz at WWVH) that sound like the ticking of a clock.

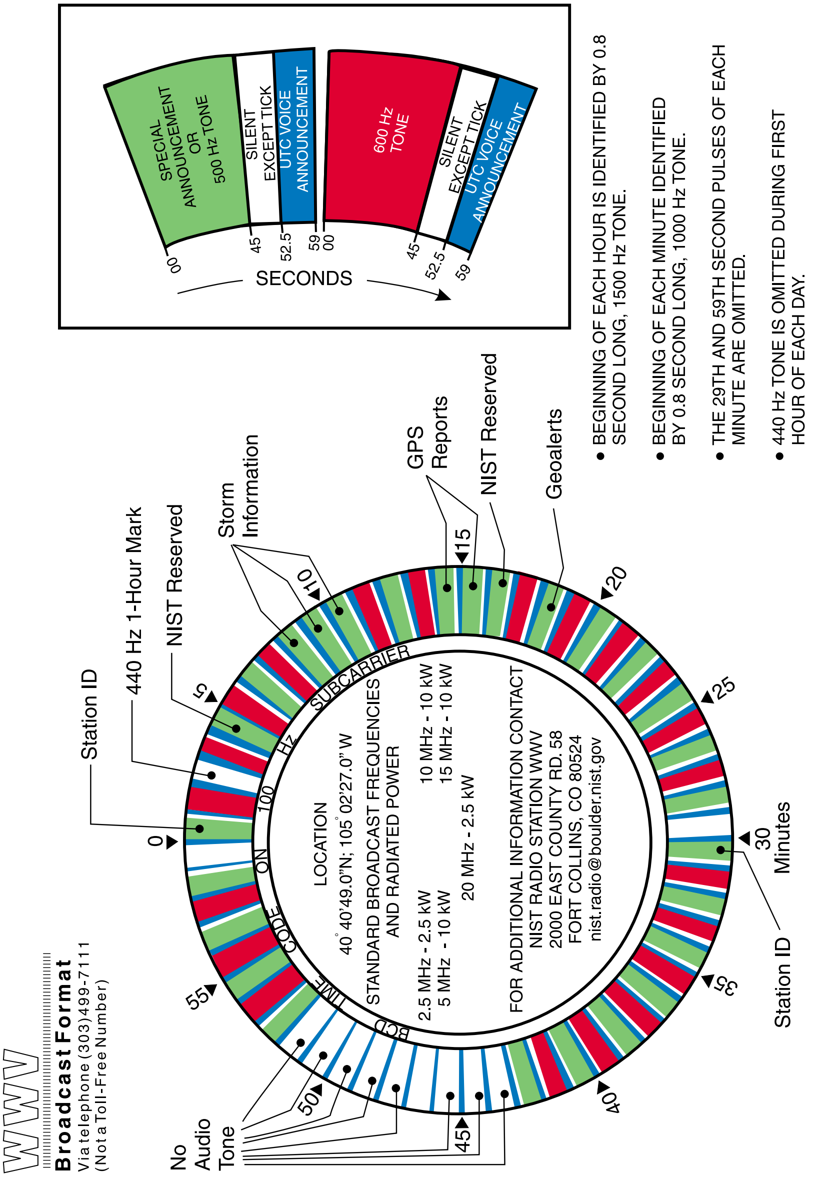
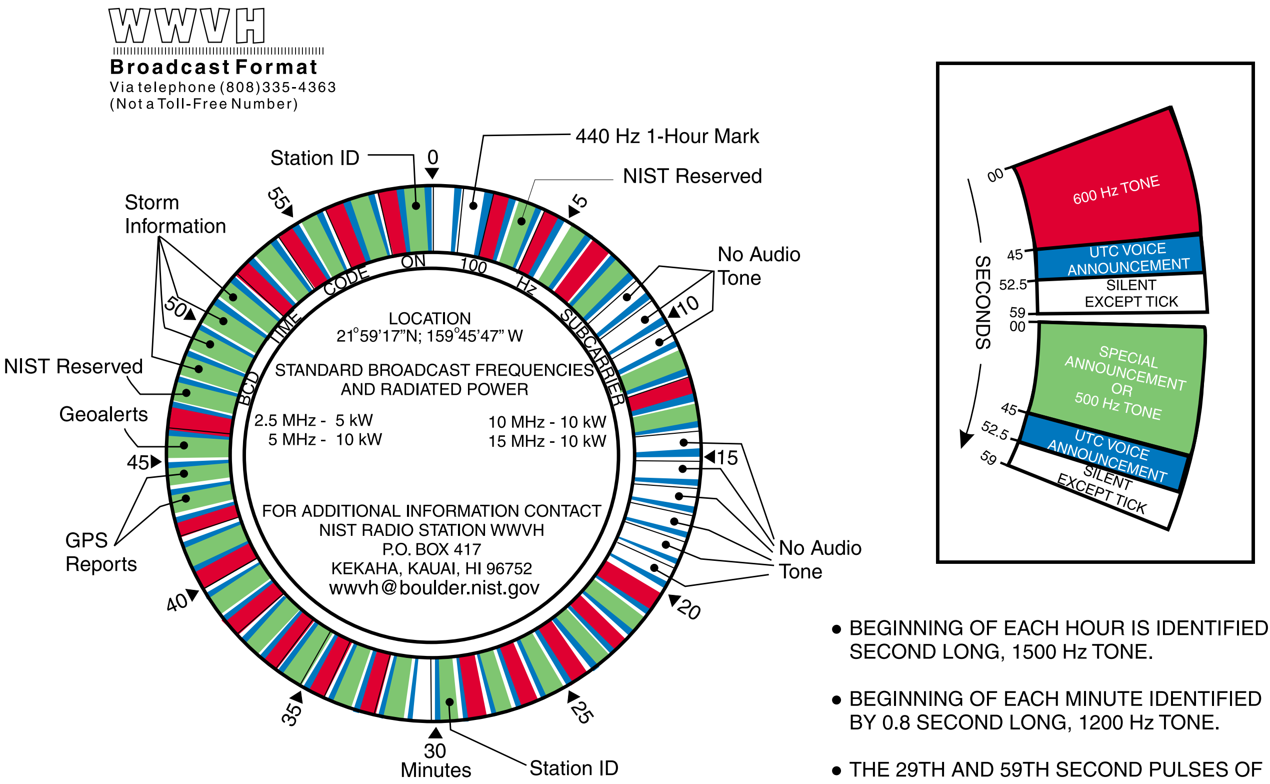


Figure 3.7. WWV Broadcast Format



- BEGINNING OF EACH HOUR IS IDENTIFIED BY 0.8 SECOND LONG, 1500 Hz TONE.
- BEGINNING OF EACH MINUTE IDENTIFIED BY 0.8 SECOND LONG, 1200 Hz TONE.
- THE 29TH AND 59TH SECOND PULSES OF EACH MINUTE ARE OMITTED.
- 440 Hz TONE IS OMITTED DURING FIRST HOUR OF EACH DAY.

Figure 3.8. WWVH Broadcast Format

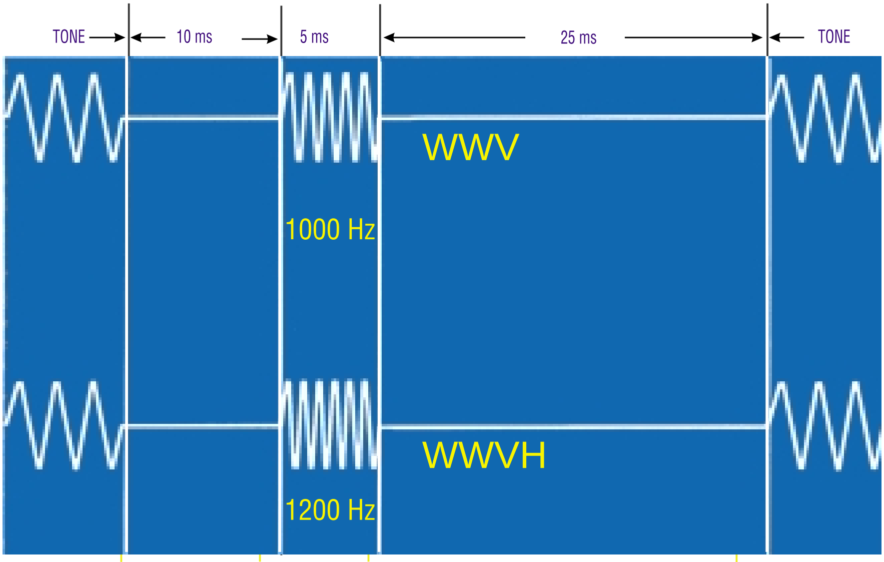


Figure 3.9. WWV and WWVH Second Pulses

Each seconds pulse is preceded by 10 ms of silence and followed by 25 ms of silence. The silence makes it easier to pick out the pulse. The total 40 ms protected zone around each seconds pulse is shown in Figure 3.9.

Standard Audio Frequencies and Silent Periods

In alternate minutes during most of each hour, 500 Hz or 600 Hz audio tones are broadcast. A 440 Hz tone (the musical note A above middle C) is broadcast once each hour. In addition to being a musical standard, the 440 Hz tone provides an hourly marker for chart recorders and other automated devices. The 440 Hz tone is omitted, however, during the first hour of each UTC day. See Figures 3.7 and 3.8 for further details.

The silent periods are without tone modulation. However, the carrier frequency, seconds pulses, time announcements, and the 100 Hz BCD time code continue during the silent periods. In general, one station will not broadcast an audio tone while the other station is broadcasting a voice message.

On WWV, the silent period extends from 43 to 52 minutes after the hour. WWVH has two silent periods; from 8 to 11 minutes after the hour and from 14 to 20 minutes after the hour. Minutes 29 and 59 on WWV and minutes 00 and 30 on WWVH are also silent.

UT1 Correction

UT1 corrections are encoded into the broadcasts by using doubled ticks during the first 16 s of each minute. You can determine the amount of the correction (in units of 0.1 s) by counting the number of doubled ticks. The sign of the correction depends on whether the doubled ticks occur in the first 8 s of the minute or in the second 8 s. If the doubled ticks are in the first 8 s (1 to 8) the sign is positive. If the doubled ticks are in the second

8 s (9 to 16) the sign is negative. For example, if ticks 1, 2, and 3 are doubled, the correction is +0.3 s. This means that UT1 equals UTC plus 0.3 s. If UTC is 8:45:17, then UT1 is 8:45:17.3. If ticks 9, 10, 11, and 12 are doubled, the correction is –0.4 s. If UTC is 8:45:17, then UT1 is 8:45:16.6. If none of the ticks are doubled, then the current correction is 0.

Official Announcements

Announcement segments are available by subscription to other United States government agencies. These segments are used for public service messages up to 45 s long. The accuracy and content of these messages is the responsibility of the originating agency. For information about the availability of these segments, contact the NIST Time and Frequency Division. The announcements that are currently part of the program schedule are described below.

Geophysical Alerts

The National Oceanic and Atmospheric Administration (NOAA) uses WWV and WWVH to broadcast geophysical alert messages that provide information about solar terrestrial conditions. Geophysical alerts are broadcast from WWV at 18 minutes after the hour and from WWVH at 45 minutes after the hour. The messages are less than 45 s in length and are updated every three hours (typically at 0000, 0300, 0600, 0900, 1200, 1500, 1800, and 2100 UTC). More frequent updates are made when necessary.

The geophysical alerts provide information about the current conditions for long distance HF radio propagation. The alerts use a standardized format and terminology that requires some explanation. After defining the terminology, we'll look at a sample message.

Solar flux is a measurement of the intensity of solar radio emissions with a wavelength of 10.7 cm (a frequency of about 2800 MHz). The daily solar flux measurement is recorded at 2000 UTC by the Dominion Radio Astrophysical Observatory of the Canadian National Research Council located at Penticton, British Columbia, Canada. The value broadcast is in solar flux units that range from a theoretical minimum of about 50 to numbers larger than 300. During the early part of the 11-year *sunspot cycle*, the flux numbers are low; but they rise and fall as the cycle proceeds. The numbers will remain high for extended periods around sunspot maximum.

Basically, solar flux is measured by counting sunspots, or storms on the surface of the sun. The greater the number of sunspots, the stronger is the ionosphere, the electrified region in the Earth's upper atmosphere. A strong ionosphere means that HF radio signals can be reflected over great distances. Therefore, high solar flux numbers usually, but not always, mean that HF propagation conditions are good. A solar flux figure might be 65 or lower in years of minimum solar activity. In most years, the average solar flux figure falls between 100 and 200.

The A and K indices are a measurement of the behavior of the *magnetic field* in and around the Earth. The *K index* uses a scale from 0 to 9 to measure the change in the horizontal component of the geomagnetic field. A new K index is determined and added to the broadcast every three hours based on magnetometer measurements made at the Table

Mountain Observatory, north of Boulder, Colorado, or an alternate middle latitude observatory. The *A index* is a daily value on a scale from 0 to 400 to express the range of disturbance of the geomagnetic field. It is obtained by converting and averaging the eight, 3 hour K index values. An estimated A index is first announced at 2100 UTC, based on seven measurements and one estimated value. At 0000 UTC, the announced A index consists entirely of known measurements, and the word "estimated" is dropped from the announcement. Table 3.5 shows the relationship between the A and K indices.

TABLE 3.5 – THE RELATIONSHIP BETWEEN THE A INDEX AND K INDEX

A Index	0	3	7	15	27	48	80	140	240	400
K Index	0	1	2	3	4	5	6	7	8	9

The A and K indices are probably the most widely discussed values in radio monitoring circles. If the A index is less than 10 or the K index is around 3, it indicates nearly ideal conditions for HF radio propagation. The lower the figure, the less the signals are absorbed by the Earth's geomagnetic field. Less absorption means that HF signals will travel farther and better.

Solar flux values and the A and K indices can also be used to compute the maximum usable frequency (MUF) and the lowest usable frequency (LUF) for a given time and location. This information is helpful to radio listeners who want to know the best time to tune in hard-to-hear signals.

Space Weather describes the conditions in space that affect earth and its technological systems. Space weather is a consequence of the behavior of the Sun, the nature of Earth's magnetic field and atmosphere, and our location in the solar system.

Space weather storms observed or expected to occur are characterized using the NOAA Space Weather scales. The tables below describe the terminology used in the announcements. The descriptor refers to the maximum level reached or predicted. These space weather scales are described in more detail on the NOAA Space Environment Center's web site (http://www.sec.noaa.gov).

TABLE 3.6 – NOAA SPACE WEATHER SCALES

GEOMAGNETIC STORMS	SOLAR RADIATION STORMS	RADIO BLACKOUTS	DESCRIPTOR
G5	S5	R5	Extreme
G4	S4	R4	Severe
G3	S3	R3	Strong
G2	S2	R2	Moderate
G1	S1	R1	Minor

Geomagnetic storm levels are determined by the estimated three hourly Planetary K-indices derived in real time from a network of western hemisphere ground-based magnetometers.

TABLE 3.7 – GEOMAGNETIC STORM LEVELS

PLANETARY K INDICES	GEOMAGNETIC STORM LEVEL
K = 5	G1
K = 6	G2
K = 7	G3
K = 8	G4
K = 9	G5

Solar Radiation storms levels are determined by the proton flux measurements made by NOAA's primary Geostationary Operational Environmental Satellite (GOES).

TABLE 3.8 – SOLAR RADIATION STORM LEVELS

FLUX LEVEL OF >10 MeV PARTICLES	SOLAR RADIATION STORM LEVEL
10	S1
10^2	S2
10^3	S3
10^4	S4
10^5	S5

Radio Blackout levels are determined by the x-ray level measured by the primary GOES satellite.

TABLE 3.9 – RADIO BLACKOUTS

PEAK X-RAY LEVEL AND FLUX	RADIO BLACKOUT LEVEL
M1 and (10^{-5})	R1
M5 and (5×10^{-5})	R2
X1 and (10^{-4})	R3
X10 and (10^{-3})	R4
X20 and (2×10^{-3})	R5

Every geophysical alert consists of three parts as shown in Tables 3.10 and 3.11. Table 3.10 describes the information contained in the geophysical alert. Table 3.11 provides example text from an actual message.

TABLE 3.10 – INFORMATION IN GEOPHYSICAL ALERT VOICE MESSAGE

SECTION	INFORMATION IN VOICE MESSAGE
1	The solar-terrestrial indices for the day: specifically the solar flux, the A index, and the K index.
2	Space weather storms observed during the previous 24 hours. Includes all observed geomagnetic storms, solar radiation storms (proton events) and Radio blackouts (class M1 and greater flares).
3	Space weather expected during the following 24 hours.

TABLE 3.11 – EXAMPLE TEXT FROM ACTUAL GEOPHYSICAL ALERT MESSAGE

SECTION	EXAMPLE OF ACTUAL GEOPHYSICAL ALERT MESSAGE
1	Solar-terrestrial indices for 08 November follow. Solar flux 173 and mid-latitude A-index 14 The Mid-latitude K-index at 1500 UTC on 08 November was 3.
2	Space weather for the past 24 hours has been severe. Solar radiation storm(s) reaching the S4 level is in progress. Radio blackouts(s) reaching the R2 level occurred.
Alternate section 2	No space weather storms have been observed during the past 24 hours.
3	Space weather for the next 24 hours is expected to be severe. Solar radiation storms reaching the S4 level are expected to continue. Radio blackouts reaching the R2 level are expected.
Alternate section 3	No space weather storms are expected during the next 24 hours.

The announcements describe the largest space weather event observed (section 2) or expected (section 3) in the first line of each section. The remaining lines give the type of events and the level observed for each one. In the example above, no geomagnetic storm information is included because none was observed or expected during the period. In the case where none of the three types of events are observed or expected, the announcement would contain section 1, plus alternate section 2 and alternate section 3.

To hear the current geophysical alert message by telephone, dial (303) 497-3235. For more information about these messages, contact: Space Weather Operations, NOAA R/SEC, 325 Broadway, Boulder, CO 80305-3328. Email: swo@sec.noaa.gov Voice: (303) 497-3171.

Marine Storm Warnings

Both WWV and WWVH broadcast marine storm warnings for the ocean areas where the United States has warning responsibility under international agreement. These brief voice messages warn mariners of storm threats present in their areas, and contain information provided by the National Weather Service. Atlantic high seas warnings are broadcast by WWV at 8 and 9 minutes after the hour and an eastern North Pacific high seas warning is broadcast at 10 minutes after the hour. WWVH broadcasts eastern and central North Pacific high seas warnings at 48, 49, 50 and 51 minutes after the hour. Additional segments (at 11 minutes after the hour on WWV and at 52 minutes after the hour on WWVH) are used when conditions are particularly bad.

The storm warnings are based on the most recent forecasts. The forecasts are updated at 0500, 1100, 1700, and 2300 UTC for WWV; and at 0000, 0600, 1200, and 1800 UTC for WWVH. All marine forecasts rely heavily on the Voluntary Observing Ship (VOS) program for obtaining meteorological observations.

A typical storm warning announcement might read like this:

> *North Atlantic weather West of 35 West at 1700 UTC; Hurricane Donna, intensifying, 24 North, 60 West, moving northwest, 20 knots, winds 75 knots; storm, 65 North, 35 West, moving east, 10 knots; winds 50 knots, seas 15 feet.*

For more information about marine storm warnings, write to: National Weather Service, NOAA, 1325 East West Highway, Silver Spring, MD 20910. Or, visit the National Weather Service web page at http://www.nws.noaa.gov.

Global Positioning System (GPS) Status Announcements

The United States Coast Guard sponsors two voice announcements per hour on WWV and WWVH, giving current status information about the GPS satellites and related operations. The 45 s long announcements begin at 14 and 15 minutes after each hour on WWV and at 43 and 44 minutes after each hour on WWVH. For further information, contact the U.S. Coast Guard Navigation Center, 7323 Telegraph Road, Alexandria, VA 22310, or call (703) 313-5900.

WWV/WWVH Time Code

WWV and WWVH each broadcast a binary coded decimal (BCD) time code on a 100 Hz subcarrier. The time code provides UTC information in serial fashion at a speed of 1 bit per second. The information carried by the time code includes the current minute, hour, and day of year. The time code also contains the 100 Hz frequency from the subcarrier. The 100 Hz frequency may be used as a standard with the same accuracy as the audio frequencies.

The time code is sent in binary coded decimal (BCD) format, where four binary digits (bits) are used to represent one decimal number. The binary-to-decimal weighting scheme is 1-2-4-8. The *least significant bit* is sent first. This is the reverse of the WWVB time code described in Chapter 2. The BCD groups and the equivalent decimal numbers are shown in Table 3.12.

TABLE 3.12 - BCD WEIGHTING SCHEME USED BY WWV AND WWVH TIME CODE

DECIMAL NUMBER	BIT 1 2^0	BIT 2 2^1	BIT 3 2^2	BIT 4 2^3
0	0	0	0	0
1	1	0	0	0
2	0	1	0	0
3	1	1	0	0
4	0	0	1	0
5	1	0	1	0
6	0	1	1	0
7	1	1	1	0
8	0	0	0	1
9	1	0	0	1

Bits are transmitted on the 100 Hz subcarrier using amplitude modulation. A 200 ms pulse (20 cycles of 100 Hz) is used to represent a 0 bit, and a 500 ms pulse (50 cycles of 100 Hz) is used to represent a 1 bit. However, tone suppression deletes the first 30 ms of each pulse. Therefore, 170 ms pulses are recognized as 0 bits, and 470 ms pulses are recognized as 1 bits. The leading edge of each pulse can serve as an on time marker, but due to the tone suppression it actually occurs 30 ms after the start of the second.

WWV and WWVH require 1 minute to send their time code (Figure 3.9). The time code frame contains the minute, hour, day of year, the last two digits of the current year, the UT1 correction, a leap second indicator, and information about daylight and standard time. Two BCD groups are used to express the hour (00 to 23), minute (00 to 59), and year (00 to 99); and three groups are used to express the day of year (001 to 366). The information in the time code refers to the time at the start of the one-minute frame. Seconds are determined by counting pulses within the frame. The individual time code bits are annotated in Table 3.13.

TABLE 3.13 – WWV AND WWVH TIME CODE BITS

BIT NUMBER	BIT DESCRIPTION	BIT NUMBER	BIT DESCRIPTION
0	Frame Reference Bit, Pr (hole)	30	Day of Year, 1
1	Reserved	31	Day of Year, 2
2	DST Indicator	32	Day of Year, 4
3	Leap Second Warning	33	Day of Year, 8
4	Year, 1	34	Reserved
5	Year, 2	35	Day of Year, 10
6	Year, 4	36	Day of Year, 20
7	Year, 8	37	Day of Year, 40
8	Reserved	38	Day of Year, 80
9	Position Marker 1, P1	39	Position Marker 4, P4
10	Minute, 1	40	Day of Year, 100
11	Minute, 2	41	Day of Year, 200
12	Minute, 4	42	Reserved
13	Minute, 8	43	Reserved
14	Reserved	44	Reserved
15	Minute, 10	45	Reserved
16	Minute, 20	46	Reserved
17	Minute, 40	47	Reserved
18	Reserved	48	Reserved
19	Position Marker 2, P2	49	Position Marker 5, P5
20	Hour, 1	50	UT1 Sign
21	Hour, 2	51	Year, 10
22	Hour, 4	52	Year, 20
23	Hour, 8	53	Year, 40
24	Reserved	54	Year, 80
25	Hour, 10	55	DST Indicator
26	Hour, 20	56	UT1 Correction, 0.1 s
27	Reserved	57	UT1 Correction, 0.2 s
28	Reserved	58	UT1 Correction, 0.4 s
29	Position Marker 3, P3	59	Frame Reference Bit, P0

Each time code frame begins with a unique spacing of pulses that mark the start of a new minute. During the first second of the minute, no pulse is transmitted. Since the pulses are already delayed 30 ms by the tone suppression, the UTC minute actually begins 1030 ms (1.03 s) earlier than the first pulse in the frame. For synchronization purposes, position markers lasting for 770 ms are transmitted every 10 s.

A *leap second* indicator is transmitted at second 3. If this bit is high, it indicates that a leap second will be added to UTC at the end of the current month. The bit is set to 1 near the start of the month in which a leap second is added. It is set to 0 immediately after the leap second insertion.

UT1 corrections are broadcast during the final 10 s of each frame. The bit transmitted at second 50 shows if UT1 is positive or negative with respect to UTC. If a 1 is sent, the UT1 correction is positive. If a 0 is sent, the UT1 correction is negative. Bits 56, 57, and 58 form a three-bit BCD group that shows the magnitude of the correction. Since the unit for the UT1 correction is 0.1 s, multiply the BCD group by 0.1 to obtain the correct value. Since only three bits are used, the WWV and WWVH time codes can only transmit UT1 corrections ranging from –0.7 to +0.7 s.

Daylight saving time (DST) and standard time (ST) information is transmitted at seconds 2 and 55. When ST is in effect, bits 2 and 55 are set to 0. When DST is in effect, bits 2 and 55 are set to 1. On the day of a change from ST to DST bit 55 changes from 0 to 1 at 0000 UTC, and bit 2 changes from 0 to 1 exactly 24 hours later. On the day of a change from DST back to ST bit 55 changes from 1 to 0 at 0000 UTC, and bit 2 changes from 1 to 0 exactly 24 hours later.

The year information is transmitted in two different parts of the time code. The last digit of the year is sent using bits 4 through 7. The next to last digit of the year, or the decade indicator, is sent using bits 51 through 54. For example, for the year 2001, bits 4 through 7 will return a decimal value of 1, and bits 51 through 54 will return a decimal value of 0.

Figure 3.10 shows one frame of the time code. The six position identifiers are labeled P0, P1, P2, P3, P4, and P5. The minutes, hours, days, year, and UT1 sets are marked by brackets, with the weighting factors printed below the bits. Wide pulses represent "1" bits and narrow pulses represent "0" bits. Unused bits are set to 0. The decoded UTC at the start of the frame is 2001, 173 days, 21 hours, and 10 minutes. Since the UT1 correction is +0.3 s, the decoded UT1 is 2001, 173 days, 21 hours, 10 minutes, and 0.3 s.

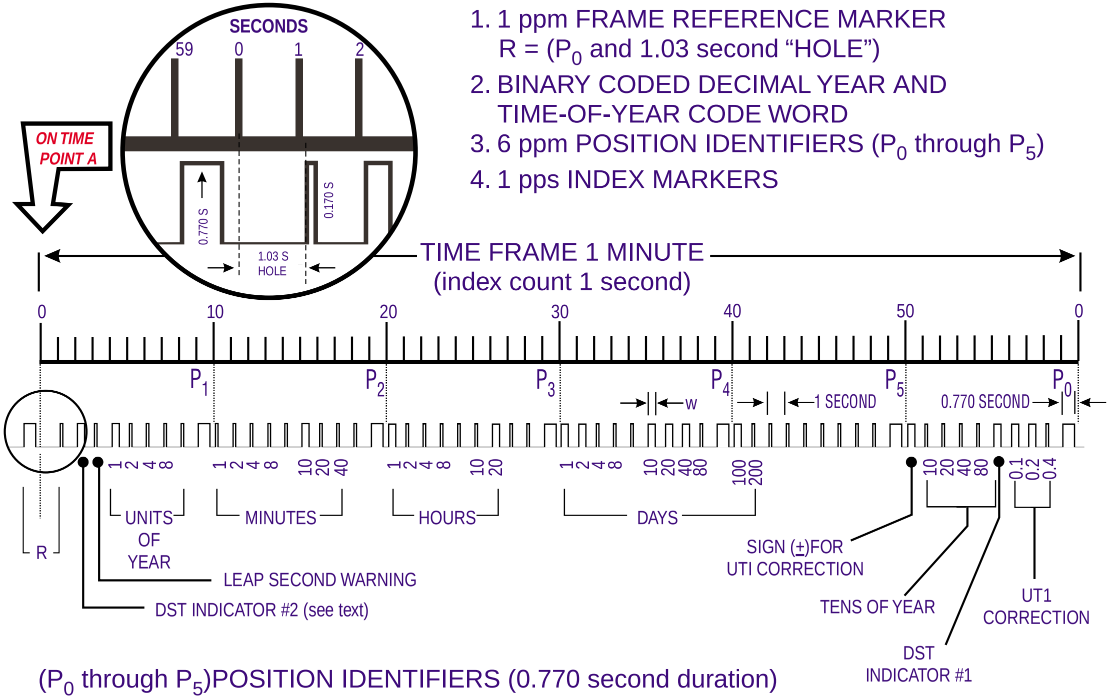
Receiving Equipment

WWV and WWVH can be heard with any *shortwave* receiver. A typical general coverage shortwave receiver provides continuous coverage of the spectrum from about 150 kHz, which is below the commercial AM broadcast band, to 30 MHz. These receivers allow reception of WWV and WWVH on all available frequencies. The best shortwave receivers are often referred to as communications receivers. These receivers are usually designed

WWV and WWVH TIME CODE FORMAT

MODIFIED IRIG H FORMAT IS COMPOSED OF THE FOLLOWING:

1. 1 ppm FRAME REFERENCE MARKER
   R = (P_0 and 1.03 second “HOLE”)
2. BINARY CODED DECIMAL YEAR AND
   TIME-OF-YEAR CODE WORD
3. 6 ppm POSITION IDENTIFIERS (P_0 through P_5)
4. 1 pps INDEX MARKERS



(P_0 through P_5)POSITION IDENTIFIERS (0.770 second duration)
W WEIGHTED CODE DIGIT (0.470 second duration)
DURATION OF INDEX MARKERS, UNWEIGHTED CODE, AND UNWEIGHTED CONTROL ELEMENTS = 0.170 SECONDS

NOTE: BEGINNING OF PULSE IS REPRESENTED BY POSITIVE-GOING EDGE.
UTC AT POINT A = 2001, 173 DAYS, 21 HOURS, 10 MINUTES
UT1 AT POINT A = 2001, 173 DAYS, 21 HOURS, 10 MINUTES, 0.3 SECONDS

Figure 3.10. WWV and WWVH Time Code Format

as tabletop or rackmount units and are often used by amateur radio operators who operate both a transmitter and receiver. They are designed to work with large outdoor antennas, with quarter-wave or half-wave length dipole antennas often providing the best results. Prices range from less than $500 to more than $5000. A typical communications receiver is shown in Figure 3.11.

Figure 3.11. A HF Communications Receiver

Less expensive shortwave radios are usually portable, and can run off batteries. They typically use a built-in telescopic whip antenna that is less than 1 m long, but most have a connector for an external antenna. Some of the lower cost models only provide coverage of the frequencies commonly used for international broadcasts; typically from about 4 to 12 MHz. These receivers will still provide reception of both WWV and WWVH on 5 and 10 MHz, which are usually the easiest frequencies to receive.

A few low-cost commercially available receivers are dedicated to the task of receiving WWV and WWVH. These receivers might receive only a single frequency, often 10 MHz, and their sole purpose is producing the WWV or WWVH audio.

Receivers that decode and display the time code are also available, but are not nearly as common as their WWVB counterparts. Some units output a time code to a serial interface and/or output a standard time code format defined by the Inter-Range Instrumentation Group (IRIG). In addition, these receivers might include an on time one pulse per second signal for use as a measurement reference. Since it is difficult for a time code receiver to stay locked to a single frequency at all times, these units generally monitor several frequencies and use the one that currently offers the best reception.

Listening to the Signals by Telephone

If you don't have a shortwave receiver, you can still listen to WWV and WWVH by simply making a telephone call. The broadcasts are simulcast by telephone via NIST's

Telephone Time-of-Day Service. The uncertainty of the time announcement depends upon the type of phone call. The time signals are usually delayed by <30 ms if you call from an ordinary telephone (land line) from within the continental United States, and the stability (delay variations) are generally <1 ms during the call. If you are calling from a mobile phone, the delay is often more than 100 ms due to the multiple access methods used to share cell channels. And if you are making an overseas call, your call could be routed through a communications satellite, which might add 250 to 500 ms to the delay.

To hear these broadcasts, dial (303) 499-7111 for WWV and (808) 335-4363 for WWVH. You can listen for about two minutes before your call is disconnected. Please keep in mind that these are not toll-free numbers. Callers outside the local calling area are charged long distance rates.

NIST has provided time signals by telephone for several decades. The WWV number has been available since July 1971, and the Hawaii number has been available since April 1973.

HF Propagation

WWV and WWVH are referred to the primary NIST Frequency Standard and related NIST atomic time scales in Boulder, Colorado. The frequencies *as transmitted* are maintained within a few parts in 10^{13} for frequency and <100 ns for timing with respect to UTC(NIST). In fact, at the transmitter site WWV's frequency is controlled just as tightly as WWVB (Chapter 2). However, the received performance of WWV and WWVH is generally worse than the received performance of WWVB. This is because a HF radio path is much less stable than a LF radio path.

Why is a HF path less stable? Although HF radio propagation is a complex subject, we can provide a simplified explanation here. We mentioned in Chapter 2 that the groundwave signals from WWVB follow a direct route to your receiver, and therefore the path length doesn't change very much. Other types of radio signals, such as those that originate from satellites, follow even a more direct route. In fact, some signals require *line-of-sight* propagation, which means that nothing can block the path between the receiving antenna and the transmitter. An example would be a GPS satellite antenna, which requires a clear view of the sky.

HF signals are different. They don't have to follow a direct route. In fact, they rely on skywave propagation, which means that they follow an indirect route. HF signals travel past their horizon line, bounce off the ionosphere, and head back down toward Earth and your receiver, which might be on the opposite side of the Earth from the transmitter. This bouncing off the ionosphere is called *refraction*, or *skip*. Sometimes the signals bounce just once off the ionosphere, sometimes they bounce more than once. Each of these bounces or *hops* adds more delay to a timing signal. As you can see, the good news about refraction is that it allows stations to be heard over great distances. The bad news is that refraction makes the signal path (and therefore the amount of the path delay) variable and hard to predict.

The ionosphere generally ranges between 50 and 1200 km above the Earth's surface. The gases in these regions become ionized by the ultraviolet radiation from the Sun. The more radiation, the more ionization occurs. Too much ionization makes the ionosphere too dense to refract signals, and it absorbs signals instead of sending them back to Earth. Not enough ionization means that the ionosphere won't be dense enough to refract or absorb signals. Instead, signals will simply pass through the ionosphere and head off into space.

The ionosphere has several layers that effect HF propagation, specifically the D, E, and F layers. The D layer is usually between 50 and 100 km above the Earth's surface, the E layer is between 100 and 160 km, and the F layer is between 160 and 320 km above the Earth. Each layer reacts differently to different frequencies at different times of day, and even during different seasons of the year. For example, consider that the D layer is very dense during the daytime, and tends to absorb signals below 7 MHz. At night, however, it becomes less dense and is able to refract signals. This means that a 5 MHz signal from WWV probably won't travel very far during the daytime. Those who can receive it during the day are probably close enough to the station to receive the groundwave. At night, however, the 5 MHz signal will refract off the ionosphere and the coverage area will become much larger.

Since the HF radio path delay depends upon so many factors—the frequency used, the time of day, the season, and the ionospheric conditions, to name just a few; it's easy to see that it limits the performance of WWV and WWVH for time and frequency applications. Even so, the signals still meet the requirements for many applications and measurements, as described in the next section.

Applications and Measurement Results

What kind of results can you get using WWV and WWVH? Let's look at the results obtained for several different applications and measurements (summarized in Table 3.13).

Manual Synchronization of a Watch or Clock — Many thousands of people set their clocks or watches to the tones from WWV and WWVH. If you are listening from within the United States either by radio or by telephone, the time should be delayed by <20 ms (less for most listeners) with respect to UTC(NIST). This delay is insignificant when compared to human reaction time, which is no better than 100 ms for most people, and is sometimes several hundred milliseconds or more.

Stop Watch and Timer Calibrations — Calibration and testing laboratories use the audio tones from WWV and WWVH as the reference for stop watch and timer calibrations. These calibrations are actually a time interval measurement, tones from the broadcast are used as signals to start and stop the timer. In between the start and stop tones the timer runs continuously, usually for an interval of at least an hour. When the timer is stopped, the measured time interval on its display is compared to the actual time interval broadcast by the station. The difference between these two values is the time offset, or error of the timer. WWV and WWVH contribute practically zero uncertainty to these measurements. Even though both the start and stop tones are delayed as they travel to the listener, the difference between the start and stop delays should always be much less than a millisecond. Once again, the largest source of uncertainty is human reaction time.

Tuning a piano — The 440 Hz tones broadcast by WWV and WWVH near the beginning of each hour serve as the ultimate reference for the calibration of pianos and other musical instruments. Since 1939, A440 (the musical note A above middle C at 440 Hz) has been the internationally recognized standard for musical pitch. The piano tuner listens to a standard musical pitch and compares it to the same note on the piano keyboard. The piano is then adjusted (by tightening or loosening strings), until it agrees with the audio standard.

What is the smallest frequency error that a piano tuner can hear? It depends on lots of factors, including the sound volume, the duration of the tone, the suddenness of the frequency change, and the musical training of the listener. However, the *just noticeable difference* is often defined as 5 cents, where 1 cent is 1/100 of the ratio between two adjacent tones on the piano's keyboard. Since there are 12 tones in a piano's octave, the ratio for a frequency change of 1 cent is the 1200th root of 2. Therefore, to raise a musical pitch by 1 cent, you would multiply by the 1200th root of 2, or 1.000577790. If you do this 5 times starting with 440 Hz, you'll see that 5 cents high is about 441.3 Hz, or high in frequency by 1.3 Hz. Obviously, WWV or WWVH will contribute no discernible uncertainty to these measurements, since their 440 Hz tone should have an error of less than 0.001 Hz.

Keep in mind that the actual piano tuning is generally done with a transfer standard such as a tuning fork or an audio tone generator, since those devices are easy to bring to the piano site and their signals are always available. In other words, if you use a transfer standard, you don't have to wait until the top of the hour to hear the tone. However, the audio from WWV or WWVH is often used as a reference for calibrating the transfer standard.

Calibrating a receiver dial — Radio amateurs and shortwave listening enthusiasts often use WWV or WWVH to calibrate their receiver dial. Receivers are usually tested after they have been turned on for at least an hour, so that their internal oscillator has a chance to stabilize. The calibration method varies for different radios, but the object is always to mix the incoming signal from WWV and WWVH with the signal from the receiver's beat frequency oscillator (BFO). This produces a beat note that sounds like a low frequency whistle. The receiver is tuned to the station, and the dial is moved up or down until the whistle completely goes away, a condition known as *zero beat*. Usually, headphones are used to listen for zero beat, since the receiver's speaker might not be able to produce the low frequency beat note signals. Since a person with average hearing can hear tones down to 20 or 30 Hz, an audio zero beat can resolve frequency within 2 or 3 parts in 10^6 at 10 MHz. To get closer, you can also look at the receiver's signal strength, or S-meter. This meter will fluctuate at its slowest rate as the beat note approaches 0 Hz. It should be possible to obtain a beat note of 1 Hz or less, as indicated by a slow "bobbing" of the S-meter back and forth. Once zero beat is reached, the difference between the receiver's dial reading and the carrier frequency of the radio station shows you the frequency offset of the radio. For example, if you zero beat the 10 MHz carrier from WWV with a dial reading of 10000.2 kHz, the receiver dial has a frequency offset of 200 Hz, or 2×10^{-5}.

Keep in mind that the precision of these calibrations is often limited by the resolution of the tuner. On some lower cost receivers the tuning resolution is 100 Hz, or even 1 or 5 kHz, so the dial will still appear to be correct even if the BFO has a fairly large frequency offset. More expensive receivers sometimes tune in 1 Hz increments. The uncertainty of WWV and WWVH is small enough to set the BFO of even the best receivers to within 1 Hz at 10 MHz, a frequency offset of 1×10^{-7}.

Frequency Calibrations (zero beat) — There are many variations of the zero beat method used to calibrate oscillators other than the BFO in a communications receiver. One simple method involves placing one end of a piece of insulated wire near the oscillator and the other end near the antenna input of your HF receiver. If the radio is tuned to 10 MHz and the oscillator under test is a 10 MHz oscillator, you should hear a slow pulsing sound (beat note) in addition to the WWV or WWVH audio. By adjusting the oscillator, this pulse should get slower and slower until zero beat is reached and no pulsing is heard. The uncertainty of this method is generally equal to 1 cycle of the carrier frequency, or 1×10^{-7} at 10 MHz. This makes it useful for calibrating oscillators such as those found in low cost frequency counters, signal generators, and other types of test equipment.

Time Synchronization — Some WWV and WWVH receivers are designed or modified to produce a 1 pulse per second (pps) signal. This signal is intended to be on time, or to coincide with the arrival of the UTC second. You can estimate the path delay with software that computes the distance between your receiving site and the station (the station coordinates are listed in Tables 3.2 and 3.3), and then calculates the time required for a radio signal to travel that distance. As we saw earlier, HF radio propagation depends on many factors. Without taking all of these factors into account, it's difficult to estimate the path delay to much better than 1 ms. Therefore, most WWV and WWVH time measurements have an uncertainty of about 1 ms, even if you compensate for the path delay. If you don't compensate for path delay at all, the uncertainty is dependent on your distance from the transmitter. It should be < 15 ms for receivers located in the continental United States or near Hawaii.

Frequency Calibrations (phase comparison) — Better results from WWV and WWVH can be obtained by comparing the received phase of the signal to the oscillator under test, and averaging for one day or longer. To use this method, you need a receiver that brings out an electrical pulse, for example a 1 pps signal referenced to the time code. A 1 pps signal is obtained from the oscillator under test using a frequency divider. The two signals are then compared using a time interval counter. While the receiver is locked to the signal, it should be stable to a few hundred microseconds or less. This translates to an uncertainty of parts in 10^9 when averaged for 24 hours, which is sufficient for measuring the frequency offset of most quartz oscillators. Lower uncertainties (parts in 10^{10}) can be realized by making a single measurement (or a short series of measurements) at the same time each day and then averaging the results over multiple days.

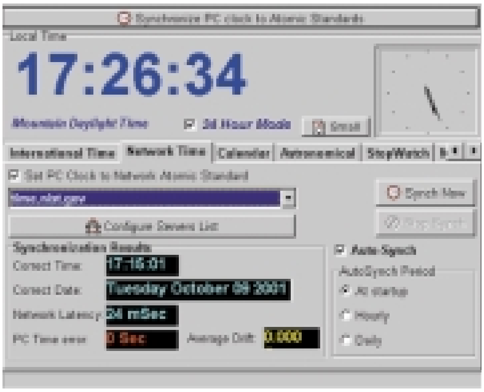
TABLE 3.13 – UNCERTAINTIES OF WWV/WWVH MEASUREMENTS

MEASUREMENT OF APPLICATION	REQUIREMENTS	BEST CASE UNCERTAINTY	LARGEST SOURCE OF UNCERTAINTY	UNCERTAINTY CONTRIBUTED BY WWV OR WWVH
Manual synchronization of a watch or clock	Audio time signal obtained with HF receiver or by telephone	100 ms	Human reaction time	Insignificant
Stop watch and timer calibrations	Audio time signal obtained with HF receiver or by telephone	1×10^{-4} in 10,000 s	Human reaction time	Insignificant
Tuning a Piano	Audio time signal obtained with HF receiver or by telephone	5 cents (~ 0.3%)	Human ear's ability to detect difference between two frequencies	Insignificant
Calibrating a Receiver Dial	HF receiver with beat frequency oscillator and S-meter, headphones	1×10^{-7} (1 Hz at 10 MHz)	Dial resolution of receiver	Insignificant for nearly all receiver calibrations
Frequency Calibrations (zero beat)	HF Receiver, oscillator whose output frequency is a multiple or sub multiple of HF carrier	1×10^{-7} (1 Hz at 10 MHz)	Radio path noise	1×10^{-7} (1 Hz at 10 MHz)
Time Synchronization	HF receiver with output pulse	1 ms	Inability to make good path delay estimate	1 ms
Frequency Calibrations (phase comparison)	HF receiver with output pulse, frequency divider for oscillator under test, time interval counter	Parts in 10^9 in 24 hours	Radio path noise	Parts in 10^9

Chapter 4

Keeping Computers on Time: NIST Computer Time Sychronization Services

Since we rely so heavily on computer systems in our daily lives, it shouldn't surprise you that one of the most common time and frequency applications is the synchronization of computer clocks. At this writing (2001) NIST is handling well over 300 million computer timing requests per day through its Internet Time Service, and this number is expected to become much larger in the coming months and years. This chapter describes the NIST services you can use to synchronize your computer clock. It also describes the nist.time.gov web site, which enables you to view NIST time with your web browser.



Local Time 17:26:34

Mountain Daylight Time

☑ 24 Hour Mode

☑ Set PC Clock to Network Atomic Standard

time.nist.gov

Synchronization Results

Correct Time: 17:16:01

Correct Date: Tuesday October 09 2001

Network Latency: 24 mSec

PC Time error: 0 Sec

Average Drift: 0.000

☑ Auto Synch

AutoSynch Period

● At startup

○ Hourly

○ Daily

Figure 4.1. ITS Client Software

Internet Time Service (ITS)

The NIST Internet Time Service allows users to synchronize computer clocks via the Internet. The time information provided by the service is directly traceable to UTC(NIST). The service responds to time requests from any Internet client in several formats including the Daytime, Time, and Network Time protocol (NTP). Using the ITS is easy. It requires only an Internet connection and client software compatible with your computer's operating system. A sample ITS software client is shown in Figure 4.1, and software can easily be obtained from a number of publishers.

ITS Servers

The NIST Internet Time Service uses multiple time servers as listed in Table 4.1. NIST maintains a number of time servers. Some are located in Boulder, Colorado, and others reside at other facilities around the country. New servers are added whenever necessary to increase the capacity of the service. Each server is identified by its unique Internet protocol (IP) address. All servers provide the same information, and the same uncertainty relative to UTC(NIST), but some handle more traffic than others and might take longer to handle your request. You can configure your client software so that it points to the server of your choice.

TABLE 4.1 – NIST INTERNET TIME SERVERS

NAME	IP ADDRESS	LOCATION
time-a.nist.gov	129.6.15.28	NIST, Gaithersburg, Maryland
time-b.nist.gov	129.6.15.29	NIST, Gaithersburg, Maryland
time-a.timefreq.bldrdoc.gov	132.163.4.101	NIST, Boulder, Colorado
time-b.timefreq.bldrdoc.gov	132.163.4.102	NIST, Boulder, Colorado
time-c.timefreq.bldrdoc.gov	132.163.4.103	NIST, Boulder, Colorado
utcnist.colorado.edu	128.138.140.44	University of Colorado, Boulder
time.nist.gov	192.43.244.18	NCAR, Boulder, Colorado
time-nw.nist.gov	131.107.1.10	Microsoft, Redmond, Washington
nist1.datum.com	63.149.208.50	Datum, San Jose, California
nist1.dc.glassey.com	216.200.93.8	Abovenet, Virginia
nist1.ny.glassey.com	208.184.49.9	Abovenet, New York City
nist1.sj.glassey.com	207.126.103.204	Abovenet, San Jose, California
nist1.aol-ca.truetime.com	207.200.81.113	True Time, Sunnyvale, California
nist1.aol-va.truetime.com	205.188.185.33	True Time, Virginia

ITS Time Code Formats

Every ITS server is constantly "listening" for one of three different types of timing requests. When it receives one of these requests, it transmits a time code in the requested format. The combination of the timing request and the time code is called a protocol, and each of the three standard timing protocols has been defined by an Internet document called a Request for Comments (RFC). Each protocol is briefly described below. You can refer to the RFC document (available from several Internet sites) if you need more information.

Daytime Protocol (RFC-867)

This protocol is widely used by small computers running MS-DOS, Windows, and similar operating systems. The server listens on port 13, and responds to requests in either tcp/ip or udp/ip formats. The standard does not specify an exact format for the Daytime Protocol, but requires that the time be sent using standard ASCII characters. NIST chose a time code format nearly identical to the one used by its older dial-up Automated Computer Time Service (ACTS) shown in Table 4.3, except that a health digit (H) replaces the UT1 correction, and the time is sent 50 ms (as opposed to 45 ms) early. The health digit indicates the health of the server. If H = 0, the server is healthy. If H = 1, then the server is operating properly but its time may be in error by up to 5 s. This state should change to fully healthy within 10 min. If H = 2, then the server is operating properly but its time is known to be wrong by more than 5 s. If H = 4, then a hardware or software failure has occurred and the amount of the time error is unknown.

Unlike the Time protocol and NTP (described below), the Daytime protocol is not a universal standard. Client software designed to work with NIST's version of the Daytime protocol won't necessarily work with other versions, and vice versa. In contrast, NTP client software should be compatible with all NTP servers.

Time Protocol (RFC-868)

No longer widely used, this simple protocol returns a 32-bit unformatted binary number that represents the time in UTC seconds since January 1, 1900. The server listens for Time Protocol requests on port 37, and responds in either tcp/ip or udp/ip formats. Conversion to local time (if necessary) is the responsibility of the client program. The 32-bit binary format can represent times over a span of about 136 years with a resolution of 1 s. There is no provision for increasing the resolution or increasing the range of years.

The strength of the time protocol is its simplicity. Since many computers keep time internally as the number of seconds since January 1, 1970 (or another date), converting the received time to the necessary format is often a simple matter of binary arithmetic. However, the format does not allow any additional information to be transmitted, such as advance notification of leap seconds or Daylight Saving Time, or information about the health of the server.

Network Time Protocol (RFC-1305)

The Network Time Protocol (NTP) is the most complex and sophisticated of the time protocols, and the one that provides the best performance. Large computers and workstations often include NTP software with their operating systems. The client software runs continuously as a background task that periodically gets updates from one or more servers. The client software ignores responses from servers that appear to be sending the wrong time, and averages the results from those that appear to be correct.

Many of the available NTP software clients for personal computers don't do any averaging at all. Instead, they make a single timing request to a signal server (just like a Daytime or Time client) and then use this information to set their computer's clock. The proper name for this type of client is SNTP (Simple Network Time Protocol).

The NIST servers listen for a NTP request on port 123, and respond by sending a udp/ip data packet in the 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.

ITS Performance

The uncertainty of Daytime, Time, and SNTP time clients is usually <100 ms, but the results can vary due to the Internet path, and the type of computer, operating system, and client software. In extreme cases, the uncertainty might be 1 s or more. The uncertainty of a continuously running NTP client is often <10 ms.

Automated Computer Time Service (ACTS)

Although the great majority of computer clocks are now synchronized via the Internet, some applications still require an accurate timing signal that can be obtained over an ordinary telephone line using an analog modem. The Automated Computer Time Service (ACTS) is provided by NIST to satisfy those requirements. Using ACTS requires a computer, an analog modem, and some simple software. When a computer connects to ACTS by telephone, it receives an ASCII time code. The information in the time code is then used to set the computer's clock.

You can connect to ACTS using either a Colorado or Hawaii phone number as shown in Table 4.2.

TABLE 4.2 – ACTS INFORMATION

PHONE NUMBER	LOCATION	PHONE LINES	CAPACITY (CALLS PER DAY)
(303) 494-4774	NIST, Colorado	24	60,000
(808) 335-4721	WWVH, Hawaii	4	10,000

ACTS Time Code

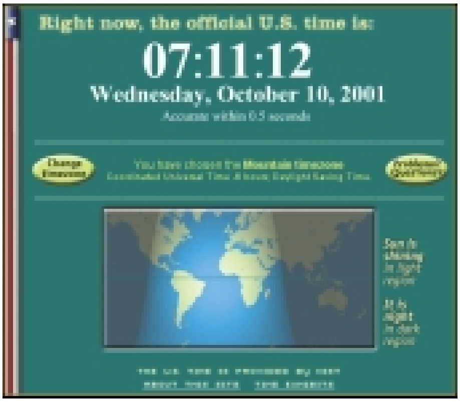
ACTS works at speeds up to 9600 baud with 8 data bits, 1 stop bit, and no parity. To receive the full time code, you must connect at a speed of at least 1200 baud. The full time code is transmitted every second and contains more information than the 300 baud time code, which is transmitted every 2 seconds and omits the MJD and DUT1 information. The full time code is described in Table 4.3 and looks like this:

JJJJJ YY-MM-DD HH:MM:SS TT L DUT1 msADV UTC(NIST) OTM

TABLE 4.3 - THE ACTS TIME CODE

TIME CODE	DESCRIPTION
JJJJJ	The Modified Julian Date (MJD). The MJD is the last five digits of the Julian Date, which is the number of days since January 1, 4713 B.C. To get the Julian Date, add 2,400,000.5 to the MJD.
YY-MM-DD	The last two digits of the year, the month, and the current day of month.
HH:MM:SS	The time in hours, minutes, and seconds. The time is always sent as Coordinated Universal Time (UTC). An offset needs to be applied to UTC to obtain local time. For example, Mountain Time in the United States is 7 hours behind UTC during Standard Time, and 6 hours behind UTC during Daylight Saving Time.
TT	A two digit code (00 to 99) 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. This code is set to 00 when ST is in effect, or to 50 when DST is in effect. On the day of the transition from DST to ST, the code is set to 01. On the day of the transition from ST to DST, the code is set to 51. The client software is responsible for implementing the change at 2 a.m. on the day of the transition. During the month of the transition, the code is decremented every day until the change occurs. For example, October is the month of the transition (in the United States) from DST to ST. On October 1, the number changes from 50 to the actual number of days until the time change. It will decrement by 1 every day, and reach 01 on the day of the transition. It will be set to 00 the day after the transition, and will remain there until the following April.
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. This means that the last minute of the month will contain 61 seconds instead of 60. If the code is 2, a second will be deleted on the last day of the month.
DUT1	A correction factor for converting UTC to UT1. It is always a number ranging from –0.8 to +0.8 seconds. This number is added to UTC to obtain UT1.
msADV	The number of milliseconds that NIST advances the time code. It is originally set to 45.0 ms. If you return the on-time marker (OTM) to the ACTS server, it will change to reflect the actual one way path delay.
UTC(NIST)	A label that indicates that you are receiving Coordinated Universal Time (UTC) from the National Institute of Standards and Technology (NIST).
OTM	OTM (on-time marker) is an asterisk (*). The time values sent by the time code refer to the arrival time of the OTM. In other words, if the time code says it is 12:45:45, this means it is 12:45:45 when the OTM arrives.

Since the OTM is delayed as it travels from NIST to your computer, ACTS sends it out 45 ms early. This always removes some of the delay. Better results are possible if the user's software returns the OTM to ACTS after it is received. When the OTM returns, ACTS measures the amount of time it took for the OTM to go from ACTS to the user and back to ACTS (round trip path delay). By dividing the round trip path delay by 2, ACTS obtains the one-way path delay. ACTS then advances the OTM by the one-way path delay and the OTM changes from an asterisk to a pound sign (#). When the # sign appears, the time code is synchronized to UTC(NIST) with an uncertainty of <15 ms.



Right now, the official U.S. time is:

07:11:12

Wednesday, October 10, 2001

Accurate within 0.5 seconds

Figure 4.2. nist.time.gov Web Site

nist.time.gov Web Site

If you point your web browser to http://nist.time.gov, you'll see a digital clock display that displays UTC(NIST), or the local time for the United States time zone that you select (Figure 4.2). Although the site can't set your computer's clock, it's useful for manually setting a clock or watch to NIST time. The estimated uncertainty of the display is shown on screen. The uncertainty is typically less than 1 s, and usually within 0.5 s of UTC(NIST).

One of the most popular United States government web sites, nist.time.gov currently (2001) receives millions of timing requests per month. It uses the Internet Time Service as its timing reference, so the time display is generally very accurate. However, keep in mind that it should be used as a time-of-day service only. It should not be used to measure frequency or time interval, nor should it be used to establish traceability to NIST.

Chapter 5

Remote Calibration Services

The services described in the previous chapters consist of signals broadcast by NIST for use as time and frequency references. These signals are provided free of charge as a service of the United States government and meet the needs of most users. However, some of the nation's calibration and testing laboratories require smaller measurement uncertainties. For these organizations, NIST offers a remote calibration service on a paid subscription basis that automates the process of establishing traceability to UTC(NIST).

NIST Frequency Measurement and Analysis Service

The NIST Frequency Measurement and Analysis Service (FMAS) was designed to make it easy for a customer to measure and calibrate any quartz, rubidium, cesium, or hydrogen maser frequency standard in their own laboratory, without sending the device to NIST for calibration. The service can measure any frequency from 1 Hz to 120 MHz in 1 Hz increments. This means it can measure standard output frequencies such as 5 and 10 MHz, telecommunication frequencies such as 1.544, 2.048, and 51.84 MHz, and even 1 Hz timing pulses. As many as five devices can be measured and calibrated at once, even if all five have different output frequencies. The FMAS uses Global Positioning System (GPS) signals as its reference frequency and will work anywhere on Earth. All measurements are made automatically, and are traceable to NIST at an uncertainty of 2×10^{-13} per day.

Subscribers to the NIST service receive a complete frequency measurement system that includes everything needed to make traceable frequency measurements. Once the system is installed, customers simply plug in the frequency standards they want to measure, and connect the system to either a dedicated phone line or Internet connection. This allows NIST personnel to remotely access the system, verify and analyze the data, and quickly troubleshoot any problems that may occur. The GPS signals provide traceability to NIST, since the same GPS signals received by subscribers are received at NIST and compared to the national frequency standard. The GPS receiver is software controlled and requires no operator attention. The customer is required to mount a small antenna in a location with a clear view of the sky. Figure 5.1 shows a two-week measurement of a hydrogen maser made at a customer's location using the FMAS.

NIST completely supports each FMAS customer. When enhancements to the software are developed, NIST installs them for the customer remotely. If any hardware component fails, NIST replaces it immediately using an overnight delivery service. Each subscriber receives a monthly calibration report prepared by NIST personnel. The calibration report documents that the customer's primary standard is traceable to UTC(NIST). It includes a graph of the performance of the customer's standard and a statement of measurement uncertainty. The FMAS specifications are listed in Table 5.1.

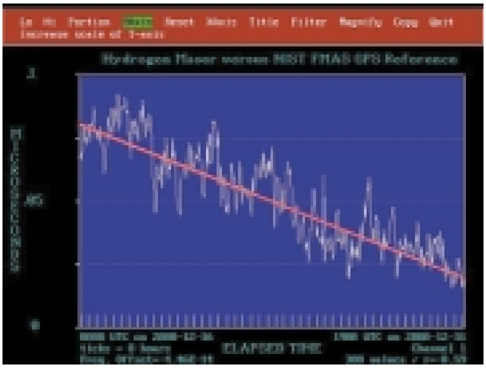


Figure 5.1. Sample FMAS Screen Display

The FMAS complies with the requirements of NVLAP (National Voluntary Laboratory Accreditation Program). Subscribers to the service who seek accreditation in the frequency calibration field can reduce or eliminate the proficiency testing and on-site assessment fees charged by NVLAP.

NIST offers the FMAS as part of its calibration program. The service identification number is 76100S. For more information, including pricing and delivery, visit the Time and Frequency Division web site at http://www.boulder.nist.gov/timefreq.

TABLE 5.1 – SPECIFICATIONS FOR NIST FMAS

FMAS	SPECIFICATION
Measurement Channels	Up to five frequency standards can be calibrated at one time. The FMAS accepts any input frequency from 1 Hz to 120 MHz in 1 Hz increments.
Measurement Resolution	<30 ps
Frequency Uncertainty using GPS	2×10^{-13} (24 h averaging time)
Relative Frequency Uncertainty without GPS (oscillator to oscillator comparisons)	2×10^{-15} (24 h averaging time)

Acknowledgments

The NIST time and frequency services described in this booklet would not be possible without the continuous efforts of a dedicated technical staff that is responsible for their development, operation, and maintenance. Thanks are due to Matt Deutch, the engineer-in-charge at WWV and WWVB; Dean Okayama, the engineer-in-charge at WWVH; and Judah Levine, who single handedly created the ITS and the current version of ACTS. Thanks are also due to Don Sullivan, the Chief of the Time and Frequency Division; John Lowe, the Services Group Leader; Andrew Novick, radio station staff members Douglas Sutton, Glenn Nelson, Bill Yates, Judy Foley, Don Patterson, Ernie Farrow, and Adele Ochinang. Since time and frequency services at NIST have such a long history, many retired NIST employees obviously made great contributions during their careers. Those I have had the pleasure to know and learn from include Wayne Hanson, Dick Davis, Roger Beehler, Chuck Snider, Joe Cateora, Jim Jespersen, and Al Clements. And finally, I would like to offer a special thank you to retired NIST engineer George Kamas for the many hours that we spent together early in my career, as he patiently and generously shared his knowledge of time and frequency metrology.

Michael A. Lombardi, NIST

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practice guide

NIST recommended

WWVB Radio Controlled Clocks: Recommended Practices for Manufacturers and Consumers

Michael A. Lombardi, Andrew N. Novick,
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FOREWORD

Radio controlled clocks represent a true revolution in timekeeping. Clocks that synchronize to NIST radio station WWVB now number in the millions in the United States, and new sales records are being established every year. As a result, many of us are now accustomed to having clocks in our homes, offices, and on our wrists that always display the correct time and that never require adjustment. This *NIST Recommended Practice Guide* was written to provide guidance to both manufacturers and consumers of radio controlled clocks. Through voluntary compliance with the recommended practices listed here, manufacturers can benefit by continuing to develop more reliable and usable radio controlled products, increasing both consumer confidence and sales. Consumers can benefit by using this guide to help them select and purchase radio controlled clock products, to learn how the products work, and to help troubleshoot reception problems.

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1. INTRODUCTION

Through its Time and Frequency Division located in Boulder, Colorado, the National Institute of Standards and Technology (NIST) maintains official time and frequency standards for the United States of America and distributes these standards to the American public. Radio station WWVB, located near Fort Collins, Colorado, is one of the most important distribution sources for these standards. The station continuously broadcasts a 50 kW signal at a frequency of 60 kHz that covers the Continental United States (CONUS), and also reaches Alaska and Hawaii during the nighttime hours.

The signals from WWVB can serve as a convenient reference standard for time interval and frequency, but their primary function is the time-of-day synchronization of radio controlled clocks (RCCs). These clocks are now sold through a variety of retail channels to United States consumers, who install them in their homes and offices and rely on them as reliable and official sources of time, accurate to within 1 second (s) or less. These clocks are sold in a variety of forms, as wall clocks, desk clocks, wristwatches, or clocks embedded into a variety of consumer electronic products, including kitchen appliances such as coffee makers and microwave ovens, home entertainment equipment, and computer systems.

As with all consumer electronic products, the quality of WWVB RCCs produced by different manufacturers varies widely. While many of the existing products are well designed and extremely reliable, some models cannot always decode the time signal even under the most favorable signal conditions, and some lack key features that limit their usefulness from a human engineering standpoint. NIST has produced this recommended practice guide for the benefit of manufacturers and consumers of WWVB radio controlled clocks. It recommends key features to manufacturers that their products should include, as well as key specifications that their products should meet.

These recommended practices are voluntary. No manufacturer or consumer is required by law to comply with them. However, it is hoped that voluntary compliance with these recommended practices will lead to the development of more reliable and usable clocks, increase consumer confidence in WWVB RCCs, and, at the same time, increase the size of the commercial RCC marketplace in the United States. It is also hoped that this guide will be useful to consumers of WWVB RCCs by providing information that helps them select RCC products and troubleshoot RCC reception problems.

The following sections contain a brief technical description of WWVB (Section 2) and product recommendations in seven different categories, including: clock displays (Section 3), synchronization (Section 4), time zone settings (Section 5), handling of daylight saving time (Section 6), handling of miscellaneous time code issues (Section 7), hardware specifications (Section 8), and product documentation (Section 9). Based on consumer feedback received at NIST, the seven categories were identified as being important to the reliability, usability, and marketability of WWVB RCC products. Not all categories share equal importance, so a summary checklist is provided in Section 10 that identifies which categories are recommended as necessary for all designs and which categories are optional. However, we recommend that manufacturers comply with as many of these optional categories as possible in an effort to produce RCC products of the highest quality.

Many consumers will find the information in Sections 2 to 10 interesting, but some will probably want to skip directly ahead to Section 11, which is included for their benefit. It provides general information about WWVB RCCs, and it provides some troubleshooting tips for consumers whose clocks are not working properly.

Please note that it was necessary to write this guide in a general fashion. We identify for manufacturers the desired functions of WWVB RCC products, but a discussion of the technical implementation of these functions is beyond the scope of this guide.

2. TECHNICAL DESCRIPTION OF WWVB

The WWVB time code includes 60 bits of information, transmitted at 1 bit per second. A full minute (60 s) is required to send a complete time code frame (Figure 1). An on-time marker (OTM) is sent every second by reducing the power of the 60 kHz carrier frequency by 10 dB at a time that coincides with the arrival of the Coordinated Universal Time (UTC) second. Bits are identified by the length of time that the carrier power is held low. A 0 bit is sent by holding the power low for 200 ms, a 1 bit is sent by holding the power low for 500 ms. Frame markers are sent every 10 s by holding the power low for 800 ms.

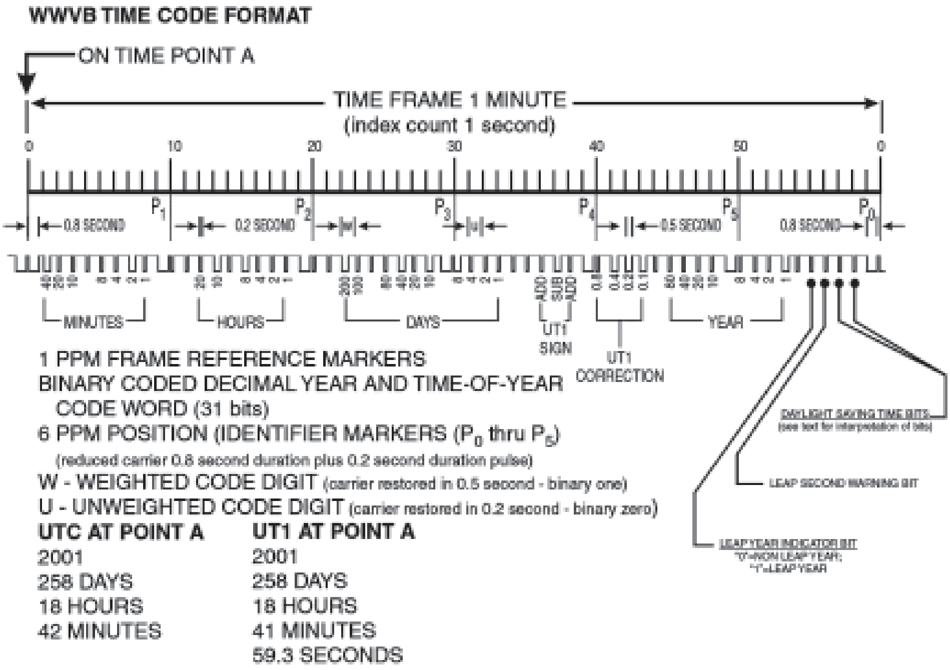


Figure 1. *WWVB time code format.*

The time and frequency reference for the station is the UTC time scale maintained by NIST in Boulder, Colorado, known as UTC(NIST). Atomic oscillators at the radio station site in Fort Collins, Colorado are steered to closely agree with UTC(NIST).

A complete technical description of the WWVB and its broadcast format is not provided here. A general technical description can be found in *NIST Special Publication 432*,[1] and a more detailed description of the station operation, format, and broadcast control is available in *NIST Special Publication 250-67*.[2] Both publications are available for download from the NIST Time and Frequency Division web site at **http://tf.nist.gov/general/publications.htm**.

3. RECOMMENDED PRACTICES FOR CLOCK ACCURACY, CLOCK DISPLAY, AND CONTROLS

All RCC products should display time accurate to at least within ±0.5 s, so that when the time is rounded to the nearest second, the seconds' value is always correct. Tighter synchronization (to within ±0.2 s) is desirable. This prevents the human eye from detecting any errors when checking a RCC display against another independent time reference, whereas a 0.5 s error could be noticeable.

The chief benefit and a key selling point of a RCC is its time accuracy. Therefore, we recommend that all clocks display seconds, or have the option of displaying seconds. With some digital clocks, such as clock radios, the seconds' digits can be made smaller than the hour and minute digits, or the consumer should be given the option to disable the seconds' display if they find it distracting. Analog clocks require either a second hand or a separate digital display that shows seconds. A digital seconds' display that can be turned on and off is often a good option because second hands are not always desirable on analog clocks. For example, a second hand on an analog alarm clock might be noisy enough to bother consumers who are trying to sleep.

3.A. Analog Clock Displays

Analog clock displays should include an hour, minute, and second hand (or a digital display of seconds), and some marking or label indicating that the clock is radio controlled. The date and other information can be displayed (if desired) in a digital inset, as shown in Figure 2.

Figure 2. *Analog clock display with digital inset for date information.*

3.B. Digital Clock Displays

Digital clock displays should display the hour, minute, second, and some marking or label indicating that the clock is radio controlled. The digital display makes it convenient to also display the month, day, year, and weekday (if desired). It is also recommended that "AM" or "PM" is displayed if the clock is set to a 12-hour format, instead of a 24-hour format. Some digital clock displays use an icon of a satellite dish as a synchronization indicator (Section 4.E), as a signal quality indicator (Section 3.E), or simply to indicate that the clock is radio controlled. To avoid confusing consumers, we recommend that a picture of a satellite dish not be used, since WWVB and the other low-frequency (LF) time-signal stations (Section 3.D) all broadcast from ground-based transmitters and not from satellites. Sample digital clock displays are shown in Figures 3 and 4.

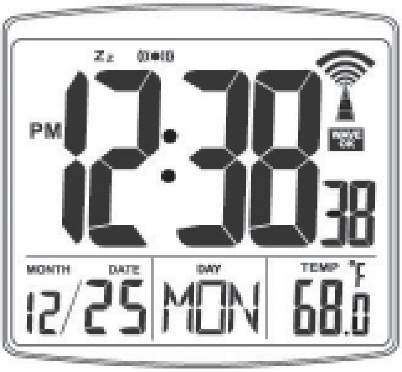


Figure 3. *Digital clock display with date information.*

Figure 4. *Digital clock display that includes year information.*

3.C. RCC Controls

RCC controls should be clearly labeled and situated in such a way that they cannot be accidentally activated; for example, everyday handling of the clock should not result in the change of a time zone setting. This is particularly important in the case of wristwatches.

3.D. Compatibility with Other Stations

Some WWVB RCC products are capable of receiving time signals broadcast by other time signal stations located in other countries. This allows the clocks to be sold and used internationally. The time signals broadcast by other countries (Table 1) use carrier frequencies different from that of WWVB in some cases, and different time code formats in all cases, but the modulation schemes are similar. We recommend that products capable of receiving more than one time signal have a way of clearly indicating to the consumer which time signal is currently being received. We also recommend that if a RCC automatically selects a station, it allows the consumer to override the automatic selection if they wish.

Table 1: **Radio Time Signal Stations Used for RCC Synchronization**

Station Call Sign	Country	Controlling Agency	Carrier Frequency
WWVB	United States	National Institute of Standards and Technology (NIST)	60 kHz
BPC	China	National Time Service Center (NTSC), Chinese Academy of Sciences	68.5 kHz
DCF77	Germany	Physikalisch-Technische Bundesanstalt (PTB)	77.5 kHz
HBG	Switzerland	Swiss Federal Office of Metrology and Accreditation (METAS)	75 kHz
JJY	Japan	National Institute of Information and Communications Technology (NICT)	40 kHz, 60 kHz
MSF	United Kingdom	National Physical Laboratory (NPL)	60 kHz

3.E. Signal Quality Indicator

Inclusion of a real-time signal quality indicator is recommended so that the consumer can find the best location and antenna orientation for their RCC product while forcing the product to attempt synchronization (Section 4.C). Since the actual signal strength is not easy to detect due to other RF noise at 60 kHz, the signal quality indicator can show the “bit strength,” or current readability level of the signal; or it can indicate the progress of the decoding process in the software.

The signal quality indicator can be simple. A three-segment display indicating a low-, medium-, and high-quality signal is generally adequate (Figures 5 and 6). When the clock is not attempting to synchronize and the radio receiver is turned off or disabled, we recommend that the signal quality indicator also be disabled or removed from the display. Otherwise, consumers might mistakenly assume that the RCC is displaying the current signal quality.

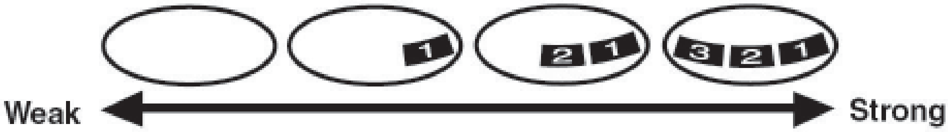


Figure 5. A three-segment display indicating four levels of signal quality.

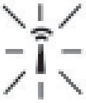
	Strong
	Weak
	No Reception
	Receiving

Figure 6. Use of a broadcast tower icon as a signal quality meter.

3.F. Antenna Orientation

Most RCC antennas are directional and achieve maximum gain when they are positioned broadside to the transmit antenna in Fort Collins, Colorado. We recommend that an arrow or pointer marker is included on the RCC case to illustrate the antenna orientation. When used in conjunction with the signal quality indicator (Section 3.E), this type of marking can assist consumers in orienting the RCC to obtain maximum signal strength.

4. RECOMMENDED PRACTICES FOR CLOCK SYNCHRONIZATION

This section recommends practices for clock synchronization. It is divided into four categories, initial synchronization (when the clock is first turned on), synchronization by radio at assigned times, synchronization by radio at a time selected by the consumer, and manual synchronization without radio control.

4.A. Initial Synchronization When Clock Is First Turned On or Reset

When a RCC is first turned on, it will begin looking for a signal and attempt to synchronize. We recommend that RCCs be designed to continuously try to synchronize on this first attempt until either the synchronization is successful or until the consumer decides to attempt manual synchronization (Section 4.D). We also recommend that RCCs that have not yet been able to synchronize should not run or attempt to display the time since their displays will be incorrect. Suggestions for what a RCC should display prior to synchronization are listed below.

All RCCs should be designed to synchronize without any interaction from the user. It should not be necessary for the user to set the display of the clock (move the hands, etc.) in order for the clock to synchronize.

4.A.1. Analog Clocks (Hand Alignment)

Analog clocks should align themselves with all hands pointed upward (pointed to the “12”) until synchronization is successful. The hands should remain motionless during synchronization.

4.A.2. Digital Clocks

Digital clocks should display 12:00:00 as the time prior to synchronization, or flash the time display on and off, or display dashes instead of the hours, minutes, and seconds. The display should not increment during synchronization.

4.B. Synchronization by Radio at Assigned Times

To meet the accuracy requirements listed in Section 3, and to periodically check the time code for notifications of daylight saving time, leap seconds, and other time code changes, all WWVB RCCs should attempt to synchronize at least once every 24 hours, and more frequently if possible.

If only one synchronization attempt is made, it should be made at night when the signal is the strongest. The signal is generally easiest to receive when it is dark at both the transmitter site in Fort Collins, Colorado, and at the site where the RCC is located, so the highest probability of a successful synchronization is during these hours. Table 2 shows the dark path hours (DPH) and dark path duration (DPD) in hours and minutes for six cities on the approximate longest and shortest days of 2004 (June 21 and December 21), based on when sunrise and sunset occurs in those cities with respect to when sunrise and sunset occur in Fort Collins. The DPH are based on the local time in the selected city. The six cities were chosen to represent the northwest, southwest, northeast, and southeast corners of the CONUS, as well as Alaska and Hawaii.

The information in Table 2 shows that the "window of opportunity" for synchronization ranges from about 4 hours (Anchorage summer) to about 14 hours (Seattle winter). Attempting synchronization on the hour at midnight, 1 a.m., and 2 a.m. guarantees a dark path at all United States locations. Therefore, if only one synchronization attempt is made, we recommend that the scheduled synchronization time is set to be midnight, 1 a.m., or 2 a.m. (local receiver time).

Table 2: ***Dark Path Hours and Duration for WWVB Signal at Selected Cities (Local Time)***

	June 21, 2004		December 21, 2004	
City	**DPH**	**DPD**	**DPH**	**DPD**
Seattle, Washington	9:11 p.m. to 4:30 a.m.	7:19	4:20 p.m. to 6:21 a.m.	14:01
San Diego, California	8:00 p.m. to 4:30 a.m.	8:30	4:46 p.m. to 6:21 a.m.	13:35
Caribou, Maine	10:34 p.m. to 4:38 a.m.	6:04	6:36 p.m. to 7:14 a.m.	12:38
Miami, Florida	10:34 p.m. to 6:30 a.m.	7:56	6:36 p.m. to 7:03 a.m.	12:27
Anchorage, Alaska	11:42 p.m. to 3:30 a.m.	3:48	3:41 p.m. to 5:21 a.m.	13:40
Honolulu, Hawaii	7:16 p.m. to 2:30 a.m.	7:14	5:55 p.m. to 4:21 a.m.	10:26

Manufacturers are cautioned to carefully choose a radio synchronization time and method that does not cause the RCC to display the wrong time (even briefly) on transition days to and from daylight saving time, when the time display should be adjusted forwards or backwards by one hour at exactly 2 a.m. local time (Section 6.A).

If the receiver and signal processing firmware (Section 8.A) inside the RCC are of sufficient quality, it should be possible for successful synchronizations to be routinely made throughout the CONUS during both the daytime and nighttime hours. Therefore, we recommend that manufacturers design products that attempt synchronization more than once per day. This has the disadvantage of perhaps reducing the battery life on battery-powered devices, but it has the advantage of relaxing the quartz oscillator accuracy requirements (Section 8.C) by shortening the interval between synchronizations. For example, if the RCC is programmed to synchronize at both midnight and 4 a.m., it reduces the amount of time that the clock free runs on its local oscillator from 24 to 20 hours, relaxing the oscillator specification by roughly 16%.

Since the small antennas used by WWVB RCCs tend to be very directional, it is difficult for a RCC to synchronize while it is moving. Therefore, it probably won't be advantageous for wristwatches to attempt to synchronize during the daytime hours when the watch is being worn and is probably in motion. As a result, we recommend that wristwatches attempt their multiple synchronizations at times when the consumer is most likely to be asleep, and the watch is motionless. Several synchronization attempts during the night are recommended to allow for the varying "bed times" of consumers.

Manufacturers should be aware of potential problems introduced by consumers who work nights or who never remove their watches. To meet the needs of these consumers, manufacturers can elect to allow an additional synchronization time (in addition to those built-in to the product) to be manually selected. If this is done, the product documentation (Section 9) should adequately explain to the consumer when the product is most likely to successfully synchronize.

4.B.1. Amount of Time Allotted to a Synchronization Attempt

We recommend that WWVB RCCs attempt to decode time codes for at least five consecutive minutes before determining that a synchronization attempt has failed.

4.C. Synchronization by Radio at a Time Selected by the User

All WWVB RCCs should include a button or control that allows the user to attempt immediate synchronization, without waiting for the next scheduled synchronization. The RCC will attempt to decode the incoming signal whenever this control is activated. The RCC display should indicate whether the synchronization attempt succeeded or failed.

This button or control should be designed so that it cannot be activated by accident if the RCC is bumped or jostled. To avoid accidental activation, it might be desirable to use a button that needs to be held in place for several seconds before the clock attempts synchronization.

4.D. Manual Clock Synchronization

All WWVB RCCs should allow the user to disable radio controlled timekeeping functions, so they can be operated as conventional clocks if necessary. This means that the consumer should be allowed to manually synchronize the time and date settings if the signal is unreceivable. This protects the RCC from becoming obsolete if it is moved to an area outside of the signal range. The display should indicate if the RCC is being operated without radio control.

4.E. Synchronization Indicator

All WWVB RCCs should indicate whether they have recently synchronized. Since the clocks are radio controlled and advertised as accurate, they are trusted by consumers, who typically assume that the displayed time is exactly right. However, this will not be true if the clock has not received the signal for a long period. All manufacturers should realize that it is extremely important to communicate to the person viewing the clock that the time can be trusted. This requires indicating whether or not the RCC has been recently synchronized.

Ideally, the RCC should be able to display the date and time of the last synchronization. If this is not possible, the RCC should indicate in some fashion whether it has been more than 24 hours since the last synchronization or, preferably, the total length of time (probably expressed in days) since the last synchronization. Since manufacturers should expect their products to work when used within the coverage area, it is more appropriate for RCCs to indicate when synchronization has failed in the last 24 hours (an abnormal condition), than it is to indicate when synchronization has succeeded (a normal condition). Examples of appropriate synchronization indicators for digital and analog clocks are provided in Sections 4.E.1. and 4.E.2.

Some manufacturers may elect to only alert the consumer if synchronization has not occurred in a period longer than 24 hours; for example, 48 hours or 72 hours could be used. However, all manufacturers should attempt to meet the Section 3 requirement of keeping time between synchronizations to within ±0.5 s of UTC(NIST). A longer interval should be used only if the local oscillator (Section 8.C) is capable of keeping time to within ±0.5 s of UTC(NIST) throughout the entire interval. For this reason, synchronization intervals longer than 24 hours might not be acceptable for many RCC products.

4.E.1. Digital Clock Synchronization Indicator

There are numerous ways that a RCC with the ability to display alphanumeric characters or symbols can provide a synchronization indicator. All are acceptable if they are clearly explained and understandable to the consumer. Figure 7 shows a watch displaying the date and time of the last synchronization. This is the preferred method since it passes the most information along to the consumer.

Figure 7. *RCC display indicating the date and time of the last synchronization.*

4.E.2. Analog Clock Synchronization Indicator

If an analog clock does not have a digital inset, a synchronization indicator should still be provided. For example, the indicator can be a light that is illuminated when synchronization has not occurred within the last 24 hours. Or advancing the second hand every two seconds instead of every second could be used to indicate that the clock has not synchronized in the last 24 hours. Other methods can be used, including the use of audio beeps or tones.

5. RECOMMENDED PRACTICES FOR TIME ZONE SETTINGS

WWVB broadcasts UTC as opposed to local time. Therefore, each RCC must have a time zone switch or control that allows the local time zone to be selected in order for the clock to display local time.

5.A. Time Zone Selection

As a minimum requirement, all WWVB products should be capable of setting to the seven time zones listed in Table 3, so they can adequately service all potential consumers in the United States. However, since some WWVB products will be used through manual synchronization outside the coverage area (Section 4.D) or are capable of receiving other time signal stations (Section 3.D), we recommend that the time zone settings include each of the 38 time zones listed in Table 4. Both tables include the name, letter designation, and abbreviation for each time zone (when information is available), as well as the offset in hours from UTC.

Please note that if a RCC has the ability to select time zones offset by ±12 hours from UTC in half-hour increments, then nearly all of the time zones in the world will be represented. Figure 8 provides a world time zone map; Figure 9 provides time zone information for the United States. Manufacturers should consider including similar maps in their product documentation (Section 9).

Table 3: **Necessary Time Zone Options for WWVB RCC Products**

UTC Offset (hours)	Letter	Abbreviation	Name	Non-United States Areas Include
–10:00	W	HST or HAST	Hawaii–Aleutian Standard Time	Central French Polynesia, Tokelau, Cook Islands, Tahiti, Johnston Atoll
–9:00	V	AKST	Alaska Standard Time	Gambier Islands (French Polynesia)
–8:00	U	PST	Pacific Standard Time	Western Canada, North Baja Peninsula
–7:00	T	MST	Mountain Standard Time	West Central Canada, South Baja Peninsula, Central and Western Mexico
–6:00	S	CST	Central Standard Time	Mexico, Easter Island, Galapagos Islands, Central Canada, Central America
–5:00	R	EST	Eastern Standard Time	Western South America, Cuba, Bahamas, Haiti, Jamaica, East Central Canada, Panama
–4:00	Q	AST	Atlantic Standard Time	Central South America, Dominican Republic, Eastern Canada, West Greenland, Bermuda

Table 4: **Recommended Time Zone Options for WWVB RCC Products Sold Internationally**

UTC Offset (hours)	Letter	Abbreviation	United States Name	Other Areas
–12:00	Y			International Date Line West
–11:00	X	SST	Samoa Standard Time	Midway Islands
–10:00	W	HST or HAST	Hawaii-Aleutian Standard Time	Central French Polynesia, Tokelau, Cook Islands, Tahiti, Johnston Atoll
–9:30	—			Marquesas Islands (French Polynesia)
–9:00	V	AKST	Alaska Standard Time	Gambier Islands (French Polynesia)
–8:00	U	PST	Pacific Standard Time	Western Canada, North Baja Peninsula
–7:00	T	MST	Mountain Standard Time	West Central Canada, South Baja Peninsula, Central and Western Mexico
–6:00	S	CST	Central Standard Time	Mexico, Easter Island, Galapagos Islands, Central Canada, Central America
–5:00	R	EST	Eastern Standard Time	Western South America, Cuba, Bahamas, Haiti, Jamaica, East Central Canada, Panama
–4:00	Q	AST	Atlantic Standard Time	Central South America, Dominican Republic, Eastern Canada, West Greenland, Bermuda

Table 4: **Recommended Time Zone Options for WWVB RCC Products Sold Internationally** *(continued)*

UTC Offset (hours)	Letter	Abbreviation	United States Name	Other Areas
–3:30	—			Newfoundland Canada
–3:00	P			Eastern South America, Central Greenland
–2:00	O			Pernambuco (Brazil)
–1:00	N			Azores, East Greenland (Svalbard and Jan Mayen), Cape Verde
0	Z			Western Europe, Iceland, West Africa, Canary Islands, Coordinated Universal Time, Greenwich Mean Time
+1:00	A			Central Europe (including France and Spain), West Central Africa, Norway, Sweden, Denmark
+2:00	B			Eastern Europe, Russia Zone 1, East Central Africa, Turkey, Syria, Jordan, Greece, Cyprus, Israel, Lebanon, Finland
+3:00	C			Russia Zone 2, East Africa, Georgia, Iraq, Saudi Arabia, Madagascar, Somalia, Sudan, Kuwait, Uganda, Yemen
+3:30	—			Iran

Table 4: **Recommended Time Zone Options for WWVB RCC Products Sold Internationally** *(continued)*

UTC Offset (hours)	Letter	Abbreviation	United States Name	Other Areas
+4:00	D			Russia Zone 3, Oman, Reunion, Mauritius, Seychelles, Azerbaijan, Armenia, West Kazakhstan, United Arab Emirates
+4:30	—			Afghanistan
+5:00	E			Russia Zone 4, British Indian Ocean Territory (Chagos), Kerguelen Island, Maldives Islands, Central Kazakhstan, Turkmenistan, Kyrgyzstan, Tajikistan, Pakistan, Uzbekistan
+5:30	—			India
+5:45	—			Nepal
+6:00	F			Russia Zone 5, Eastern Kazakhstan, Bangladesh, Bhutan, Sri Lanka
+6:30	—			Cocos Islands, Burma
+7:00	G			Russia Zone 6, Western Indonesia, Southeast Asia
+8:00	H			Russia Zone 7, Western Australia, China, Hong Kong, Malaysia, Philippines, Central Indonesia, Singapore, Mongolia, Taiwan

Table 4: **Recommended Time Zone Options for WWVB RCC Products Sold Internationally** *(continued)*

UTC Offset (hours)	Letter	Abbreviation	United States Name	Other Areas
+9:00	I			Russia Zone 8, Japan, Korea, Palau, Eastern Indonesia
+9:30	—			Central Australia
+10:00	K	ChST	Chamorro Standard Time	Russia Zone 9, Eastern Australia, Chamorro (Guam and N. Mariana Islands), Micronesia, Papua New Guinea
+10:30	—			Lord Howe Island
+11:00	L			Russia Zone 10, Vanuatu, Solomon Islands, New Caledonia, East Micronesia Islands
+11:30	—			Norfolk Island
+12:00	M			Russia Zone 11, New Zealand, Fiji, Tuvalu, Marshall Islands, Nauru, Gilbert Islands (Kiribati), Wake Island, Wallis and Futuna, Kiribati Islands, International Date Line East
+12:45	—			Chatham Islands
+13:00	—			Tonga, Phoenix Islands (Kiribati)
+14:00	—			Line Islands (Kiribati)

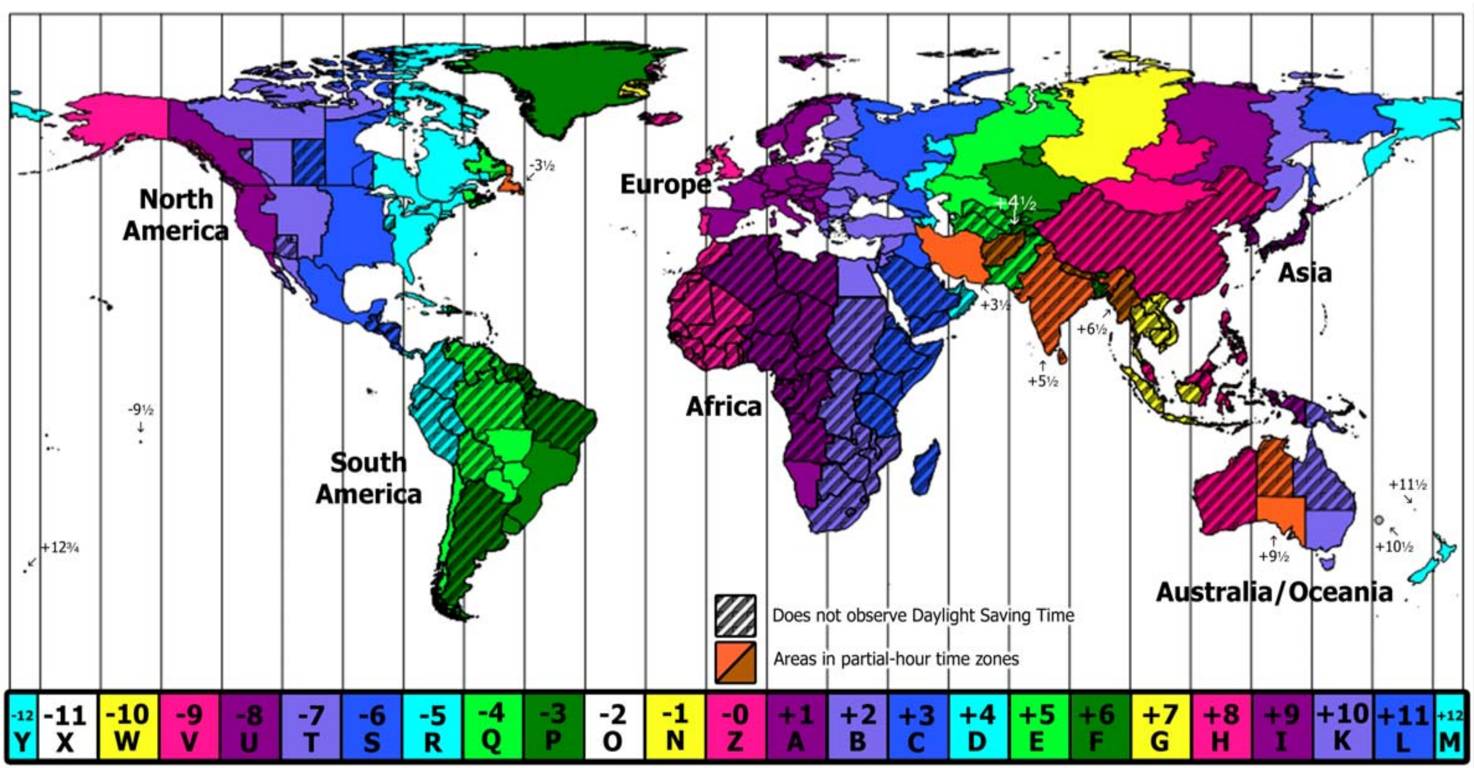


Figure 8. *World time zone map.*

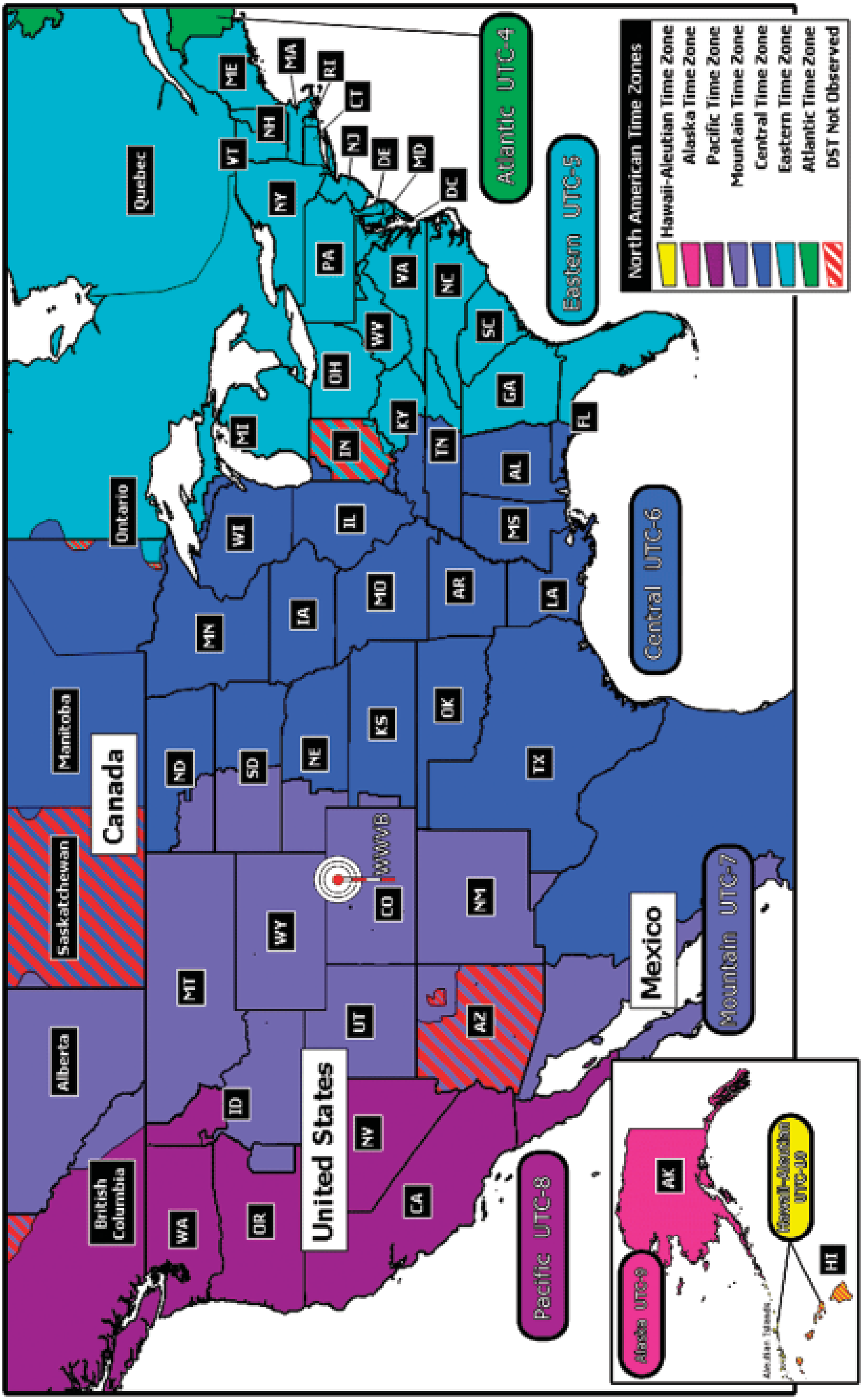


Figure 9. United States time zone map.

6. RECOMMENDED PRACTICES FOR DAYLIGHT SAVING TIME (DST)

The WWVB time code (Figure 1) includes information that tells the RCC whether standard time (ST) or daylight saving time (DST) is currently in effect, and also whether the current day is a transition day from ST to DST, or from DST to ST. All RCC products should decode this information so that consumers do not have to reset their clocks on the day of a time change. Figure 9 shows the areas within the United States that currently observe DST.

6.A. Handling of Transition Days

RCCs in areas that observe DST should advance one hour at 2 a.m. local time on the first Sunday of April each year, and move back one hour at 2 a.m. local time on the last Sunday of October of each year.[3] RCCs must properly interpret the information in the time code (Figure 1) and apply the time zone settings (Section 5), so the transition takes place at exactly 2 a.m. local time. Special attention to the DST code is required when implementing this feature as some manufacturers have misinterpreted the code. It might be necessary for analog clocks to move forward 11 hours (rather than back one hour) on the transition from DST to ST, if their clock mechanisms do not allow the hands to be moved backwards.

Manufacturers might elect to design products that implement the DST rule[3] at the assigned time, even if the RCC has been unable to recently read the DST information in the WWVB time code. This will allow the RCC to handle the DST transition even if the signal has not been recently received. However, if the DST rules change (they were last changed in 1986 and could conceivably change again), clocks programmed to follow them will fail, whereas the WWVB time code will always comply with the current rules. Therefore, we recommend that the DST information in the time code be used whenever possible and that the programmed rule only be used for backup or verification.

Another less important issue is that WWVB might be received under optimal conditions in areas (including South American countries such as Chile) that do not follow the same DST rules as the United States. This means RCCs located in these regions would be wrong at certain times of the year, regardless of whether the WWVB time code or the programmed DST rule for the United States was used to select the DST transition days. If a manufacturer sells products to consumers in these areas, we recommend that they allow the transition days and times to and from DST to be selected by the consumer through some type of user interface. Inclusion of this feature also guards against product obsolescence if the DST rules in the United States are changed again.

6.B. Disabling/Enabling DST Switch

Certain regions of the United States do not observe DST (Figure 9). Therefore, all RCC products must provide the consumer with the option to disable DST so that clocks located in those regions remain on ST throughout the year. Care should be taken to inform the consumer that this is normally a one-time setting; DST should be disabled only if their area does not observe DST, and not simply if ST is currently in effect.

6.C. DST Indicator

We recommend that the RCC has a display or switch setting that informs the consumer whether DST or ST is currently in effect.

7. RECOMMENDED PRACTICES FOR LEAP SECONDS, LEAP YEARS, AND THE TWO-DIGIT YEAR CODE

This section discusses the handling of miscellaneous time code settings, in particular the handling of leap seconds, leap years, and the two-digit year code.

7.A. Handling of Leap Seconds

When necessary (typically less than once per year), leap seconds are inserted into the UTC time scale on June 30th and/or December 31st. This keeps UTC within ±0.9 s of an astronomical time scale called UT1. The WWVB time code (Figure 1) includes a leap second bit (transmitted at second 56) that indicates whether a leap second will occur at the end of the current month. This allows the RCC to automatically insert the leap second. When a leap second does occur, the final minute of the day has 61 seconds. The UTC sequence looks like this:

23 hours, 59 minutes, 59 seconds

23 hours, 59 minutes, 60 seconds

0 hours, 0 minutes, 0 seconds

In order to properly display the occurrence of a leap second, digital RCCs must be capable of displaying a value of 60 in the seconds' field so that leap seconds can be indicated, for example 11:59:60 p.m. Analog RCCs cannot display a minute containing 60 seconds; therefore the second hand must remain in the same position (pointed straight up) for two consecutive seconds to indicate that a leap second has elapsed.

7.B. Handling of Leap Years

The WWVB time code (Figure 1) contains a leap year indicator (transmitted at second 55) that indicates whether the current year is a leap year. All RCCs that display date information must decode the leap year indicator so that dates after February 28th are correctly displayed. For example, if the RCC assumes that a leap year is a non-leap year, it will display a date of March 1st on February 29th.

The leap year rule is simple, and manufacturers can elect to design products that automatically know whether a year is a leap year by looking at the year code. However, since the WWVB time code uses two-digit year codes (Section 7.C), these must first be converted to four digits before testing to see whether the year is a leap year, due to the problem with centurial years (years that end with 00). Year numbers that are evenly divisible by 4 are leap years, with the exception of centurial years, which must be evenly divisible by 400.[4] Thus, 2000 was a leap year, whereas 2100, 2200, and 2300 will not be leap years. It is highly unlikely that the leap year rule will change, but in the event that it did, we recommend that the leap year information in the time code be used when possible. If the leap year rule is programmed into the product, we recommend that it be used only to backup or verify the time code information.

7.C. Handling of Two-Digit Year Code

The WWVB time code (Figure 1) includes only two digits of year information, so year information is ambiguous to the century. For example, the year 2004 is represented by "04." This is generally not a problem for most RCCs since a twenty-first century consumer viewing the clock will intuitively know that "04" means 2004. However, if the RCC is designed to interface with other devices, such as computer systems, the manufacturer should convert the year information to four digits. Simply adding 2000 to the two-digit year code will keep the four-digit year correct until the year 2100. While this seems like a good solution in the early part of the 21st century, other solutions should be sought if the RCC is expected to output the correct year information indefinitely.

8. RECOMMENDED PRACTICES FOR HARDWARE SPECIFICATIONS

This section discusses hardware specifications for the receiver, antenna, and local oscillator.

8.A. Receiver Specifications

Complete receiver specifications are beyond the scope of this document, but the minimum goal of the manufacturer should be to include a receiver and antenna sufficiently sensitive to work anywhere within the CONUS during the nighttime hours. We recommend that RCC products should be sensitive enough to successfully synchronize to signals from WWVB with a field strength of 50 µV/m, if the signal to noise ratio exceeds 20 dB. The RF bandwidth of the receiver should be narrow, typically ±10 Hz or less.

We recommend that digital signal processing (DSP) firmware be included in the receiver design to improve the RCC's ability to read the time code. The redundancy of the time code information (Figure 1) can be used to considerably improve reception. During a given hour, only the minute information in the time code changes from frame-to-frame (except during the rare hours when leap second, DST, or UT1 information happens to be inserted or deleted). Therefore, the time code normally changes from frame-to-frame in an entirely predictable fashion, which makes bit and frame averaging possible and desirable. When properly implemented, the use of bit and frame averaging can be more effective than increasing the sensitivity of the receiver, or increasing the field strength presented to the RCC by many decibels.

8.B. Antenna Considerations

Although external antennas obviously can provide better reception, we recommend that antennas be embedded inside the casing of the RCC to make the form factor more attractive and to prevent the antenna and/or its connecting wires from being damaged when the device is moved. Wristwatch antennas should not be contained in the band, so that RCC watch bands can be replaced in the same manner as the bands of ordinary watches when they are damaged or worn out. While external antennas are not recommended for stand-alone clocks and watches, they might be desirable for RCCs embedded in other devices, such as appliances.

8.C. Local Oscillator Specifications

As recommended in Section 4.B, all RCCs will attempt to synchronize at least once per day. Therefore, in order to meet the Section 3 requirement of keeping time between synchronizations to within ±0.5 s of UTC(NIST), the local quartz crystal oscillator must keep time to within about 0.48 s (we allow an 0.02 s error for signal propagation and internal clock synchronization delays) during a typical synchronization interval of 24 hours (86400 s). Therefore, the maximum allowable frequency offset of the quartz crystal oscillator, given a time change Δt in a period T, can be calculated as:

$$\frac{\Delta t}{T} = \frac{0.48}{86400} = 5.55 \times 10^{-6}$$

If the RCC uses a crystal oscillator with a nominal frequency of 32768 Hz, the maximum allowable frequency offset from nominal is about 0.18 Hz. If the synchronization period is shortened, for example if the RCC is able to synchronize every 12 h instead of every 24 h, these requirements are relaxed. For example, reducing the synchronization interval by a factor of 2 (from 24 h to 12 h) would double the maximum allowable frequency offset to 0.36 Hz. Care should be taken by the manufacturer to choose a quartz crystal oscillator that is accurate and stable enough to stay within its allowable tolerance over its normal operating temperature range, without requiring adjustment during the expected lifetime of the RCC.

Manufacturers may also choose to employ schemes that digitally compensate for the frequency offset of the quartz crystal, allowing the ±0.5 s/day specification to be met with a less stable oscillator.

8.D. Battery Powered RCCs

If a RCC product is battery powered, we recommend that a "low battery" indicator be included on the display, so the consumers are aware that the battery or batteries need to be changed. When the voltage of a battery-powered device drops below a certain threshold determined by the manufacturer, the clock should stop completely rather than attempt to keep time with an insufficient power supply.

9. RECOMMENDED PRACTICES FOR PRODUCT DOCUMENTATION

Although WWVB RCCs are not technically complex when compared to other consumer electronic products, they do require more documentation than conventional clocks. An instruction sheet or manual that describes how to use all of the product's features should be included with every product sold. We also recommend that all buttons and controls on RCC products be clearly labeled; for example, identify the button(s) or control(s) used to change time zones. The documentation (preferably on the packaging itself) should indicate which time zones are supported by the product, and the approximate coverage area, so that consumers do not mistakenly buy products that won't work in their area. When space allows, such as on the back of a wall clock, it is helpful to engrave or stamp a condensed instruction sheet on the product itself.

Manufacturers are also encouraged to include text in their product documentation that describes how to troubleshoot RCC reception problems. Some examples are provided in Section 11 of this guide.

In numerous cases, consumers have complained that the loss of an instruction manual has made their product unusable. Therefore, we recommend that all instruction manuals for current and past models be made available to consumers on-line, where they can be downloaded free of charge if necessary.

9.A. Mention of NIST

We recommend that instruction manuals for WWVB RCC products mention that National Institute of Standards and Technology (NIST) radio station WWVB, located in Fort Collins, Colorado, is the source of the time signal received by the clock. It also should be noted that NIST is an agency of the United States government that provides official time to the United States. If manufacturers wish to provide a point of contact for obtaining more information about WWVB, they should reference the NIST Time and Frequency Division web site at **http://tf.nist.gov**. However, manufacturers should not direct consumers to NIST for technical support since NIST is unable to provide it.

9.B. Use of "Atomic Clock" Nomenclature

Many WWVB RCC products are labeled (on the product itself or in the documentation) as "atomic clocks." This is probably seen by manufacturers as a useful marketing tool intended to capture the imagination of potential customers, and some might argue that it is appropriate since atomic clocks are located at the WWVB radio transmitter site. However, we contend that use of the term "atomic clock" is technically incorrect and misleading to consumers, and its usage should be avoided. Unless there is actually an atomic oscillator inside the RCC (such as a cesium or rubidium oscillator), we recommend that the term "radio controlled clock" be used to correctly describe the product. Labeling products or documentation with the term "atomic timekeeping" is also considered acceptable.

10. COMPLIANCE CHECKLIST

The checklist below is included to assist both manufacturers and consumers of RCC products. By answering the questions in the table, it can quickly be determined whether or not a given product complies with the recommendations provided in this handbook.

Section	Question	N = Necessary O = Optional	Product Complies with Recommendation (Preferred Answer Is Always Yes)	
			Yes	No
3	Is time always displayed to within ±0.5 s during the entire interval between clock synchronizations?	N		
3	Is time always displayed to within ±0.2 s during the entire interval between clock synchronizations?	O		
3	Does the clock display seconds?	N		
3.A/3.B	Does the clock have a label or icon indicating that it is radio controlled?	N		
3.A/3.B	Does the clock display the date?	O		
3.B	If the clock is digital, does it include a.m. and p.m. indicators?	O		
3.B	Was the clock designed without an icon or picture of a satellite dish on its display?	O		
3.C	Are the clock controls clearly labeled and situated?	N		
3.D	If the clock is capable of receiving more than one time signal station, does it indicate which station it is receiving?	O		
3.E	Does the clock have a way to indicate signal quality?	O		

Section	Question	N=Necessary O=Optional	Product Complies with Recommendation (Preferred Answer Is Always Yes)	
			Yes	No
3.E	Is the signal quality meter not visible or disabled when the clock is not attempting to synchronize?	O		
3.F	Does the case have a marker indicating the orientation of the antenna?	O		
4.A	Does the clock continuously try to synchronize when it is first turned on?	N		
4.A	Does the clock refrain from displaying the time prior to its first synchronization?	N		
4.A	Can the clock synchronize without having the display or hands preset by the consumer?	N		
4.B	Does the clock attempt to synchronize by radio at least once every 24 hours?	N		
4.B	Does the clock attempt to synchronize during the nighttime hours when the signal from WWVB is the strongest?	N		
4.B	Does the clock attempt more than one synchronization every 24 hours?	O		
4.B	Does the clock allow at least five minutes for a synchronization attempt?	N		
4.C	Does the clock include a button or control that allows the consumer to attempt to synchronize at any time?	N		

Section	Question	N = Necessary O = Optional	Product Complies with Recommendation (Preferred Answer Is Always Yes)	
			Yes	No
4.D	Can the clock be set manually, without radio synchronization?	N		
4.E	Does the clock include a synchronization indicator?	N		
5.A	Does the clock allow each of the time zones listed in Table 3 to be selected?	N		
5.A	Does the clock allow each of the time zones listed in Table 4 to be selected?	O		
6	Does the clock automatically adjust on the transition days from ST to DST, and from DST to ST?	N		
6.A	Does the clock change from standard time to DST at 2 a.m. local time and vice versa?	N		
6.B	Does the clock have a way to disable DST for areas that do not observe it?	N		
6.C	Does the clock include a DST indicator?	O		
7.A	Does the clock properly handle leap seconds?	O		
7.B	If the clock displays date information, does it properly handle leap years?	N		
7.C	If the clock displays four-digit year information, does it properly handle the two-digit year code?	O		

Section	**Question**	**N = Necessary O = Optional**	**Product Complies with Recommendation (Preferred Answer Is Always Yes)**	
			Yes	**No**
8.A	Does the clock's receiver meet specifications?	N		
8.B	Is the antenna concealed inside the clock unit?	O		
8.C	Does the local oscillator meet specifications?	N		
8.D	If the clock is powered by batteries, is a "low battery" indicator included?	O		
9	In the case of wall clocks, are condensed instructions included on the product itself?	O		
9	Does the manufacturer make instructions manuals for the clock available on-line?	O		
9.A	Does the product documentation mention NIST and WWVB?	O		
9.B	Does the product documentation and/or labeling use the term "radio controlled clock" or "atomic timekeeping," instead of the incorrect "atomic clock?"	O		

11. RECOMMENDED PRACTICES FOR CONSUMERS OF WWVB RCCS

The first and foremost reason that consumers purchase RCCs is accuracy. A RCC has a tremendous advantage over a conventional clock: when working properly, it is always right! Consumers never need to adjust a RCC, not even during the transition between daylight saving time and standard time. However, this section covers a few items that consumers need to know about to ensure that their RCC is working properly and providing the correct time.

11.A. How a WWVB RCC Works

WWVB RCCs are conventional quartz clocks with a miniature radio receiver inside that is permanently tuned to receive the 60 kHz signal from NIST radio station WWVB (Section 2). This station is located near Fort Collins, Colorado, about 100 km north of Denver. It broadcasts a time signal continuously, 24 hours per day, 7 days per week, with a complete time message (called a time code) sent every minute. However, RCC products only attempt to read this time code periodically, often only once every 24 hours, typically during the night when the signal is strongest (Section 4.B).

The 60 kHz signal is located in a part of the radio spectrum called LF, which stands for low frequency. This is an appropriate name, because the FM radio and TV broadcasts that we are accustomed to listening to use frequencies thousands of times higher. The lowest frequency received by any other consumer radio is probably 530 kHz, the bottom of the AM broadcast band, and even that frequency is nearly nine times higher than the WWVB frequency.

The 60 kHz signal does not provide enough bandwidth to carry audio information. Instead, all that is sent is a time code. The time code is simply a message containing time and date information. This information is sent in the form of binary digits, or bits, which have two possible values (0 or 1). Frame markers are also sent as part of the message, so the RCC can align the time code and read the bits in their proper order. The time code bits are generated by raising and lowering the power of the WWVB signals. They are sent at a very slow rate of 1 bit per second, and it takes a full minute to send a complete time code or a message that tells the clock the current date and time. When a RCC is first turned on, it will probably miss the first time code, so it usually takes at least two minutes to synchronize, depending upon the signal quality and the receiver design.

11.B. Time Zone Settings

Since the WWVB signal originates from a single location in Colorado, it does not contain any time zone information. Therefore, WWVB RCCs can not determine which time zone they are in unless this information is supplied by the consumer. Well-designed products (Section 5) allow the selection of all time zones where the clock could possibly be used.

The time broadcast by WWVB is Coordinated Universal Time (UTC), or the time kept at the Prime Meridian that passes through Greenwich, England. Clocks all over the world are synchronized to the same second as UTC in all cases and the same minute as UTC in nearly all cases.* However, the local hour is different than the UTC hour, based on the number of time zones between the local time zone and the Prime Meridian. While a few consumers want their clocks to display UTC (ham radio operators, for example), most prefer to display local time. WWVB RCCs apply a time zone correction of the UTC hour to convert UTC to local time. The size of this correction is shown in Table 5 for the four major time zones in CONUS.

When consumers move a WWVB RCC to another time zone, they need to change the time zone setting accordingly. Consumers that travel with RCCs should familiarize themselves with the procedure for changing time zones, so they can adjust their clocks whenever necessary.

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* A few time zones (Table 4) differ from UTC by a non-integer number of hours (3.5 hours, for example). Clocks synchronized to local time in these regions will display a different minute than a clock synchronized to UTC, but the second will be the same.

Table 5: **Difference between UTC and Local Time for the Four Major Time Zones in the CONUS**

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

11.C. Coverage Area of the WWVB Signal

During the nighttime hours, the WWVB signal is strong enough to synchronize clocks in the 48 states of the CONUS, in parts of Alaska and Hawaii, in all of Mexico, in most of the populated areas of Canada, and in some regions of Central and South America. (For coverage maps and signal strength information recorded at various sites, see **http://tf.nist.gov/stations/wwvb.htm**.)

The size of the coverage area is estimated using a field strength figure of 100 μV/m, which in theory is more than enough signal for a well-designed RCC to synchronize (Section 8.A). However, in practice, simply having a large signal doesn't mean that a RCC will be able to work. What really matters is the signal-to-noise ratio, or the size of the signal compared to the size of the electrical noise near the same frequency. Raising the noise level is just as harmful as reducing the signal level. For example, if the RCC clock is near a source of interference, the noise level increases, and the clock might not be able to synchronize even if the local field strength of the time signal is high. Potential sources of interference are discussed in Section 11.D.1.

11.D. General Troubleshooting Tips for WWVB RCCs

WWVB RCC products have different specifications, and use different controls and user interfaces, so technical support must be provided by the manufacturer and not by NIST. We recommend that consumers save the instruction sheets that come with their clocks, so they can refer to them in the future if necessary. Having said that, this section offers a few general tips for consumers whose RCCs aren't displaying the correct time.

Nearly all problems reported by consumers with WWVB RCCs are related to the clock itself and not to the WWVB broadcast. Consumers should be aware that RCC problems caused by the WWVB broadcast are extremely rare. WWVB has a number of safeguards in place to help ensure that the correct time is always being broadcast, and time is kept at the station to within 100 nanoseconds of UTC.[2] The station does occasionally have signal outages, and all outages over five minutes in length are reported on the WWVB web site (**http://tf.nist.gov/stations/wwvb.htm**). However, most outages are maintenance related and occur in the daytime hours when RCCs are not attempting to synchronize, so they have no effect on consumer products. Unplanned outages during the nighttime hours are responded to as quickly as possible and rarely last for more than 1 or 2 hours. While it is possible that one of these outages can cause a RCC to miss one daily synchronization period, it is highly unlikely that this will happen two days in a row. Field strength varies due to the time of year and the current weather conditions, but it should be sufficient for RCCs in the CONUS to synchronize during each night of the year.

Consumers who suspect that their WWVB RCC is not displaying the correct time can check it by comparing it to other NIST time services, including the NIST web clock (**http://nist.time.gov**) or the audio time signals from NIST radio stations WWV and WWVH.[1] The audio time signals can be heard using a shortwave radio or by telephone (dial 303−499−7111). WWVB RCCs should be within ±0.5 s of either source. Please note that the NIST web clock allows time zone selection and displays local time, but consumers must convert from UTC to get local time from WWV or WWVH (Table 5).

11.D.1. General Troubleshooting Tips for RCCs That Won't Synchronize at All

If their RCC won't synchronize, we recommend that consumers try the following:

- If the RCC uses batteries, check them and replace if necessary. Low batteries can cause a variety of RCC problems. If the RCC used to work, but doesn't work now, try changing the batteries before deciding it has failed.

- If you have a desktop RCC, try rotating it 90°. If you have a wall clock, try mounting it on a wall perpendicular to the one it is currently on (*e.g.*, if it is on a north–south wall try an east–west wall). The antennas are directional, and reception can be improved by turning the antenna. If your RCC has a signal quality indicator and antenna orientation markers (Sections 3.E and 3.F), use them to help determine the proper antenna orientation.

- Place the RCC along a wall or near a window that faces Fort Collins, Colorado.

- If you are staying in a hotel and traveling with a WWVB alarm clock or wristwatch, it will probably work best if you leave it near the window overnight.

- If you have a WWVB wristwatch, remove it from your wrist at night so that it is motionless during the synchronization period (Section 4.B).

- Locate the clock away from the potential sources of interference listed in Table 6.

Table 6: **Potential Sources of Interference for WWVB RCCs**

Source of interference	**Reason for interference**
Computer monitors and televisions	Some monitors have a scan frequency at or near the WWVB carrier frequency of 60 kHz. Place RCCs at least 1 to 2 meters away from computer monitors or televisions for best results.
Metal or ferroconcrete buildings	Buildings made out of metal (such as mobile homes) or buildings with metal roofs or steel siding might prevent the clock from working by blocking or weakening the incoming signal. Ferroconcrete buildings (where the concrete has metal added to provide extra support), can also interfere with the signals. Place the clock near a window to give it the best chance of synchronizing.
Refrigerators, air conditioners, household appliances, or other devices with electric motors	Electric motors can generate radio frequency interference (RFI) at the AC line frequency of 60 Hz, which is a subharmonic of the 60 kHz WWVB carrier. Place the RCC at least 1 or 2 meters away from these devices for best results.
Basements or underground locations	WWVB signals can reach underground locations better than higher frequency signals, but the signal quality will be lessened if the RCC is placed in a basement. Also, basement walls are often made of ferroconcrete material (see above). Try placing the clock above the ground if it doesn't work in a basement location.
Neon or fluorescent lights	Neon or fluorescent lights can sometimes emit RFI that interferes with RCCs. If consumers suspect that lights are producing RFI, they can perform a simple test with a battery-powered AM radio. The radio should be tuned to a dial location between stations so that only noise is heard.

Table 6: **Potential Sources of Interference for WWVB RCCs** *(continued)*

Source of interference	**Reason for interference**
Neon or fluorescent lights *(continued)*	If possible, turn off the lights to see if this noise level goes down. If it is not possible to turn off the light, walk towards the light with the radio to see if the noise increases. Try placing the RCC where the noise level is lowest to see if that helps.
Electrical storms	Electrical storms can generate RFI in the part of the spectrum used by WWVB. Lightning along the path between the consumer's receiver and Fort Collins, Colorado, can potentially cause an RCC to miss a scheduled synchronization, but the problem should cease when the storm is over.
Overhead electrical wires or other equipment related to electrical power generation	The 60 Hz RFI emitted by electrical wires or power generating equipment can be a problem since it is a subharmonic of the 60 kHz WWVB carrier. Try moving the RCC as far from the RFI source as possible.
Broadcasting stations	RCCs located near a radio or television station can be overloaded by the local signal. This can be a particular problem if 60 kHz is a subharmonic of the local carrier.

If nothing else works, we recommend that consumers take the clock outdoors after dark and power it down (remove the batteries or unplug it), then power it up again to force it to look for the WWVB signal. If it works outdoors but not indoors, there is probably a local interference problem inside the building where the clock is located. If it doesn't work outdoors at night, it's probably best to return it and try a different model.

Keep in mind that not all WWVB RCCs are created equal. Consumers who think their clock is defective or that it is simply unable to work at their location should ask the manufacturer or dealer for a replacement.

11.D.2. General Troubleshooting Tips for RCCs Off by One Hour or More

Remember, minutes and seconds are the same in nearly all time zones, only hours are different. Therefore, if a clock is off by exactly one hour or by a multiple of exactly one hour, it probably has to do with a time zone setting. Consumers should make sure that they have properly selected their local time zone using the instructions that came with the RCC. If the clock does not have a setting for the consumer's local time zone (Section 5.A), we recommend that they return it to the dealer. Consumers outside the CONUS should make sure that a RCC product handles their time zone prior to purchasing it.

Consumers who live in areas that do not observe Daylight Saving Time (Figure 9) must make sure that DST is disabled on their RCC (Section 6.B). If the RCC lacks this feature, consumers might still be able to select another time zone to make the RCC display the correct time when DST is in effect.

11.D.3. General Troubleshooting Tips for RCCs Off by a Few Minutes or Seconds

Properly working and designed RCCs should display time accurate to within ±0.5 s or better (Section 3). However, a malfunctioning RCC can be off by a few seconds or even minutes, for the reasons listed below:

- **Reception Problem** — If a RCC isn't receiving the signals from WWVB at least once per day, the time will "drift" and gradually get further and further from the correct time. Remember, if WWVB isn't being received, the clock is no longer radio controlled, it's just a conventional quartz clock. Its accuracy will then depend on the quality of the quartz crystal (Section 8.C). Most quartz clocks can keep time to 1 s per day or better, but some could be off by several seconds per day and a time error always accumulates between synchronizations. Consumers are advised to purchase only RCCs with synchronization indicators (Section 4.E), so they will know whether or not the clock has recently synchronized. If the product does not have a synchronization indicator and the consumer cannot tell if the signal is being received, we recommend powering down the clock (by unplugging it or removing the batteries), then powering it up again to see if it can synchronize. If it doesn't, see Section 11.D.1 for tips on improving reception.

- **Alignment Problem** — Some consumers might obtain analog RCCs whose hands aren't properly aligned. This could cause the clock to be off by 1 s or more even if it is receiving the signal properly. The clock might not have been properly aligned at the factory, or it might have been jostled during shipment, causing the hands to move. Some manufacturers explain how to align the hands on their instruction sheet. If the consumer is unable to do this, and if the small error bothers them, we recommend that they return the clock to the dealer for replacement.
- **Parallax Problem** — The parallax problem refers to the apparent shifting of an object when viewed at different angles and can prevent problems when viewing analog RCCs. When consumers check the accuracy of an analog RCC, they need to be sure they are looking straight at the clock face and not viewing it from an angle. Consumers who view the clock from an angle might think it is off by a few seconds even if it is not. This is similar to trying to read the speedometer from the passenger seat of a car and thinking the speed is faster or slower than it actually is.

11.D.4. General Troubleshooting Tips Concerning Daylight Saving Time (DST)

Problems related to DST are among the most common problems experienced by RCC consumers. If a RCC doesn't change during the transition from DST to standard time, or vice versa, it probably means that it has not received the signal recently, so it didn't know about the time change. See Sections 11.D.1 and 11.D.3 for tips on improving reception.

If reception appears to be fine and the RCC didn't change, consumers should make sure that DST is not disabled on their RCC (Section 6.B), if their area observes DST. Conversely, if the area does not observe DST and the RCC did change, consumers need to disable the DST setting.

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WWVB IMPROVEMENTS:

New Power from an Old Timer

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Abstract

In response to advancements in receivers and increased emphasis of traceability of frequency to the national standard, the time-and-frequency radio station, WWVB, of the National Institute of Standards and Technology (NIST) recently underwent numerous improvements, including a 7 dB boost in radiated power, resulting in significantly greater signal availability throughout North America. This paper describes the history of WWVB, the improvements recently made to the station, theoretical coverage, and consumer-oriented receivers projected to number in the millions of units in the next few years.

1 INTRODUCTION

1.1 HISTORY OF VLF/LF IN TIME AND FREQUENCY BROADCASTS

The U.S. Naval Observatory broke new ground in 1904 when it broadcast an experimental time transmission from the city of Boston as an aid to navigation. Soon it was recognized that large areas could be covered and that navigation would benefit from accurate broadcasts of time and frequency at very low and low frequencies (VLF/LF). Other applications were developed as well. For example, as the airwaves became more crowded a means was needed to calibrate radio equipment. WWV, a high-frequency (HF) station that currently coexists at the WWVB site, started out as an LF station in 1923. It broadcast standard “wave” signals to the public on frequencies ranging from 75-2000 kHz.

Since about 1960 the Navy has used its VLF stations for transmitting precise frequencies.

Another source of time and frequency was the Omega Navigation system, which just recently ceased operation. It transmitted accurate navigation signals around 10 kHz. At this low frequency, changes in phase are easily noted and position can be determined to a high degree of accuracy. The long-range navigation (LORAN) system, which began development during WWII, operates around 100 kHz. By having stable and accurate LORAN transmissions, ships and aircraft can find their position with excellent accuracy. LORAN is also used as a frequency reference.

1.2 FREQUENCY ALLOCATION IN ITU REGIONS 1, 2, AND 3

The International Telecommunication Union (ITU), which is an agency of the United Nations, has divided the globe into three regions. (Figure 1) In order to minimize interference between radio broadcasts, frequency allocations are determined for each region at the World Administrative Radio Conferences held every 2 years. VLF and LF time and frequency broadcasts in all three regions are 14-19.95 kHz, 20 kHz, and 20.05-70 kHz. Region 1 also uses 72-84 kHz and 86-90 kHz.

1.3 PROPAGATION CHARACTERISTICS

The propagation of VLF/LF electromagnetic energy has many properties that make VLF/LF well suited for time and frequency transfer. At these longer wavelengths, losses in the earth's surface are low. Thus, the ground wave can travel well for thousands of kilometers and moderate amounts of power can cover large portions of a hemisphere. Other advantages are stable path, low attenuation by the atmosphere, and reliability during ionospheric disturbances. These characteristics make it possible to transfer frequency with an uncertainty of $< 1 \times 10^{-11}$, and to transfer time with an uncertainty of < 100 us (calibrated for path delay.)

1.4 EXISTING STATIONS

Numerous stations worldwide are broadcasting time and frequency standards via VLF/LF and more are planned. Many of these stations are designated as navigation systems. Some, such as WWVB, are used to distribute the standard second to the public.

2 WWVB BEFORE UPGRADE

2.1 HISTORY OF WWVB AND WWVL

The first standard frequency broadcast of 60 kHz started in July 1956, from Station KK2XEI. This 2 kW transmitter (located at the National Bureau of Standards (NBS) in Boulder, Colorado) was the forerunner of WWVB. The radiated signal was less than 2 watts but was monitored at Harvard University in Massachusetts. The purpose of this experimental transmission was to show that the frequency error due to Doppler shift induced by the ionosphere was small.

NBS (currently NIST) also began an experimental VLF standard frequency broadcast from a valley span antenna at Sunset, Colorado, just northwest of Boulder in April 1960. This signal, though less than 15 watts, was observed in New Zealand.

In 1962, NBS began construction of a transmitter site north of Fort Collins, Colorado, to be the new home of radio stations WWVB and WWVL. The 390-acre site was selected because of its exceptionally high ground conductivity, which was due to the high alkalinity of the soil. WWVB became operational at the Fort Collins site on July 5, 1963, transmitting a 7 kW standard 60 kHz signal. Housed in the same transmitter building was WWVL, which began transmitting a 500 watt standard 20 kHz signal in August 1963.

On July 1, 1965, WWVB added a time code to its broadcast. This time code is sent in binary-coded decimal (BCD) format. Bits are sent by shifting the power of the carrier. During the mid-1960s improvements to the station raised the power level to approximately 13 kW and the power of the WWVL signal was raised to 1 kW. On July 1, 1972, WWVL transmissions were ended and WWVL was no longer in service. WWVB continued to broadcast its time code, but its equipment was aging and lacked good documentation.

2.2 DESCRIPTION OF WWVB AND WWVL ANTENNA SYSTEMS

When the new site for the NBS stations was established in 1962, two identical antennas were constructed. The north antenna was built for the WWVL 20 kHz broadcast, and the south antenna was built for the WWVB 60 kHz broadcast. The configuration chosen for each antenna was a top loaded dipole. Each antenna consisted of four 122-m masts arranged in a diamond shape. (Figure 2) Suspended between the four towers was a system of heavy cables, often called a capacitance hat or top hat. This top hat was electrically isolated from the towers, and it was electrically connected to a downlead that was suspended from the center of the top hat. The downlead was the radiating element.

Ideally, to have an efficient radiating system, the radiating element needs to be at least a one-quarter wavelength long. At 60 kHz, where the wavelength is nearly 5000 m, it is impossible to have the desired one-quarter wavelength antenna since it would be 1,250 m tall. However, a compromise can be made by building the radiating element as tall as possible and adding some of the missing length horizontally to the top of this vertical dipole. Even with the top load the WWVB and WWVL antennas were still only a fraction of the transmitted wavelength, and were inherently capacitive and had a small radiation resistance.

The downlead of each antenna was terminated at its own helix house under the top hats. The helix houses each contained a large inductor to cancel the capacitance of the short antenna and a variometer (variable inductor) to tune the antenna system during periods when snow or wind loaded the antenna.

Energy was fed from the transmitters to the helix houses on a 500 ohm open-air balanced transmission line that ran approximately 435 m to each house. The many utility poles that held up the transmission lines became cracked and damaged over the years.

When WWVL ceased operation in 1972, its 20 kHz antenna was rematched to a WWVB transmitter to operate as an emergency standby 60 kHz antenna. However, it rarely saw any service.

2.3 DESCRIPTION OF WWVB TRANSMITTERS

Not much is known about the origins of the two transmitters that carried the WWVB broadcast for so long. They were nicknamed “Blue” and “Gray” in reference to their color. They are thought to be WWII era HF transmitters that were highly modified. Gray served as the primary transmitter and Blue served as the backup. Either could be switched into the 500 ohm balanced feed line that ran to the helix house where it was matched to the antenna.

2.4 PERFORMANCE EVALUATION

Except for the occasional equipment fault, WWVB broadcast for many decades without significant interruption in service. Enough redundancy was built in so that backup systems could restore the time code signal until an electronics technician could respond to the original problem.

One significant problem was that the WWVB antenna was subject to icing, which could occur once or twice each winter. Most icing "events" were inconvenient but short-lived. When conditions were right, frost would form around 4 or 5 am and be gone by 8 or 9 am as the sun came out and the temperature rose. Radiated power would drop due to resistive losses across frost-covered insulators and the variometer would approach it tuning limit as the ice distorted the antenna.

On the morning of February 7, 1994, a heavy mist froze to the antenna and the temperature dropped below freezing for two days. The variometer reached its tuning limit and the broadcast was interrupted. For approximately 30 hours the broadcast was off, becoming an inconvenience for users across North America. Brainstorming about solutions to the icing problem made it apparent that any quick fixes would be too expensive for what would be gained. The entire WWVB system needed to be rethought.

Before an adequate solution could be found, it would be beneficial to start with baseline measurements to determine which areas would benefit most from improvements. The Naval Command, Control and Ocean Surveillance Center Research, Development, Test and Evaluation Division (NraD) and the Pacific Sierra Research Corporation (PSR) accomplished this in October 1994. The antenna measurements are summarized in Table 1. A model of the antennas is shown in Figure 3.

One of the positive findings in the report was that the arid Colorado climate has protected the overall antenna system well. Another result of the measurements was the proposition that using the WWVB and the WWVL antennas in parallel could increase the efficiency of the entire system.

3 ENGINEERING STUDIES

3.1 A NEW STATION IS ENVISIONED

In November 1996, PSR submitted an engineering plan to NIST that laid out the overall concept of how WWVB could be modified to negate the effects of icing, improve reliability, and increase the radiated signal power by at least 6 dB. The plan suggested replacing Blue and Gray with three more powerful, modern transmitters; replacing the open balanced transmission line with a buried 8 cm diameter 50 ohm semi-ridged coaxial cable; and replacing the helix and variometer in the helix house with a variometer having a greater tuning range.

3.2 THE SEARCH FOR NEW HARDWARE

Every effort was made to seek out affordable, high quality parts and equipment for the entire system. It was difficult to find "off the shelf" LF parts. Insulators had to be ordered and many parts had to be handmade. Nearly one kilometer of 50 ohm coaxial cable was purchased and installed in trenches to the helix houses. Some old vacuum tube equipment was also replaced with new solid-state components.

3.3 EQUIPMENT RECYCLED

When new equipment could not be purchased or fabricated it was acquired from surplus. Careful searching, good communication and cooperation with other departments at the highest levels made acquisition of surplus equipment possible. The late Secretary of Commerce Ron Brown petitioned John Dalton, the Secretary of the Navy, for three FRT-72 transmitters that were available from Navy operations in Virginia, Scotland, and Iceland. Two variometers with extended tuning capability came from the decommissioned Navy LF station NSS in Annapolis, Maryland. Several trips were made to La Moure, North Dakota, by NIST staff to obtain Litz wire and other components that would be used in the WWVB helix houses. One of the largest contributions of recycled equipment came from the old WWVL system, which had been virtually unused for

25 years. The WWVL antenna would make it possible to continue the WWVB broadcast uninterrupted as the WWVB antenna system was rebuilt and later would make the more efficient dual antenna system possible.

One of the greatest challenges was to build the new WWVB system while keeping both the current WWVB and the HF station WWV operational. This would have to be done with the current staff at the station, a minimum of contractors, and some staff from the Boulder NIST Time and Frequency Division when they could be spared from their own duties. Also, during this time, fewer standby options would be available during construction in the helix houses or on one of the antenna systems.

4 THE WWVB UPGRADE AND FINAL SYSTEM

The upgrade to the WWVB system went through several phases over the six years it took to complete. The first realistic short-term goal was to improve the radiated power by 4 dB. This could be done quickly by matching one antenna and one 50 kW transmitter, then using the transmitter it had replaced as a standby. This 4 dB increase of radiated power was achieved on December 19, 1997. This provided users with greater signal strength until the south helix house could be rebuilt and two more FRT-72 transmitters installed. Also, the means to combine the north and south systems needed to be completed. The second increase of 3 dB was completed on August 5, 1999.

4.1 SCHEMATIC OF NEW SYSTEM

The final configuration of the WWVB system consists of one FRT-72 transmitter delivering an amplified time code signal into the north antenna system, and one FRT-72 transmitter feeding the south antenna system. (Figures 4 and 5) The low-level time code is fed to the console where it is passed through a control system and then delivered to the two operating transmitters. The matrix controls the system by providing the operator’s selections at the matrix to a programmable logic controller (PLC).

4.2 DESCRIPTION OF TRANSMITTERS

There are a total of three FRT-72 transmitters at the WWVB site. Two are in constant operation and one serves as a standby. Each FRT-72 transmitter consists of two identical power amplifiers (PA), which are combined to produce the greatly amplified signal sent to the antenna. (Figure 6) Each of the two power amplifiers consists of two 4CX15000 tubes in a push-pull configuration. The front end of each transmitter has been replaced with a solid state amplifier that provides a 200-watt drive signal to the grids of the FRT-72 PA tubes, which are biased as class AB amplifiers.

4.3 DESCRIPTION OF ANTENNA SYSTEMS

Probably the most radical change to the WWVB system occurred in the antenna systems. As mentioned earlier, the arid Colorado climate inflicted little aging on the antenna. All antenna parts that were sound were cleaned and inspected. When new or higher quality materials were available, deteriorating items were replaced. The antennas were fitted with new high voltage insulators; also, both downleads are now steel core aluminum cable. All electrical and mechanical connections were inspected and cleaned and broken parts were replaced.

The helix houses were gutted and refitted with the surplus variometers, loading coil, and RF switches that could enable the station to switch from one to two antenna operation. Between the helix houses fill dirt was brought in, compacted and trenched, and the trenches were lined with concrete. For greater protection, the new 50 ohm coaxial cable along with all new control and power cables were laid in the trench.

A matrix was installed to enable an operator to select which transmitter will go into a particular antenna or dummy load. Automatic tuning was added to provide a dynamic match between the transmitter and the antenna system during icy and/or windy conditions. When operating in "single" mode, the PLC looks for a phase difference between voltage and current at the PA. If one is detected, an error signal is sent to a 3-phase motor in the helix house that rotates the rotor inside the variometer. This retunes the antenna and restores the match between the antenna and transmitter. While operating in dual mode (one transmitter in each antenna) one transmitter acts as the master and the other is the slave. The difference in phase between voltage and current at the PA is sensed at only one transmitter, but is used to tune both antennas.

4.4 THEORETICAL EFFICIENCY OF SYSTEM

An advantage at low frequencies, such as 60 kHz, is that even low power signals propagate well. As mentioned in section 2.2, a disadvantage of an antenna system for these low frequencies is that its physical length is much less than a quarter wavelength. As the length of a vertical radiator becomes shorter compared to wavelength, the radiation resistance falls quickly and the ratio of radiation resistance (R_{rad}) to gross resistance ($R_{gross} = R_{rad}$ + resistance due to losses) becomes small. The efficiency of the north antenna system was determined to be 50.6% (R_{gross}=0.91 ohms, R_{rad}=0.46 ohms.) The south antenna had an efficiency of 57.5% (R_{gross}=0.80 ohms, R_{rad}=0.46 ohms.)

The first phase of the upgrade (completed in December 1997) permitted the use of one FRT-72 to the north antenna system. A forward power of 50 kW produced a radiated power of about 25 kW. One advantage of transmitting from each antenna is that the combined system produces a total efficiency of 65%. Now with a forward power from each transmitter of only 38 kW, the combination of the two transmitting systems will produce a radiated power of 50 kW.

4.5 WWVB COVERAGE

One benefit of the dual antenna operation is that there is a 1 dB increase of power in the east to west direction over that of an omni-directional pattern due to the antenna pattern "lobes" created by this phased array. NRaD has also created computer models that predict signal strength. (Figures 7-10) Note that the coverage area is much larger at night. Signal strength charts in dB above one microvolt per meter were also generated. (Figures 11-14) Also, the Y axis of these figures can be stated in microvolts per meter, where 10db equals 3.2uv/m, 20db equals 10uv/m, 30db equals 32uv/m, 40db equals 100uv/m, etc.

5 SUMMARY

Radio broadcasts of time and frequency, now nearly 100 years old, will continue with new vigor into the next century. After 35 years of operation, NIST radio station WWVB has undergone a thorough redesign and rebuilding of its transmitter facilities that will increase its usefulness and availability to the public for years to come. Through the efforts of many people, WWVB has acquired and installed high quality U.S. Navy transmitters and variometers. The former WWVL 20 kHz antenna system was also returned to full-time operation as part of WWVB. These improvements enable NIST to provide dependable time and frequency dissemination even in inclement weather. The demand for this service is constantly growing as manufacturers continue to create new, lower cost products, all in an effort to place "Atomic Time" in every home and office.

More information about WWVB and its time code can be found at the NIST Time and Frequency web site: http://www.boulder.nist.gov/timefreq.

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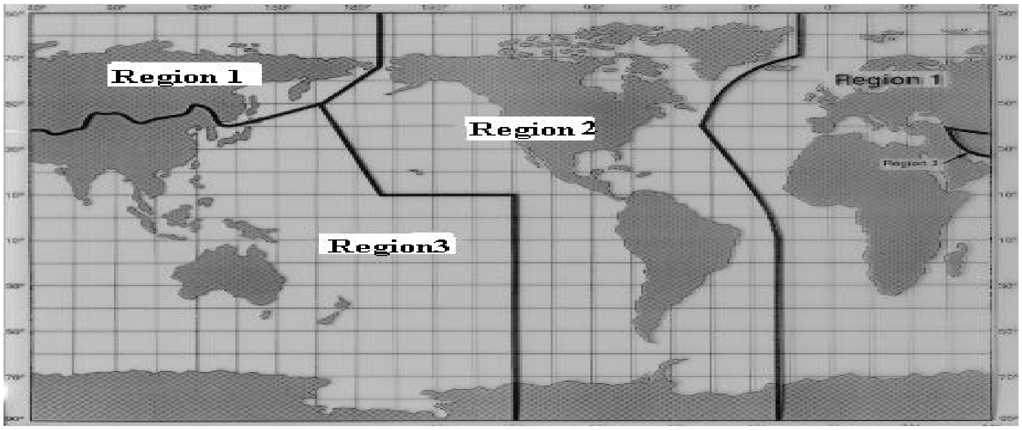

Figure 1 Map of ITU Regions

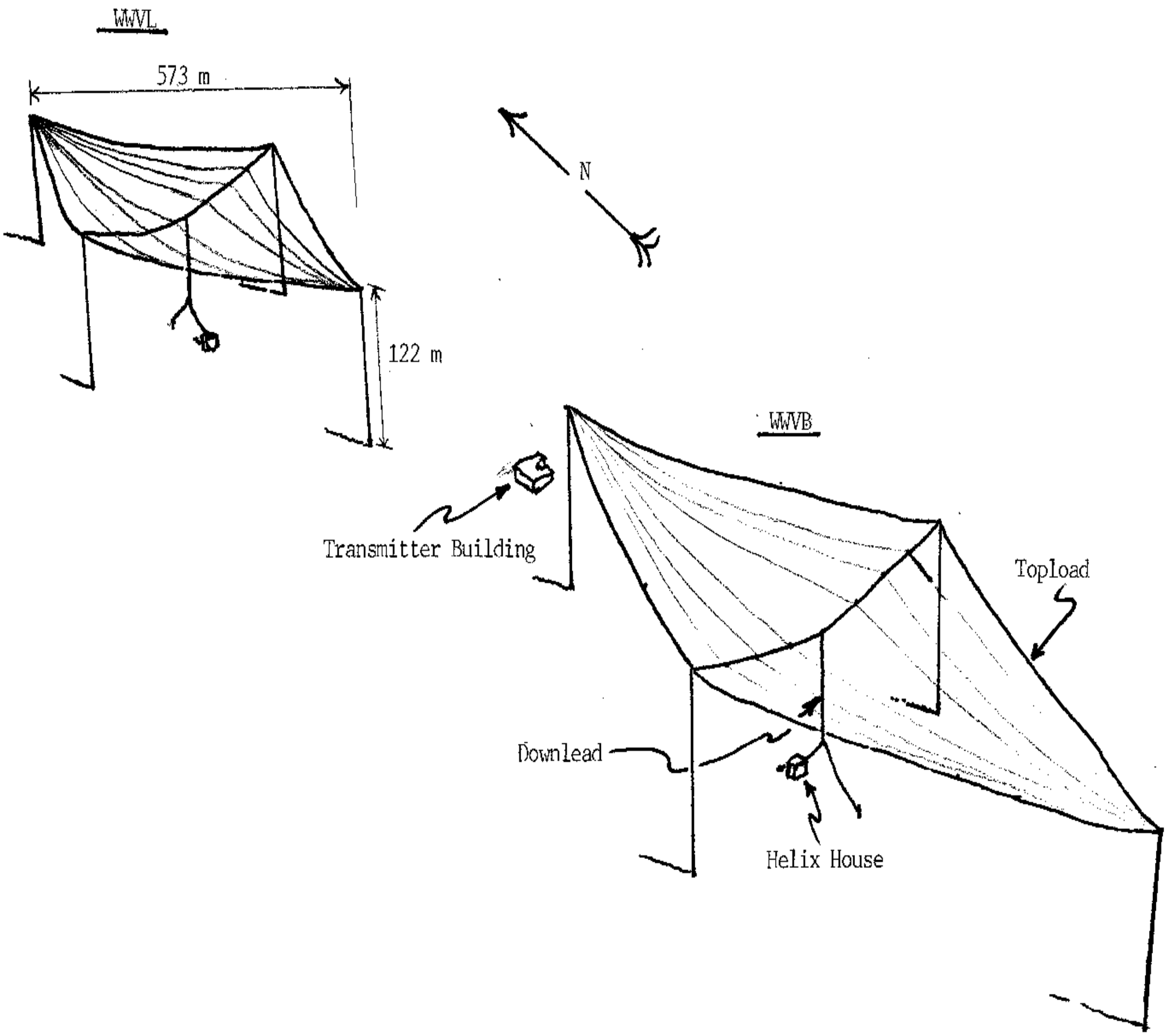

Figure 2 WWVB and WWVL Antenna Systems

Shunt Capacitance (Cs) = 1.06 nF (south), 1.00 nF (north)
Downlead Inductance (Id) = 208.8 uH (s), 208 uH (n)
Toplaod Capacitance (Ct) = 13.6 nF (both antennas)
Antenna Resistance (Ra) = 0.80 ohms (s), 0.91 ohms (n)

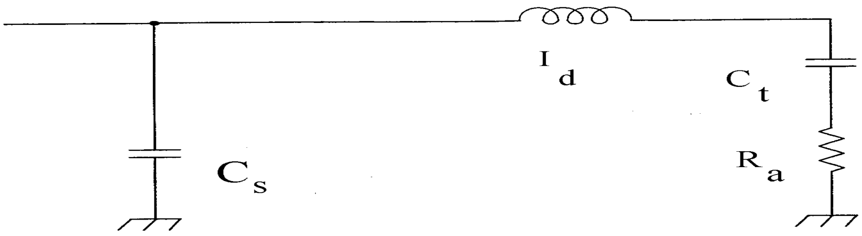

Figure 3
Antenna model and component values for WWVB and WWVL.

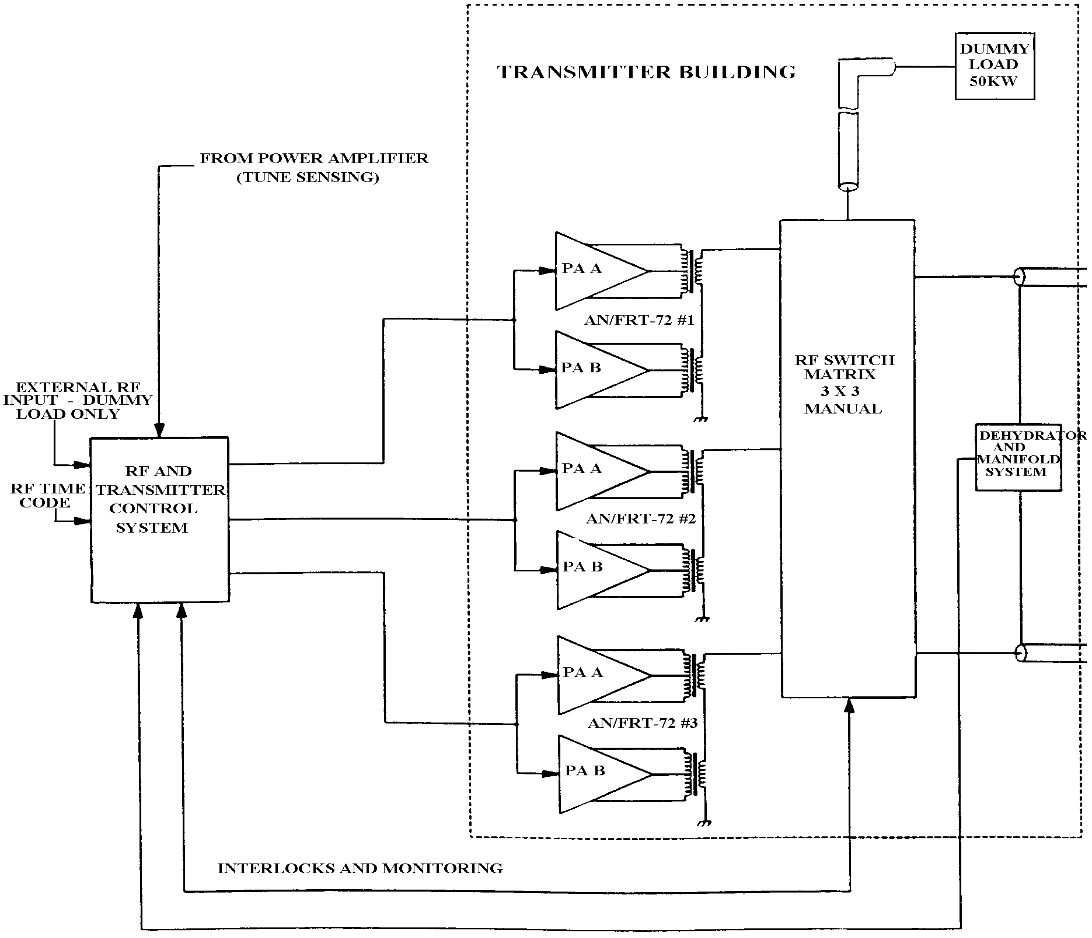

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Figure 4
Block diagram of WWVB transmitter room.

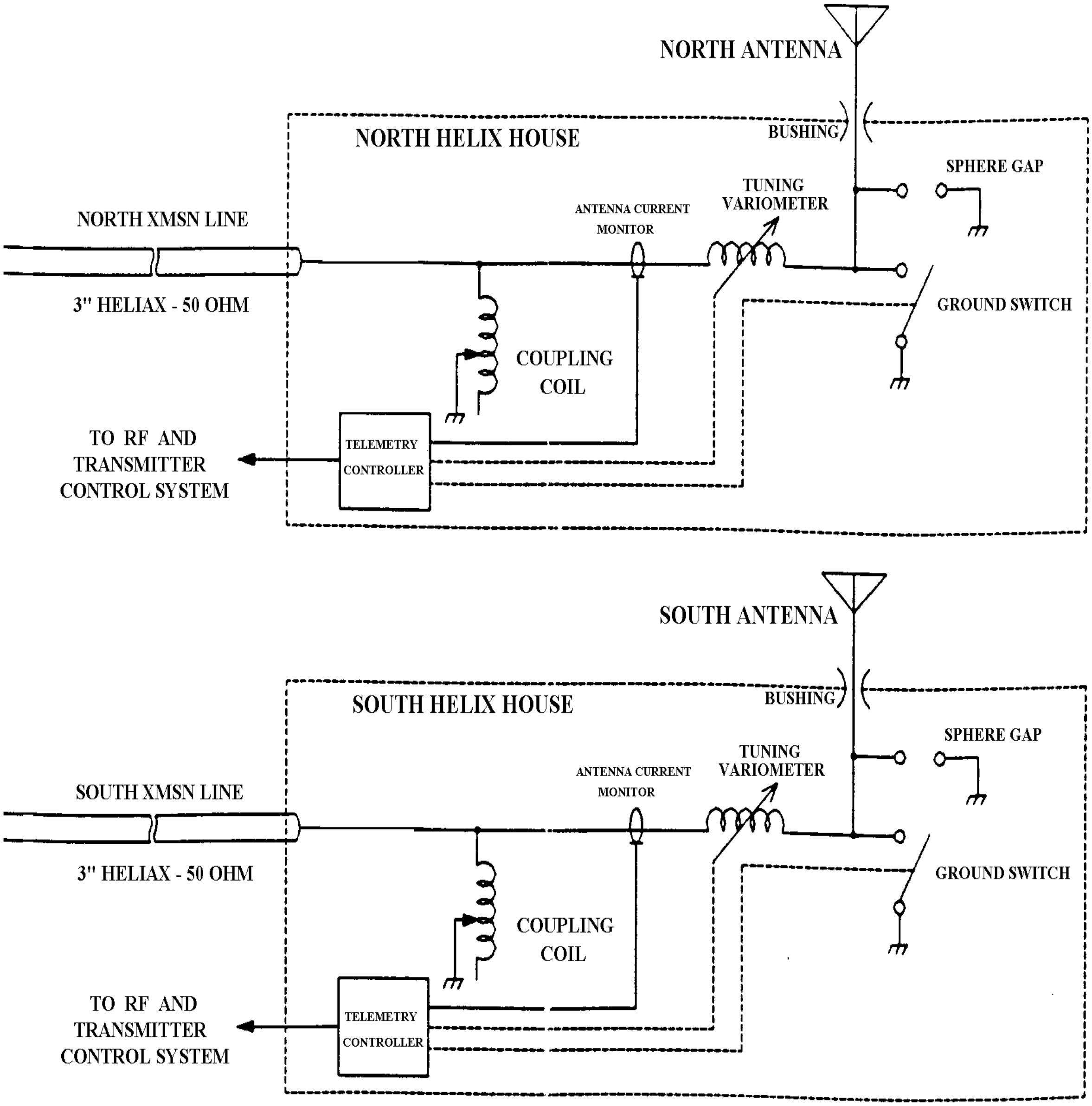

Figure 5
Block diagram of WWVB helix houses.

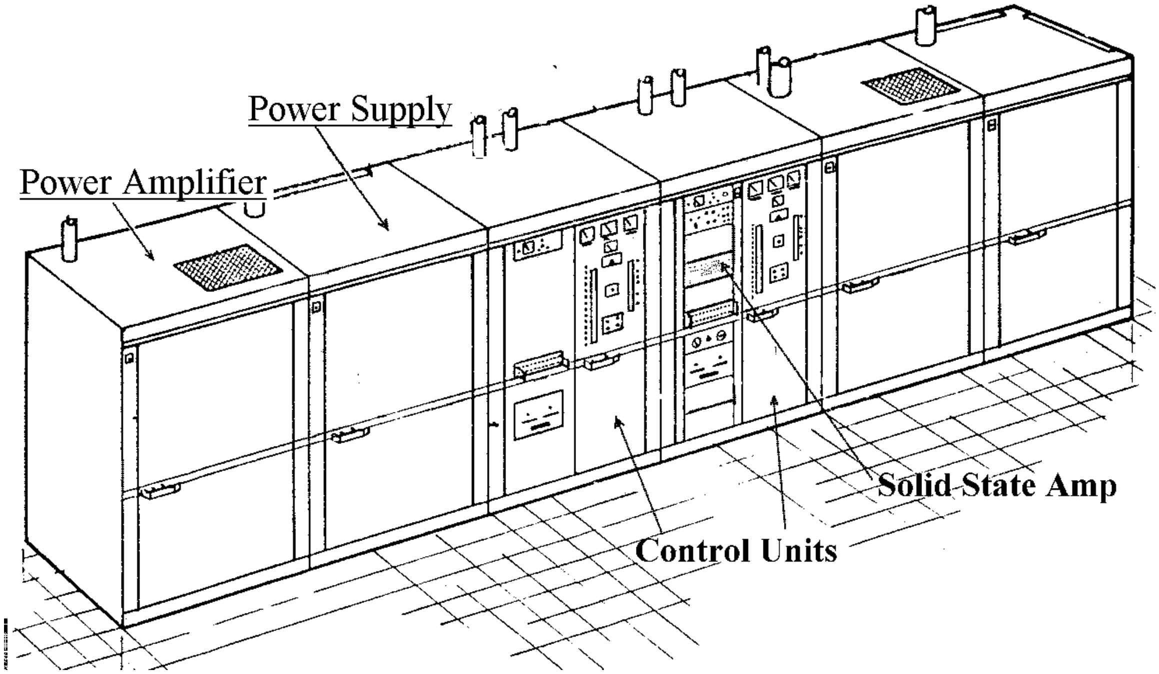

Figure 6
Diagram of FRT-72

60 kHz Parameters	South Antenna	North Antenna
Radiation Resistance (Ohms)	0.46	0.46
Antenna Gross Resistance (Ohms)	0.80	0.91
Antenna Radiation Efficiency	57.5%	50.6%
Antenna Base Reactance (Ohms)	-114.9	-112.9
Antenna Downlead Inductance (microheneries)	208.8	208.0

Table 1
Measured antenna parameters at 60 kHz for both the north (WWVL) and south (WWVB) antennas.

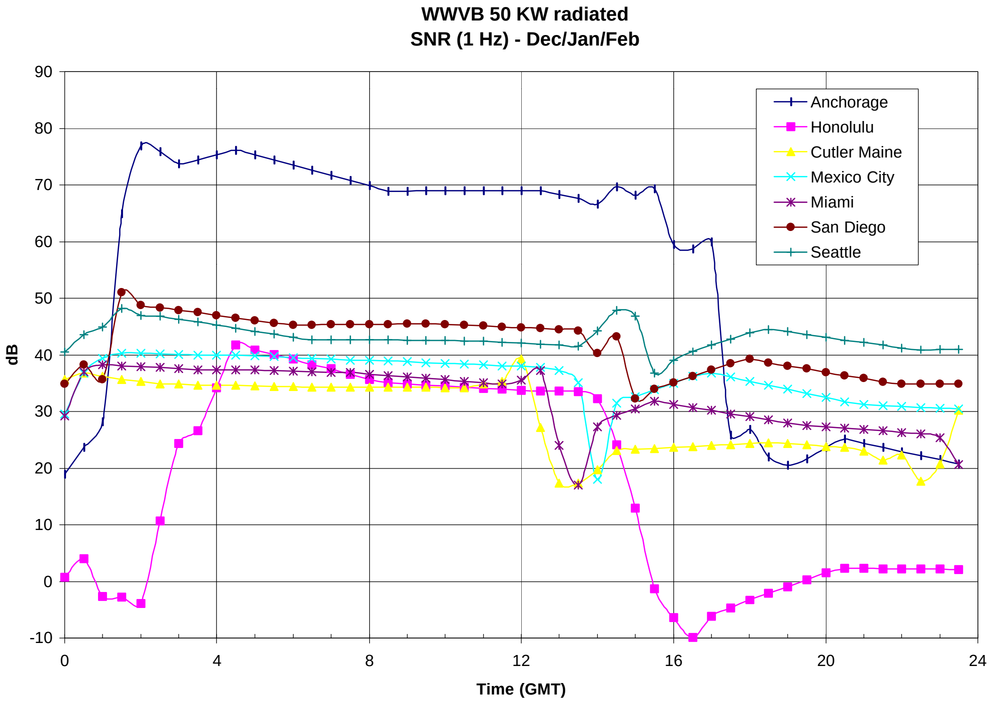

Figure 7 - Signal to noise ratio with 1 Hz Bandwidth during the winter months.

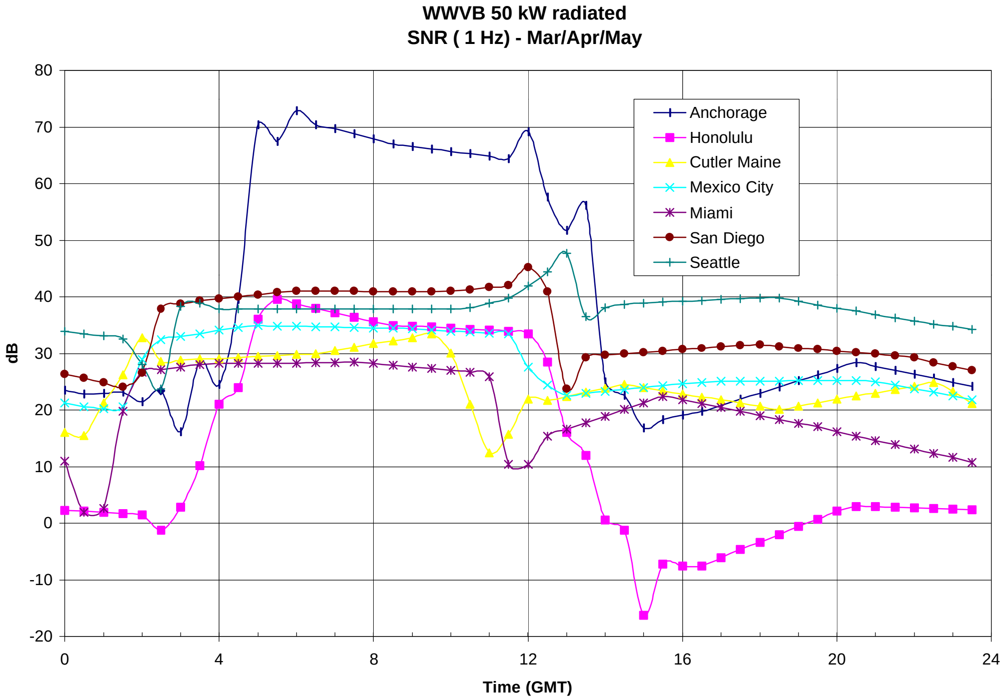

Figure 8 - Signal to noise ratio with 1 Hz Bandwidth during the spring months.

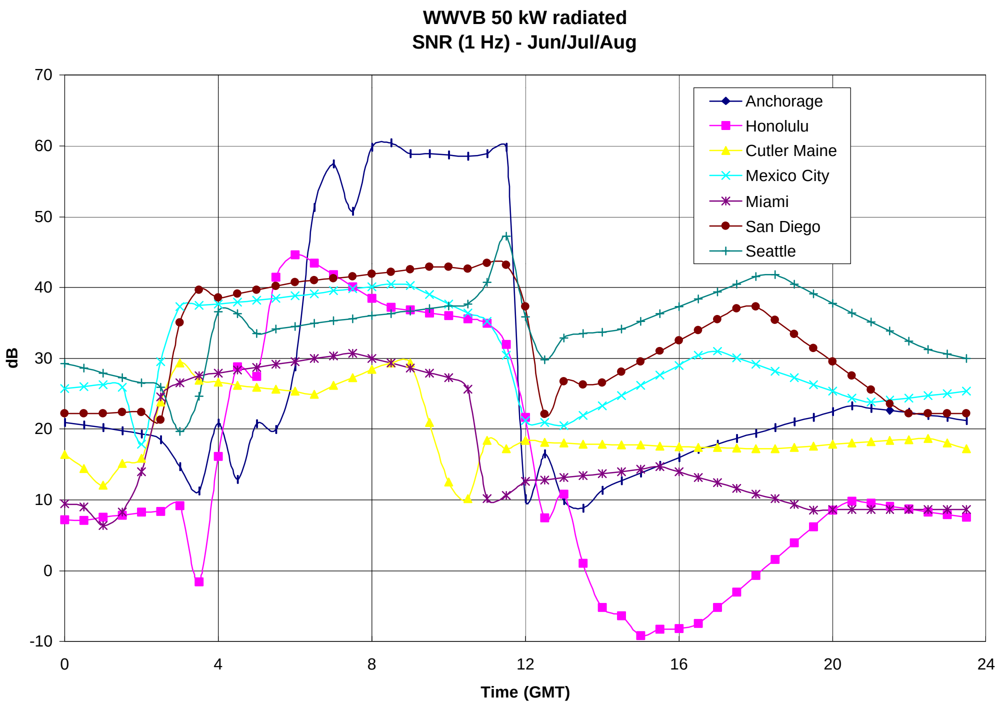

Figure 9 - Signal to noise ratio with 1 Hz Bandwidth during the summer months.

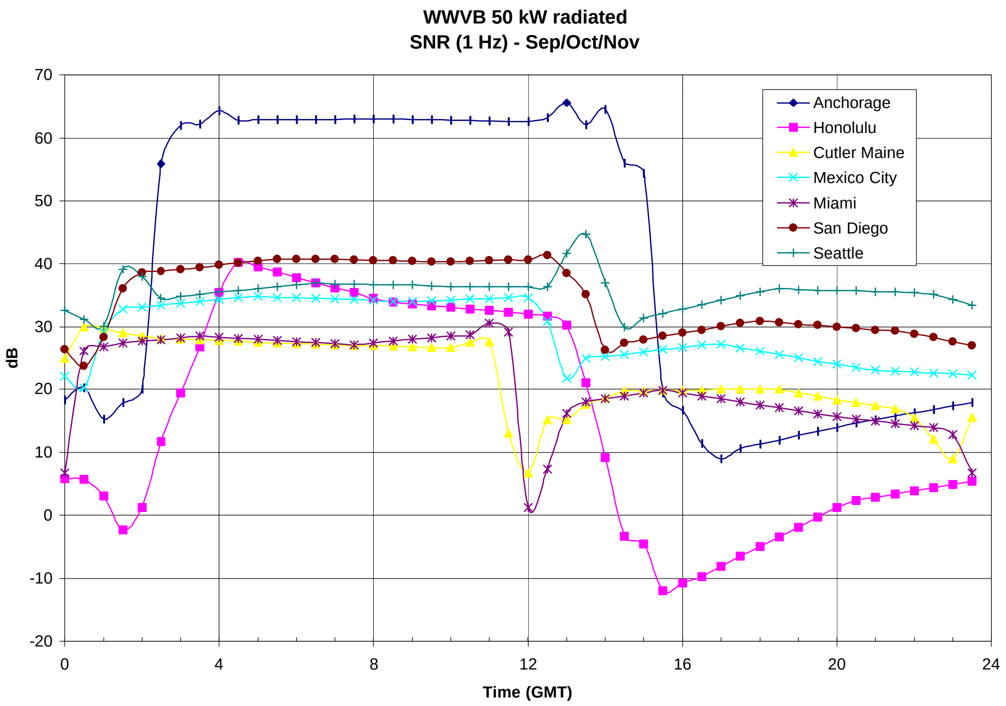

Figure 10 - Signal to noise ratio with 1 Hz Bandwidth during the autumn months.

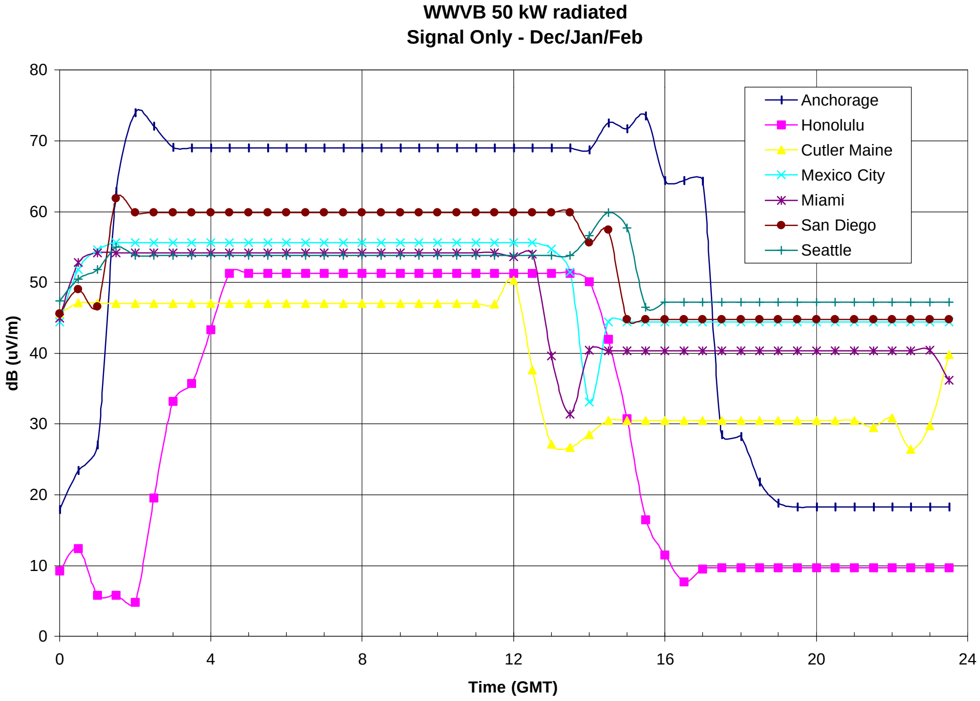

Figure 11 - Signal strength during the winter months.

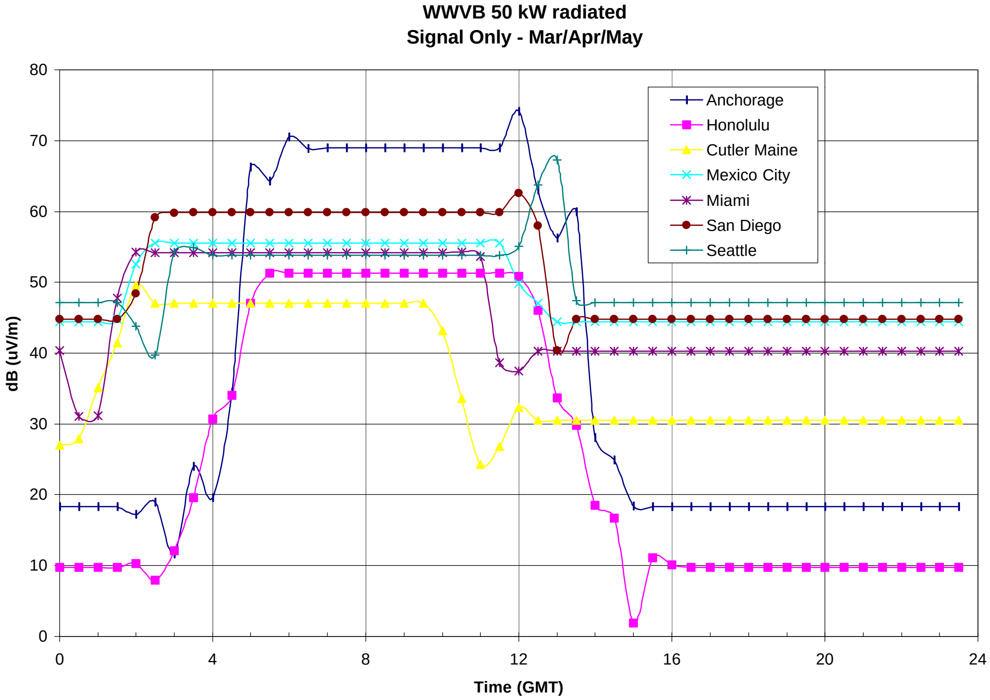

Figure 12 – Signal strength during the spring months.

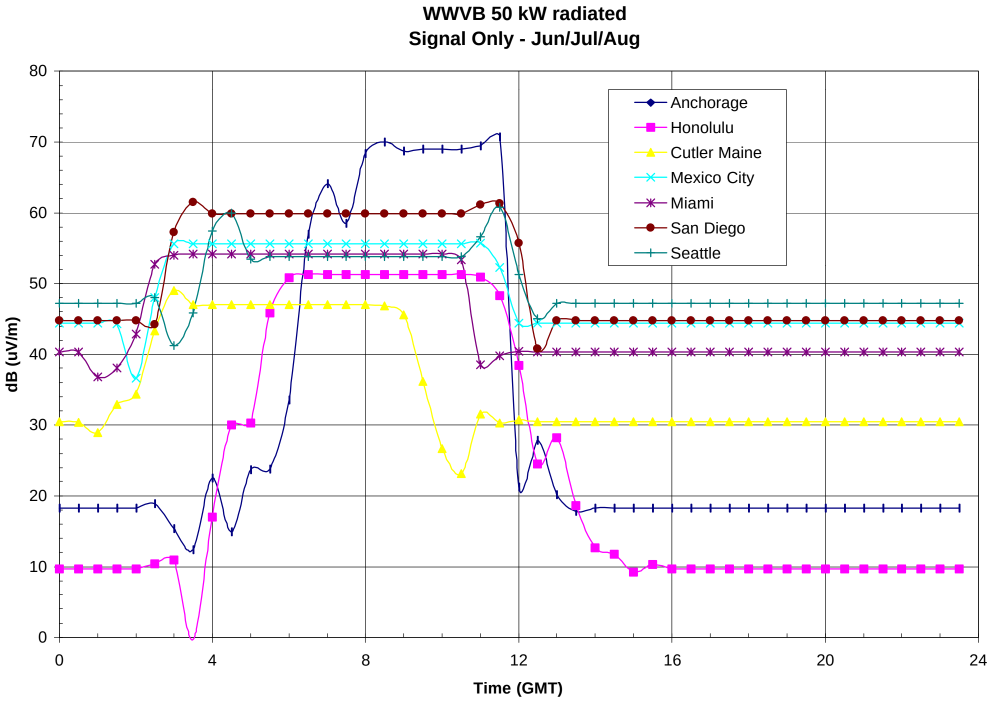

Figure 13 - Signal strength during the summer months.

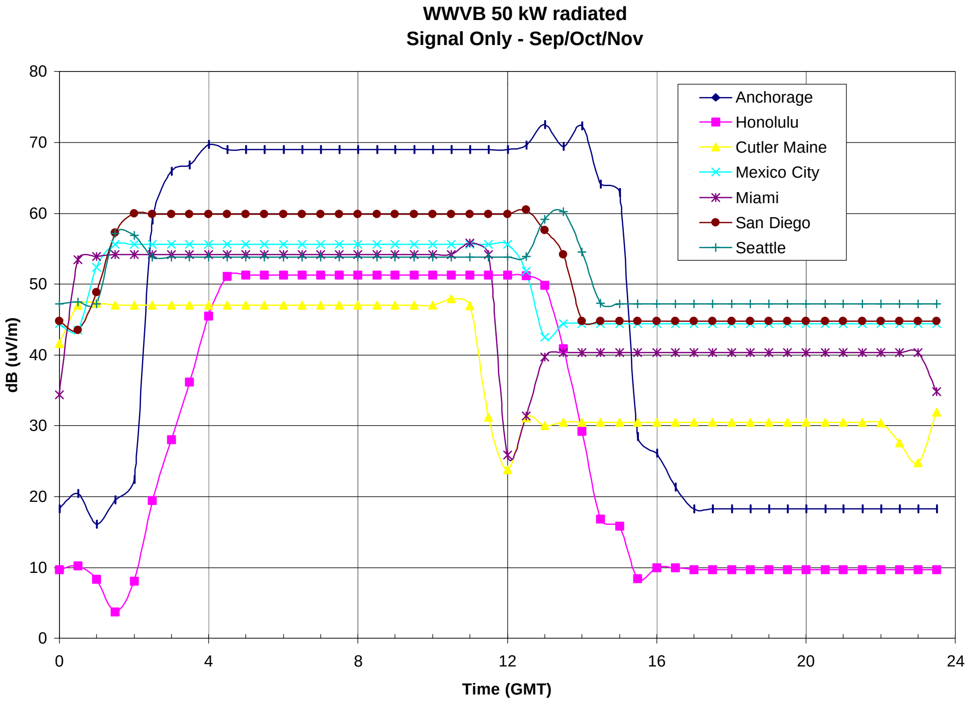

Figure 14 - Signal strength during the autumn months.