Time Flies! Radio Signals Used for Time and Frequency Measurements

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The widespread use of the Global Positioning System (GPS) as a time and frequency measurement reference was discussed in the July-September 2001 issue of *Cal Lab*. This article describes other radio signals that serve as alternatives or backups to GPS. It describes signals used to calibrate and control frequency standards, and signals that synchronize time-of-day clocks in products including wristwatches, cellular phones, pagers, televisions, video cassette recorders, and car radios.

Introduction

Radio signals have served as time and frequency measurement references for nearly 100 years. The use of radio to distribute time and frequency was reported as early as 1904,[1] and the National Institute of Standards and Technology (NIST) has continuously broadcast time and frequency signals from radio station WWV from 1923 to the present.[2] Today, radio signals throughout the spectrum are used to control or calibrate frequency standards or to synchronize clocks.

It makes sense to use radio signals as time and frequency measurement references. For both legal and practical reasons, many radio signals are kept very close to their assigned frequencies. Time codes require only a small amount of bandwidth and are usually easy to add to a radio signal. Radio navigation systems such as GPS and LORAN-C require precise time and frequency information to be contained in their signals, or their navigation solutions will fail. And unlike wired, finite capacity systems such as Internet time servers, more users can be added to a radio system without putting additional burden on the transmitter. The same signal delivers time and frequency to all receivers within the coverage area.

All radio signals consist of a carrier frequency, and all but the simplest carry information that is modulated on to the carrier. If the signal is to be used as a time reference, this modulated information must include a time code. In addition to providing date and time-of-day information such as the hour, minute, and second, the time code usually includes an on-time marker (OTM) that is synchronized with the Coordinated Universal Time (UTC) second. For signals with wide coverage areas, the time-of-day message refers to the UTC time zone located near the prime meridian at 0° longitude. The receiver applies a time zone correction to convert UTC to local time. Transmitters with small coverage areas, such as cellular telephone base stations, sometimes broadcast UTC plus a local time zone correction. If the signal is to be used as a frequency reference, either the carrier or the time code (preferably both) must be locked to an oscillator (preferably a cesium oscillator) steered to agree with the UTC frequency.

Receivers that produce time information obtain time-of-day by decoding the time code, and often output an OTM as a 1 pulse per second (pps) signal that serves as both a time interval and synchronization reference. Receivers that produce frequency signals generally phase lock a local oscillator to a reference frequency derived from either the carrier or the time code. The local oscillator then generates signals at standard frequencies such as 5 or 10 MHz as sine waves or square waves. Some receivers use both the carrier and the time code to obtain frequency. If the time code is used, the received frequency information might be limited to the slow 1 Hz OTM frequency, although frequencies faster than 1 Hz can sometimes be obtained from the individual time code bits.

In theory, if good time and frequency is kept at the transmitter, it can be delivered to users via the airwaves using any type of radio signal. In practice, however, noise is introduced as the signal travels the path between the transmitter and receiver, causing some accuracy to be lost. Some carrier frequencies work better than others, since their

Figure 1. The NIST Boulder laboratories.

signal paths are more stable. Line of sight signals, such as satellite or local area ground-based signals, usually have more stable paths and smaller measurement uncertainties than signals that follow the Earth's curvature.

Due to its excellent performance, worldwide coverage, and high reliability, GPS is now the dominant radio system used for high accuracy time and frequency distribution. GPS provides frequency, time interval, and time-of-day to the entire world, and the use of GPS in time and frequency metrology was described in detail in an earlier *Cal Lab* article.[3] However, most time and frequency users agree that exclusive reliance on a single system such as GPS is not a good idea. This article describes radio signals that can potentially serve as backups or alternatives to GPS. Some signals described here provide capabilities that GPS cannot provide, and are ideal for applications where GPS will not work. The article does not discuss all signals available worldwide, but limits itself to signals usable in the United States.

Traceability Issues

Measurement traceability to the UTC time scale and the SI second is usually easy to establish if the radio signal is controlled or monitored by a national metrology institute (NMI) such as NIST.[4] Figure 1 is a photograph of the NIST Boulder Laboratories where the Time and Frequency Division and the UTC(NIST) time scale are located. Some of the signals described in this article are controlled by NIST (WWV, WWVH, WWVB, and GOES), and others are monitored by NIST (GPS and LORAN-C). Establishing traceability with signals not monitored or controlled by a NMI is more difficult, but is possible if the traceability chain can be documented.

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 band properly known as HF (high frequency), but commonly called shortwave. WWV is located near Fort Collins, Colorado, and WWVH is on the island of Kauai, Hawaii. Both stations broadcast continuous time and frequency signals on 2.5, 5, 10, and 15 MHz, and WWV is also available on 20 MHz. All frequencies carry the same program, and at least one frequency should be usable at all times. WWV and WWVH can be used in one of three modes:

- The audio portion of the broadcast includes seconds pulses or ticks, standard audio frequencies, and voice announcements of the UTC hour and minute. WWV uses a male voice, and WWVH uses a female voice.
- A time code is sent on a 100 Hz subcarrier at a rate of 1 bit per second. This time code can actually be heard as a low frequency audio tone. It contains the hour, minute, second, year, day of year, leap second and daylight saving time indicators.
- The carrier frequency can be used for simple frequency calibrations. This is done most often with the 5 and 10 MHz carrier signals, since they match the output frequencies of time base oscillators.

The time broadcast by WWV and WWVH is late when it reaches the user's site. The time offset depends upon the receiver's distance from the transmitter, but should be less than 15 ms in the continental United States. A good path delay estimate requires knowledge of HF radio propagation, since most users receive a signal that has bounced off the ionosphere and was reflected back to Earth. Since the height of the ionosphere changes, the path delay also changes. Path variations limit the received frequency uncertainty to parts in 10^9 when averaged for 1 day, and the timing uncertainty to about 1 ms.[5]

WWV and WWVH are the only precision audio time signals broadcast in the United States and are invaluable for the manual synchronization of clocks and calibrations of stopwatches and timers. However, low frequency (LF) and satellite signals are better choices for more demanding applications.

WWVB

NIST radio station WWVB is the synchronization source for millions of wall clocks, desk clocks, clock radios, wristwatches, and other consumer electronics devices. The 60 kHz WWVB station shares the WWV site near Fort Collins, Colorado, and its sole purpose is to provide time and frequency information to the American public. WWVB went on the air in 1963, but the station's radiated power was not increased to its current 50 kW level until 1999.[6] The power increase expanded the coverage area to include most of North America, and made it easy for tiny receivers with simple antennas to receive the signal. As a result, many low cost radio controlled clocks now synchronize to UTC(NIST).

The WWVB time code is synchronized with the 60 kHz carrier and broadcast continuously at a rate of 1 bit per second using pulse width modulation. An OTM is sent each second by reducing the carrier power 10 dB. If full power is restored 200 ms later, it represents a 0 bit. If full power is restored 500 ms later, it represents a 1 bit. The bits contain time-of-day, date, and daylight saving time information. It takes one minute to send a complete time code.

WWVB receivers can be divided into two broad categories: the low cost radio controlled clocks now available at thousands of stores throughout the United States, and the carrier phase tracking receivers used by calibration and testing laboratories. WWVB units dominate the radio controlled clock market because the low frequency (LF) signal can be received indoors. The 60 kHz signal has a wavelength of about 5000 m and can penetrate buildings and walls, which gives it an advantage over line-of-sight systems such as GPS that require an outdoor antenna.

WWVB clocks work by synchronizing an inexpensive quartz oscillator to the WWVB time code. Many units synchronize only once every 24 hours, usually at night when the signal is strongest. One synchronization per day is usually enough to keep a clock's display on the right second, since a typical time base oscillator can keep time within a few tenths of a second per day.

Sources for WWVB carrier phase tracking receivers have unfortunately become rare, but these receivers serve as a capable backup or alternative to GPS for the calibration of electronic instruments and frequency standards. These receivers typically phase lock their local oscillator to the WWVB carrier and then derive standard frequencies such as 5 MHz and 10 MHz from the local oscillator. They are designed to stay locked to the carrier at all times, so they can correct their local oscillator whenever necessary.

The received performance of WWVB depends upon the signal quality, the receiver and antenna type, and the distance between the receiver and the transmitter. The low cost radio controlled clocks receive a signal that is not corrected for path delay. The delay depends upon the distance to the transmitter, but the longest possible delay in the continental United States is less than 15 ms.

For frequency measurements, path delay is unimportant. The important issue is path stability or path delay changes. Short paths work better than long paths. If the receiver is relatively close to the transmitter (< 1000 km), most of the signal should be groundwave. Carrier phase tracking receivers that stay locked to the same groundwave cycle can produce frequency with uncertainties of parts in 10^{12} when averaged for one or more days. The peak-to-peak variation in the received phase was slightly more than 1 µs over the one month period graphed in Figure 2. The data points are one-hour averages, and the graph shows a daily noise pattern caused by path length changes at sunrise and sunset [2, 7].

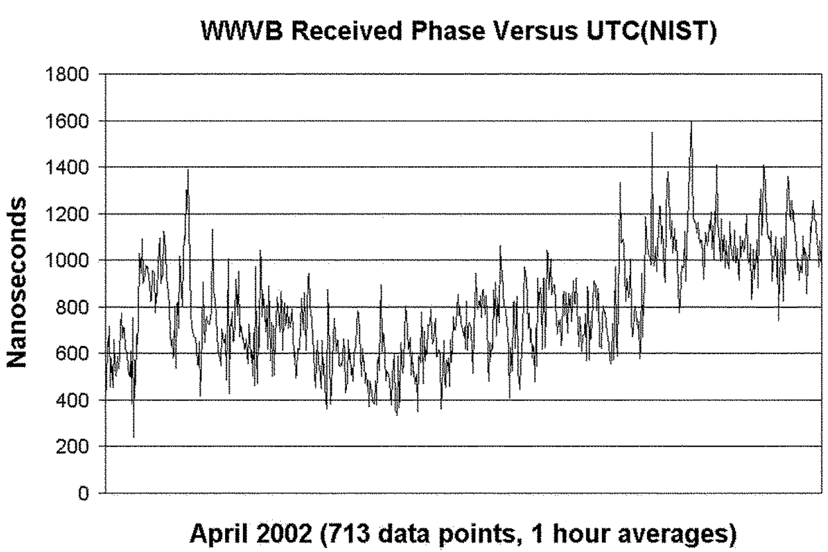

Figure 2. WWVB received phase versus UTC(NIST).

LORAN-C

LORAN-C is a ground-based radio navigation system controlled by the United States Coast Guard. It predates GPS, and operates in the LF (30 to 300 kHz) spectrum like WWVB. The system consists of synchronized groups of stations called chains. Each chain has one master station (designated as M), and two to five secondary stations (designated as V, W, X, Y, and Z). Navigation requires signals from the master and at least two secondaries. Frequency calibrations require reception of just one station, either a master or a secondary.

All LORAN-C stations use a 100 kHz carrier frequency. Chains are identified by a unique Group Repetition Interval (GRI), which refers to the time interval between transmitted pulse groups. For example, the 7980 chain sends a pulse group every 79.8 ms. Each pulse group begins with pulses from the master station, followed by pulses from each secondary station. The pulses from each station are separated by a fixed emission delay, so that pulses do not interfere with each other anywhere in the coverage area. The emission delays also help identify individual stations. LORAN-C receivers lock to the carrier frequency of a station by continuously tracking the same cycle of a pulse group.[8]

LORAN-C usage was reduced when GPS became operational, and the future of the system is uncertain. However, supporters of LORAN-C feel that it is a necessary backup system to GPS, and it might be available for many years to come. There are currently 24 LORAN-C transmitters operational in the United States (Table 1).

At least two companies still manufacture and sell LORAN-C receivers designed to work as frequency standards. These receivers provide standard frequency outputs such as 5 and 10 MHz, and some models provide a 1 Hz timing pulse. The receivers are limited as time standards, since the signal does not include a time code. However, some receivers can generate an OTM if time-of-coincidence (TOC) data are supplied to the receiver. A TOC occurs when a GRI pulse group coincides with the UTC second. TOC tables and a TOC calculator are available from

GRI	Location	Peak Radiated Power (kW)
5930-M, 9960-W	Caribou, ME	800
5930-X, 9960-X	Nantucket, MA	400
5980-X, 9990-X	Attu, AK	400
5990-Y, 9940-W	George, WA	1400
5990-X, 7960-Y	Shoal Cove, AK	560
7960-M	Tok, AK	560
7960-X, 9990-Z	Kodiak, AK	400
7960-Z, 9990-Y	Port Clarence, AK	1000
7980-M, 8970-W	Malone, FL	800
7980-W, 9610-Z	Grangeville, LA	800
7980-X, 9610-Y	Raymondville, TX	540
7980-Y	Jupiter, FL	350
7980-Z, 9960-Y	Carolina Beach, NC	600
8290-M	Havre, MT	400
8290-W, 8970-W	Baudette, MN	800
8290-X, 9610-V	Gillette, WY	540
8970-M, 9960-Z	Dana, IN	400
8970-X, 9960-M	Seneca, NY	800
8970-Z, 9610-M	Boise City, OK	900
9610-W, 9940-Y	Searchlight, NV	540
9610-X	Las Cruces, NM	540
9940-M	Fallon, NV	400
9940-X	Middleton, CA	400
9990-M	St. Paul, AK	400

Table 1. LORAN-C Transmitters in the United States

the United States Naval Observatory (USNO) [9]. If a receiver has TOC capability, and if the user compensates for path delay, the timing uncertainty is less than 1 μs.

LORAN-C receivers are excellent frequency standards if located relatively close to the transmitter. The signals can be received at distances up to about 2000 km, and the groundwave can usually be received at distances up to 1000 km. LORAN-C is extremely reliable, and there are few broadcast outages. Receivers within the groundwave coverage area can often stay locked to the carrier frequency for many months, without cycle slips, and the received frequency uncertainty is about 1×10^{-12}. To illustrate this, Figure 3 compares transmissions from the station in Boise City, Oklahoma (9610-M) to UTC(NIST) for the month of January 2002. The distance between the transmitter and receiver is about 439 km. The peak-to-peak time variation shown on the graph is less than 200 ns, proving that the carrier frequency is tightly controlled and that the groundwave signal path is stable. Current LORAN-C monitoring data is published by the USNO and NIST. [9]

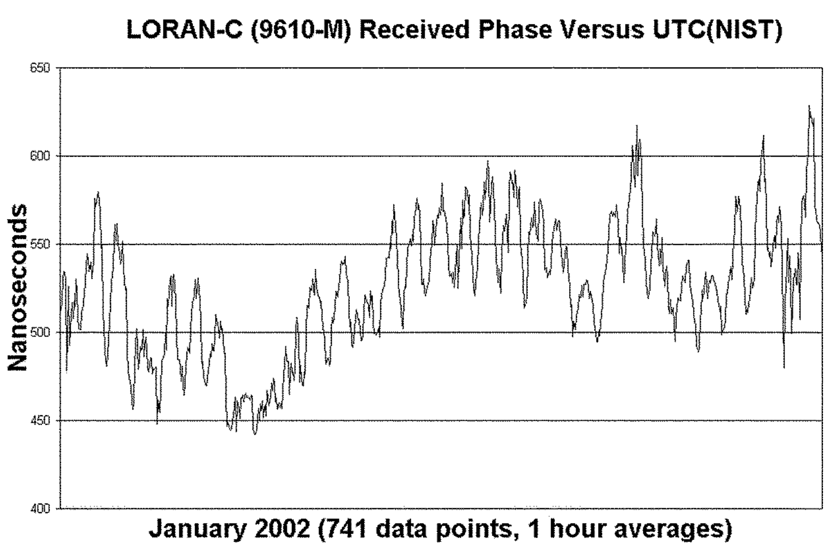

Figure 3. LORAN-C (9610-M) received phase versus UTC(NIST).

VLF Broadcasts

VLF (very low frequency) is the name given to the radio spectrum between 3 and 30 kHz. The United States Navy has used VLF broadcasts for submarine communications for nearly 50 years, since the long wavelength signals can penetrate the ocean's surface, which blocks radio waves at higher frequencies. The Navy still operates several VLF stations in the United States, as listed in Table 2. The signals do not contain a time code, but the carriers are locked to atomic oscillators and can potentially serve as a frequency reference.

The Navy VLF signals are mentioned here for completeness only. They were once routinely used by the United States military to calibrate oscillators with frequency uncertainties of parts in 10^{10}, [10] but they are seldom used for that purpose today. The tunable VLF carrier phase tracking receivers once sold as frequency standards disappeared from the marketplace over 20 years ago. Even if an old receiver is available, use of these stations is not recommended for several reasons: the

Call Letters	Carrier Frequency (kHz)	Location	Estimated Radiated Power (kW)
NPM	21.4	Lualualei, HI	480
NAA	24.0	Cutler, ME	1000
NLK	24.8	Jim Creek, WA	192
NML4	25.2	LaMoure, ND	Unknown

Table 2. VLF transmitters operated by the United States Navy.

broadcasts might be intermittent, modulation modes other than CW (continuous wave) might be used which makes it difficult to track the carrier, and the future of the transmitters is uncertain since other systems now assist with submarine communications.

AMPS and PCS Cellular Telephone Signals

You may not have noticed, but the time displayed on your cellular telephone should always be correct. Cellular signals originate from Code Division Multiple Access (CDMA) base stations that operate in compliance with Telecommunications Industry Association (TIA/EIA) Standard IS-95.[11] All base stations contain GPS receivers, and by definition, IS-95 time is GPS time. The base stations act as GPS repeaters by retransmitting the GPS time they receive from the satellites.

There are two types of IS-95 CDMA systems, distinguished by their frequency bands. The original analog cellular system, called the Advanced Mobile Phone System (AMPS), transmits base station signals (forward link signals) using frequencies from 869 to 894 MHz. The newer Personal Communications Systems (PCS) band sends forward link signals in the 1930 to 1990 MHz range. AMPS signals travel farther and penetrate buildings more easily than PCS signals, and are preferred for time and frequency applications, where most receivers are located indoors. However, some regions are covered only by PCS. Since the time and frequency information on either band is receive-only (no reverse link signals are sent), it is not necessary to subscribe to a telephone service to use the signals. It might be possible to receive the time and frequency information in an area where a cell phone will not work, since the forward link signal from the base station usually has more range than the reverse link signal from a cell phone.

IS-95 is a spread-spectrum system that uses CDMA techniques to distinguish between multiple, simultaneous users of the same frequency channel. All base stations in the system transmit on the same frequency, and send the same spread spectrum code. Although each base station sends the same code, it sends the code with a different time delay offset relative to the on time, or zero offset code. Time delay offsets that are multiples of about 52 μs (long enough to allow for the limited coverage area) are used to ensure that a cellular phone user could never be close enough to one base station, and far enough from another, to have codes from two different base stations interfere. The base station clocks must be synchronized, so that each base station knows when to transmit its replica of the spread spectrum code.

For this reason, the IS-95 standard defines CDMA system time to equal GPS time and requires that base stations be synchronized to within 10 μs, even when GPS is unavailable for up to 8 hours. During normal operation, when GPS is available, base stations are synchronized within 1 μs. The IS-95 standard only requires the base station's carrier frequency to be controlled to within 5×10^{-8}, but in practice the carrier is phase locked to GPS, and the uncertainty is at least several orders of magnitude better than the requirement.[12, 13]

The received time uncertainty depends upon the distance from the receiver to the base station, and is often related to the population of the area (more population generally means more cells). Time uncertainty due to path delay ranges from less than 5 μs (urban areas) to more than 100 μs (rural areas). If cell phones work in the area, however, there is usually an available base station with a path delay of less than 25 μs. Since both the base station and the receiver are stationary, the path delay does not affect the frequency uncertainty, which is generally 1×10^{-12} or less. If a base station signal becomes unavailable, the receiver switches to another base station with the strongest available signal. Both the path delay and the timing uncertainty change when this occurs. The base station's position is included in the broadcast, so it is possible for a receiver with known coordinates to correct for path delay.

There is currently at least one commercial manufacturer of AMPS band time and frequency reference receivers, and PCS band receivers are expected to appear soon.[13] These receivers produce an on-time 1 pulse per second (pps) signal, and standard frequency outputs such as 10 MHz. A comparison of the 1 pps output of an AMPS band cellular receiver to UTC(NIST) for a 16 day period is shown in Figure 4. Note that the receiver stayed locked throughout most of this data run to two base stations, with path delays of about 22 and 26 μs, respectively, as indicated by the straight lines on the graph. However, the receiver was locked for brief periods to other base stations, with respective path delays of roughly 10 and 12 μs. The data points represent 5 minute averages, and the points in between the straight lines represent transition periods when the receiver was switching from one base station to another.

Cellular receivers have higher uncertainties and smaller coverage areas than GPS receivers, but still meet the requirements of many users. They

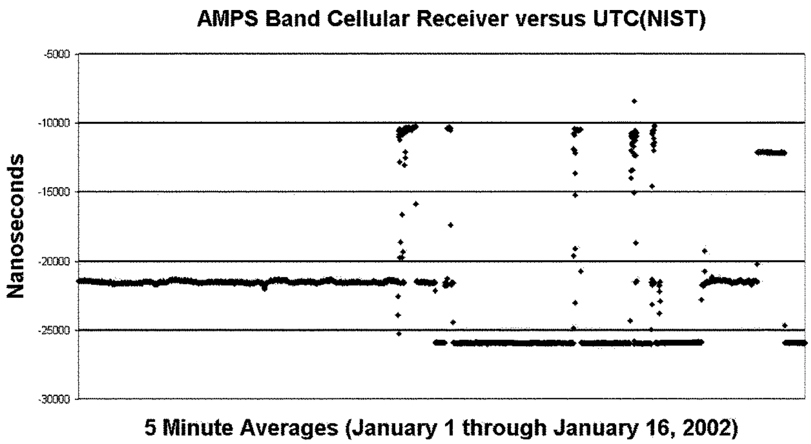

Figure 4. AMPS band cellular receiver versus UTC(NIST)

have at least two advantages over GPS receivers: the received time code is local time (no time zone conversion is needed), and the receivers work indoors with tiny cell phone antennas. This makes them usable in buildings where installing a rooftop antenna is impractical or impossible.

Paging Networks

Paging technology is somewhat similar to cellular technology; and like cell phones, the time-of-day display on a pager is referenced to GPS. Paging technology has many potential applications for the synchronization of time-of-day clocks, although is not likely to be used as a frequency or time interval reference. Several wristwatches now sold in the United States automatically synchronize using the FLEX paging protocol developed by Motorola, and other paging protocols have also been used for clock synchronization.

Paging protocols are designed to send an alert or to deliver a message to one specific receiving device, called a pager. The FLEX paging protocol is a synchronous time-slot protocol that uses GPS as its time base. Each pager is assigned to a base frame in a set of 128 frames (0 to 127). Each frame lasts for 1.875 s, and a 4-minute cycle is required to send all 128 frames. Fifteen cycles (0 to 14) occur each hour, and are synchronized to the start of the GPS hour.

Frames consist of a synchronization field, and 11 data blocks (0 to 10) that last for 160 ms each. The synchronization field determines the speed used for sending the data blocks using frequency shift key (FSK) modulation (speeds range from 1600 to 6400 bits per second). Block 0 contains a block information field, with a time code containing the date, local time, and time zone offset from UTC.The transmitted time refers to the time at the leading edge of the first bit in the synchronization field of frame 0 in the current cycle.

The FLEX time code is modulated on to a forward link frequency near 931 MHz. As with the cellular phone systems described earlier, it is not necessary to subscribe to a paging service to use the time code.[14]

GLONASS

GLONASS is the Global Navigation Satellite System operated by the Russian Federation Ministry of Defense. The system is somewhat similar to GPS, and some receivers are capable of both GPS and GLONASS reception.

Although the first GLONASS satellite was launched in 1982, the constellation has never been completed. The fully deployed constellation would consist of 24 satellites in three orbital planes. About 15 satellites were once operational, but at this writing (2002), only seven satellites remain operational. Each satellite carries a cesium oscillator, and has an orbital height of 19100 km, an inclination angle of 64.8°, and an orbital period of 11 hours and 15 minutes (43 minutes shorter than GPS). Unlike GPS, the GLONASS satellites use individual carrier frequencies. The system uses two frequency bands, L1 (1602.5625 to 1615.5 MHz) and L2 (1240 to 1260 MHz). Channel separation is 562.5 kHz on the L1 band. Although two satellites could potentially share the same frequency channel, the system was designed so that satellites sharing a channel would never be simultaneously visible to a receiver on Earth.

Since the constellation has not been completed, there are extended periods when no satellites are receivable on Earth. This alone has stopped GLONASS from becoming a viable alternative or backup system to GPS, but this could change if the full constellation is launched. GLONASS time has some peculiarities that should be noted. The time code refers to Moscow Time, and differs from UTC by three hours. The OTM is currently maintained within about 500 ns of UTC, but this has not always been true. In 1997, a time step of about 36 μs was needed to bring GLONASS time into agreement with UTC.[15]

WAAS

WAAS is the GPS Wide Area Augmentation System. The system was developed by the Federal Aviation Administration (FAA) to make GPS work better for enroute aviation navigation and for precision flight approaches. A WAAS capable GPS receiver can provide positioning solutions about five times better than a standard GPS receiver, with a positioning uncertainty of less than 3 m (2σ).

The WAAS system consists of approximately 25 ground reference stations positioned across the United

States. These stations monitor GPS satellite data and forward the data to two master stations, located on either coast, that create a GPS correction message. This correction accounts for GPS satellite orbit and clock drift plus signal delays caused by the atmosphere and ionosphere. The correction message is sent through a satellite uplink station to two geostationary satellites, currently located at 180° and 54° west longitude, respectively. The corrected differential message is then broadcast through one of two geostationary satellites as an overlay on the GPS L1 frequency in the 1559 to 1610 MHz frequency band. Since the WAAS signal uses the GPS L1 frequency and GPS-type modulation, WAAS capability can be integrated into GPS receivers. WAAS was designed to assist United States users, and the coverage is limited to the 48 contiguous states, plus Hawaii, Puerto Rico, and parts of Alaska.[16]

WAAS was designed to augment or improve the performance of GPS receivers, and is not a really a standalone alternative or backup to GPS, since if GPS is unusable for a given application, WAAS will probably also be unusable. However, receivers exist that allow using WAAS signals for time and frequency without using signals from the orbiting GPS satellites. A more promising development involves GPS timing receivers that improve their performance by receiving WAAS.[17] While WAAS capable receivers are becoming common in the navigation marketplace; they are still relatively rare in the time and frequency market, although this could change in the near future.

GOES

GOES (Geostationary Operational Environmental Satellites) is a system operated by the National Oceanic and Atmospheric Agency (NOAA), which like NIST, is part of the United States Department of Commerce. These satellites are primarily used to collect weather and solar information, but two of the satellites (GOES/East and GOES/West) broadcast a time code referenced to UTC(NIST). GOES/East is located at 75° west longitude and broadcasts on a carrier frequency of 468.825 MHz, GOES/West is at 135° west longitude and broadcasts at 468.8375 MHz. A 100 bit per second code modulated onto the carrier delivers data to the receiver, and 4 bits every half-second contain timing and position information. A complete time code frame consists of 240 bits and requires 30 seconds to receive.

GOES is historically significant as the first timing system (1974) where the transmitter broadcast its position in addition to the time. This allows GOES receivers to calculate the path delay, correct the received time,[18] and easily maintain a timing uncertainty of 100 µs. Frequency uncertainty is typically limited to parts in 10^{10} when averaged for one day, largely due to errors in the satellite position estimates.

GOES receivers were once common in the aviation and electric power industries, but most units have now been replaced by GPS. No new receivers are being sold, and NIST has announced it is ending its involvement with the GOES time code on January 1, 2005. It is unknown whether NOAA will continue to broadcast a time code from the satellites after that date.

Terrestrial Television

Terrestrial television signals were widely used in the pre-GPS era as references for time and frequency calibrations. Still used for frequency calibrations in Europe with excellent results,[19] terrestrial TV signals are primarily used in the United States to synchronize clocks in televisions and videocassette recorders (VCRs) with time codes sent by the Public Broadcasting System (PBS). The analog signal formats described here pertain to both VHF (54 to 216 MHz, channels 2 through 13) and UHF stations (470 to 890 MHz, channels 14 through 83).

Television signals captured the attention of time and frequency metrologists in the 1960's because of their stable line-of-sight signal paths, and because their bandwidth allows them to carry several signals that can potentially serve as measurement references. The National Television System Committee (NTSC) video format for analog television signals uses about 6 MHz of bandwidth. About 4.2 MHz is used for video; the rest is used for the vestigial sideband, buffers, and sound.

Images are placed on a television screen by moving an electron beam in a "raster scan" pattern across and down the screen. Black and white televisions have one beam; color televisions have three (red, green, and blue). The beam "paints" 525 horizontal lines from the top to the bottom of the screen. Each line is painted from left to right. When the beam reaches the right side of the screen, it quickly moves back to the left side (a move called the horizontal retrace), moves down slightly, and paints another horizontal line.

The horizontal retrace signal is a 5 µs wide synchronization pulse that repeats at a frequency near 15.734 kHz, which equals the number of lines painted per second. When the beam reaches the last line on the screen, it quickly moves back to line 1 (a move called the vertical retrace). The vertical retrace signal is 400 to 500 µs wide, and repeats at a frequency near 60 Hz. During the horizontal and vertical retraces, the beam is turned off so it does not paint a trail on the screen. The electron beam paints every other line as it moves down the screen, alternating between even-numbered and odd-numbered lines on each pass. The entire 525 lines are painted about 30 times per second in two fields of 262.5 lines. Each video frame has a period of about 33.3 ms.

The first 21 lines of each field are not part of the visible picture, and are collectively referred to as the vertical blanking interval (VBI). Lines 1 through 9 are used for vertical synchronization, and to allow time for the vertical retrace. Lines 10 through 21 are available for data transport.

For color televisions programs, a 3.579545 MHz sine wave (called the color burst frequency) is superimposed onto the standard black-and-white signal. Right after the horizontal synchronization pulse, eight cycles of the color burst frequency are added. A ninth cycle, shifted in phase, indicates the color to display. For example, a 75° phase shift is sent to display the color red.

During the 1970's, NIST (then the National Bureau of Standards) engineers worked with the national television networks to make television signals a measurement reference for time and frequency. Atomic oscillators were installed at network television stations whose broadcasts were continuously monitored by NIST. A time code was sent using a line in the VBI, and a frequency calibration service was implemented using the 3.579545 MHz color burst signal. Time was routinely transferred with an uncertainty of only a few microseconds, and frequency with an uncertainty of a few parts in 10^{11}.[20, 21]

For various reasons (some technical and some political), the use of network television signals as a precision time and frequency reference was short lived. The VBI time codes designed by NIST were never implemented by the networks, and today, the Federal Communications Commission (FCC) requires the color burst frequency to be kept only within ±10 Hz, a frequency uncertainty of about 3×10^{-6}. However, today's TVs and VCRs do have the ability to synchronize their clocks. Based in part on work done by NIST, the networks began using line 21 of the VBI to send text messages for closed captioning, a service for the hearing impaired. Since 1993, all television sets of 13 in. and larger sold in the United States have closed captioning capability. Line 21 (field 2) is also used for the Extended Data Service (XDS), which includes a time code containing UTC, the date, daylight saving time information, and a time zone offset.[22]

By mutual agreement within the broadcasting industry, the XDS time code is inserted by PBS stations only. TVs and VCRs use a feature (developed by PBS and the Sony Corporation), where each channel is scanned for a time code beginning with channel 2. Once a time code is found, the TV or VCR synchronizes its clock. PBS is currently working on a system to insure that all of its stations broadcast a signal that is "frame accurate", or within 33.3 ms of UTC. Due to transmitting systems that can buffer several frames, the received uncertainty might still be as large as 100 ms. The XDS time code is broadcast by over 160 PBS stations and reaches nearly all of the United States population.

DBS Satellite Television

Direct Broadcast Satellite (DBS) television providers now have many millions of subscribers in the United States. DBS signals are transmitted in the upper half of the Ku band (12.2 to 12.7 GHz), and the receivers use a small dish antenna (about 46 cm in diameter) that is pointed towards a specific geostationary satellite. Satellites with full continental United States (CONUS) coverage are located at 101°, 110°, and 119° west longitude. As with terrestrial television, DBS signals contain time-of-day information, although the MPEG (Motion Picture Experts Group) digital format used by DBS makes the decoding process different. To maintain compatibility with existing televisions, many DBS receivers still convert the digital video signals back to analog.

DBS receivers are low cost and widely available, and a few hobbyists have reported modifying them to extract a standard frequency signal. Although the satellite signals are typically referenced to atomic oscillators located at the uplink station, the satellite's motion causes a Doppler frequency shift that typically limits the received frequency to parts in 10^9 when averaged for one day. Geostationary satellites aren't really stationary; they move in a figure-8 like pattern, returning to approximately the same spot at approximately the same time each day. During the day, however, the path delay between the receiver and transmitter constantly changes. If the arrival time of the DBS signal is continuously measured, it might show peak-to-peak variations of several hundred microseconds or more over the course of a day.

Satellite systems used for timing (such as GPS, WAAS, GLONASS, and GOES) partially correct for the Doppler shift by having the satellite broadcast accurate real-time position data (called the ephemeris) that the receiver uses to calculate and correct for the path delay. Unfortunately for time and frequency users, DBS satellites do not broadcast an ephemeris. Another way to remove the Doppler shift is to steer the reference oscillator at the satellite uplink station using a feedback loop. A monitoring station receives the satellite signal on Earth, and provides data to a system that adjusts the reference oscillator to correct for the frequency offset. In simple terms, if the frequency received on Earth is too high, the frequency of the reference oscillator is lowered, and vice versa. This method has been used successfully in Europe to transfer frequency from their digital television satellite system with uncertainties of parts in 10^{12}.[19] This method only optimally corrects the frequency for relatively small regions on Earth that are near the monitoring station, but demonstrates the potential of DBS signals for time and frequency measurements.

AM and FM Radio

The FCC requires commercial AM and FM radio stations to only be within about 1×10^{-5} of their assigned frequencies (20 Hz for AM, and 2000 Hz for FM, FCC Rule 73.1545). Therefore, it is highly unlikely that these stations will maintain atomic oscillators at their transmitters sites, or control their carrier frequencies very tightly. Even so, amateur radio operators and hobbyists have used commercial radio signals as a reference for simple calibrations when no other signal is available or simply to show that it can be done. One amateur radio operator designed a 10 MHz frequency generator that phase locked a 10 MHz oscillator to any AM station.[23] However, even if an AM radio transmitter were locked to an atomic oscillator, performance would probably be limited to parts in 10^8 or 10^9. AM broadcasts (530 to 1710 kHz) have a short range, relatively stable groundwave path in the day time, and a long range, unstable skywave path at night.

FM radio (87.5 to 108 MHz) has some potentially interesting time and frequency uses. FM stereo broadcasts contain a 19 kHz pilot tone whose presence tells the receiver to decode two audio channels. The allowable tolerance on the 19 kHz signal is ±2 Hz, which makes it an unacceptable reference for all but the simplest measurements. However, a 1970's experiment referenced the pilot tone to a cesium oscillator and showed that the delay variations in the received signal were consistent to within a few microseconds or less. This suggests that frequency within parts in 10^{11} could be distributed over a small region using FM radio, similar to what can be done with analog terrestrial television.[24]

FM receivers can obtain time-of-day information from the Radio Data System (RDS) broadcast by many FM radio stations on a 57 kHz subcarrier. RDS is used to identify stations and radio programs, and to provide automatic tuning and time synchronization for portable and car

Table 3. Radio signals used for time and frequency measurements.

Signal	Carrier Frequency	Time Code	On-Time Pulse	Frequency Standard Receivers Available	Time Uncertainty	Frequency Uncertainty, 24 Hour average	Available Long-Term?
GPS	1575.42 MHz (L1)	Y	Y	Y	20 ns	2×10^{-13}	Y
WWV and WWVH	2.5, 5, 10, 15, 20 MHz	Y	Y	Y	1 ms	$<1 \times 10^{-8}$	Y
WWVB	60 kHz	Y	Y	Y	100 μs	1×10^{-12}	Y
LORAN-C	100 kHz	N	Y, with TOC	Y	200 ns	1×10^{-12}	Unknown
VLF beacons	20 to 30 kHz	N	N	N	NA	1×10^{-10}	Unknown
AMPS and PCS Telephone	869 to 894 MHz (AMPS), 1930 to 1990 MHz (PCS)	Y	Y	Y	<25 μs is typical, without path delay correction	1×10^{-12}	Y
GLONASS	1602.5625 to 1615.5 MHz (L1)	Y	Y	Y	<1 μs	1×10^{-12}	Unknown
Flex Paging Signals	930 to 931 MHz	Y	Y	N	<100 μs	NA	Y
WAAS	Overlay on GPS L1 frequency	Y	Y	Y	20 ns	2×10^{-13}	Y
GOES	468 MHz	Y	Y	N	<100 μs	5×10^{-10}	Unknown (c)
Terrestrial Analog TV	Various, VHF and UHF bands	Y, PBS	N	N	100 ms	3×10^{-6} (a) $<1 \times 10^{-10}$ (b)	Y
DBS Satellite TV	12.2 to 12.7 GHZ	Y	N	N	100 ms	$<1 \times 10^{-8}$ (a) $<1 \times 10^{-11}$ (b)	Y
AM Radio	530 to 1710 kHz	N	N	N	NA	1×10^{-5} (a) $<1 \times 10^{-8}$ (b)	Y
FM Radio RDS or SPOT	87.5 to 108 MHz	Y	N	N	<100 ms	1×10^{-5} (a) $<1 \times 10^{-10}$ (b)	Y

(a) probable performance, based on legally required or typical system tolerance (b) potential performance
(c) NIST to discontinue involvement on January 1, 2005

radios. An estimated 15% of the approximately 5000 FM radio stations in the United States now utilize RDS. The RDS includes a time code containing the Modified Julian Date (MJD), the UTC hour and minute, and the local time zone offset. This time code is transmitted every minute. Although not intended for precise timekeeping, the RDS specification calls for the time as broadcast to be within 100 ms, or for the transmitted codes to be set to zero.[25]

The Smart Personal Objects Technology (SPOT) developed by Microsoft and SCA Data Systems is similar to RDS, but uses a 67 kHz FM subcarrier to send a time code. Watches and other small electronic devices that receive the SPOT signals are expected to appear in late 2003 and work in 100 large metropolitan areas across the United States.

Summary

Many signals scattered throughout the radio spectrum can be used for frequency calibrations and time synchronization. Table 3 provides a summary.

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