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The Evolution of Time Measurement, Part 5: Radio Controlled Clocks

Frustrating as it is to time metrologists, a group of independent clocks can't keep the exact same time. To prove this, synchronize a group of wristwatches and then check them again a month later. You'll likely find that they disagree with each other by at least a few seconds. If you attempt the same exercise with a group of cesium clocks, the time differences will be tiny, nanoseconds instead of seconds, but again, the clocks won't keep the exact same time.

The British horologist Frank Hope-Jones recognized these problems more than a century ago and became an advocate for collectivism, rather than individualism in clocks. The clocks of Hope-Jones' era were typically self-wound, were synchronized from different sources, and ran at very different rates. Therefore, none of them would come close to agreeing with the others. In 1900, he wrote:

> *Time-keeping is essentially one of those things that can be done much better by a Municipality, or a Company than by the individual. What is every one's business is nobody's. There is not an argument in favour of the public supply of such commodities as electricity, gas, or water, which does not apply with equal or even greater force to the distribution of time. Anything like correct measurement of time is a delicate operation, so difficult indeed that absolute accuracy is impossible even with the aid of carefully compensated seconds pendulums in our observatories. How then can we expect to do it for ourselves in every room and in every office, with clocks in which the length of the pendulum and the quality of the works are sacrificed to the ornaments of the cases?* [1]

Hope-Jones realized that there was more to timekeeping than simply designing more accurate clocks. He noted that to make clocks keep uniform time, "we must strike at the root of the evil – their *independence*." No matter how perfect their oscillators, all clocks needed to be periodically synchronized to a common reference so they could lose their independence. It would be best if this synchronization were automatic. Hope-Jones devoted years to this problem by developing systems where a master clock synchronized a group of electrically connected slave clocks to display the same time [1], [2].

Before clocks distributed across a large geographic area could lose their independence, a reference clock would have to somehow send time signals across long distances. This was an old idea even at the time of Hope-Jones' suggestions – time signals from the Royal Observatory in England were sent as electrical impulses over telegraph lines as early as 1852 [3]. However, the perfect medium for distributing time would prove to be wireless telegraphy, later known as radio. We'll begin the final installment of this series by looking at the origins of the radio controlled clock (RCC) and then move on to explore more recent developments.

Early History

The idea of a RCC is nearly as old as radio itself. Sir Howard Grubb, an optical instrument maker and engineer, made the first public suggestion of an RCC in November 1898, some five months before Guglielmo Marconi sent wireless signals across the English Channel. While addressing the Royal Dublin Society, Grubb remarked that:

> *There is something very beautiful in this action of the "Marconi" wave. In a city supplied with this apparatus we should be conscious as we hear each hour strike that above us and around us, swiftly and silently, this electrical wave is passing, conscientiously doing its work, and setting each clock in each establishment absolutely right, without any physical connection whatsoever between the central distributing clock, and those which it keeps correct by means of this mysterious electrical wave.*
>
> *… [I]t undoubtedly would be perfectly possible to carry an apparatus in one's pocket, and have our watches automatically set by this electrical wave as we walk about the streets* [4], [5].

Within five years of Grubb's prophetic suggestion, the United States Navy had broadcast a radio time signal in telegraphic code. The transmitter was in Navesink, New Jersey,

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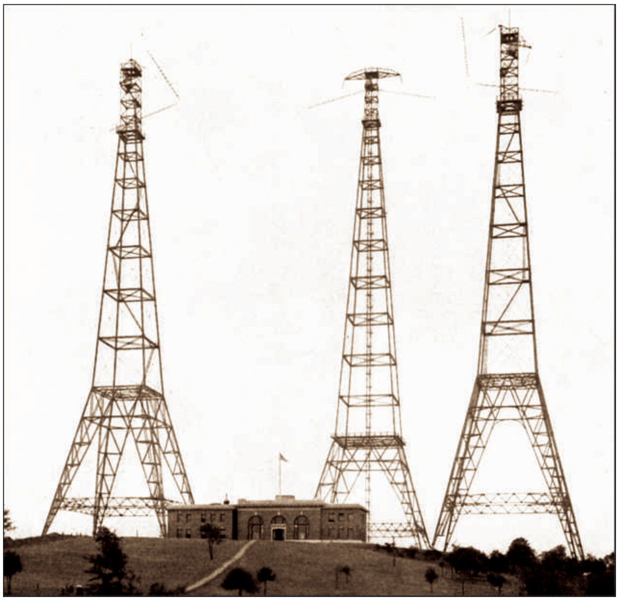
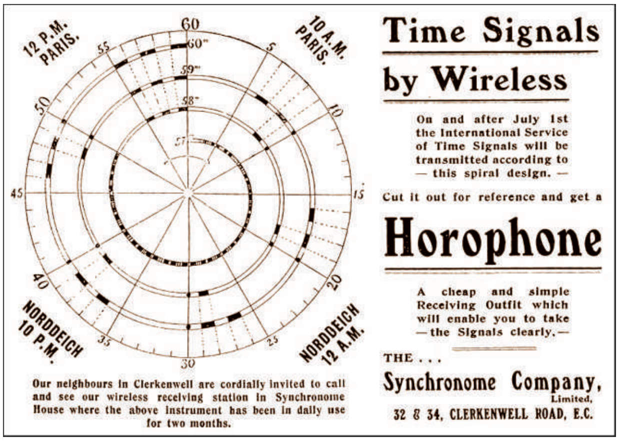


Fig. 1. The NAA transmission towers at Arlington, Virginia. The tallest tower was 183 m high, about 14 m taller than the nearby Washington Monument.

where time signals were received over telegraph lines from a reference clock located at the United States Naval Observatory (USNO) in Washington, DC. Regularly scheduled time signal broadcasts began about a year later, on August 9, 1904, from the Navy Yard in Boston, Massachusetts [6], [7].

The Navy was serious about timekeeping. They developed a network of time signal stations that remained in operation until World War II. The best known station was NAA, which began broadcasting in 1913 from Arlington, Virginia. Once the world's most powerful radio station, NAA broadcast a 54 kW signal at a frequency near 120 kHz (other frequencies were also used) from three large transmission towers (Fig. 1). The reference time came by wire from a USNO clock across the Potomac River, and the time was said to be accurate to "1/20 of a second" when it reached San Francisco [8], [9]. The time signals sent by the Navy stations were easy to decode. All stations began sending dots at 11:55 a.m., five minutes before noon. The dots were sent one second apart, with no signal sent on the twenty-ninth second of each minute or during the last five seconds of each of the first four minutes. During the last minute before noon, the dots would stop ten seconds before the end of the minute. A long dash was sent exactly at noon, serving as an on-time marker [10].

The best known time station in Europe was operated by the French Bureau of Longitude in Paris. Radio station FL began broadcasts from an antenna atop the Eiffel Tower on May 23, 1910. The frequency of the original broadcast was near 150 kHz, and the radiated power was about 40 kW.



Time Signals by Wireless

On and after July 1st the International Service of Time Signals will be transmitted according to — this spiral design. —

Cut it out for reference and get a

Horophone

A cheap and simple Receiving Outfit which will enable you to take —the Signals clearly.—

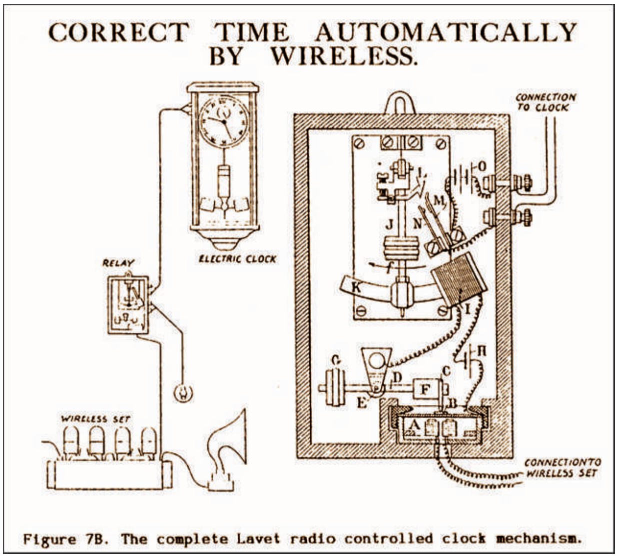
THE . . .
Synchronome Company,
Limited,
32 & 34, CLERKENWELL ROAD, E.C.

Our neighbours in Clerkenwell are cordially invited to call and see our wireless receiving station in Synchronome House where the above instrument has been in daily use for two months.

Fig. 2. Advertisement for the Horophone.

Time signals were sent daily, referenced to the clocks at the nearby Paris Observatory. The signals spanned the Atlantic Ocean and served their intended purpose, which was to allow ships at sea to adjust their marine chronometers. Others, including railroad workers, clock makers, and jewelers, soon began decoding the signals to obtain accurate time. Regularly scheduled time broadcasts began in June 1913. The frequency, format, and schedule for the time signals were repeatedly changed, but the French somehow managed to keep FL on the air through World War I and into the 1920s [11], [12].

The first devices that could be loosely classified as RCCs weren't really clocks at all. Rather, they were receiving sets designed for listening to time signals from FL, NAA, and other stations. These sets were equipped with signal charts that explained the telegraphic code.



CORRECT TIME AUTOMATICALLY BY WIRELESS.

Figure 7B. The complete Lavet radio controlled clock mechanism.

Fig. 3. One of Lavet's Early RCC Designs.

Fig. 4. Junghans MEGA 1, the first radio controlled wristwatch.

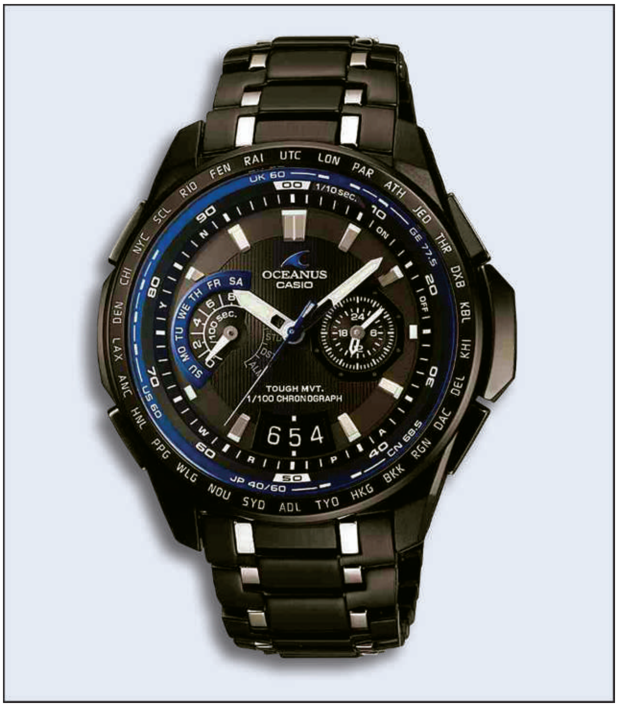


Fig. 5. A "multiband" radio controlled watch.

Listeners who decoded the signals could then manually set a clock on time. The clock sometimes came with the set. One early product was the *Horophone*, invented by Frank Hope-Jones and offered for sale in 1913 by the Synchronome Company in London (Fig. 2). Several other companies sold products of this type, including the radio company founded by Marconi.

Semi-Automatic Radio Controlled Clocks

There were obviously no digital time codes or microprocessors in the early days of radio, so there was no easy way for a clock to automatically set itself. Thus, the first RCCs were semi-automatic. An operator needed to set the clock display close to the correct time before the reception of a radio time marker. Once the time marker was received, the clock would synchronize by aligning itself with the marker and continue to correct its time when further markers were received. Building such a clock was a daunting task, and early RCCs were elaborate electro-mechanical machines built for research purposes and specialized applications. Few were ever sold commercially.

There is no clear consensus on who invented the RCC, although two strong candidates are Marius Lavet and Alfred Ball. Lavet, a French horologist and inventor, worked on RCC designs throughout the 1920s (Fig. 3 shows one design), although apparently none went into production [13]. He went on to invent the Lavet type stepping motor found in many millions of electrical clocks and wristwatches.

Ball is probably the stronger candidate. An English clockmaker, Ball began his wireless experiments before 1915 and was an early advocate of the "wireless control, or rather supervision, of public clocks" [14]. From 1928 until his death in 1932, he published an intermittent series of two to three page articles in the *Horological Journal* entitled "The Automatic Synchronisation of Clocks and Wireless Waves". Ball's work centered around the use of the *Pul-Syn-Etic* clock system which he had helped invent. This system included a master clock that could synchronize the dials of other clocks. In 1922, Ball patented a device that could synchronize the master clock to the Eiffel Tower time signals. His later clocks synchronized to the Greenwich Time signals broadcast by the British Broadcasting Corporation (BBC).

Ball's clocks used electrical impulses from radio signals to set the hands on time and to regulate the speed of the pendulum [15]. It was noted in 1928 that Ball's clock "has operated without any attention whatever for the last six months, and the maximum error recorded has not exceeded one second fast or slow" [16]. Other "semi-automatic" RCCs were built and patented during the period from about 1920 to 1960, including some notable work in the 1920s by Thaddeus Casner of the Radio Electric Clock Corporation, who designed clocks that synchronized to NAA [10], [17]. However, RCCs remained a novelty until digital time codes and advances in electronics made automatic time setting possible in the 1960s.

Digital Time Codes and the First "Automatic" RCCs

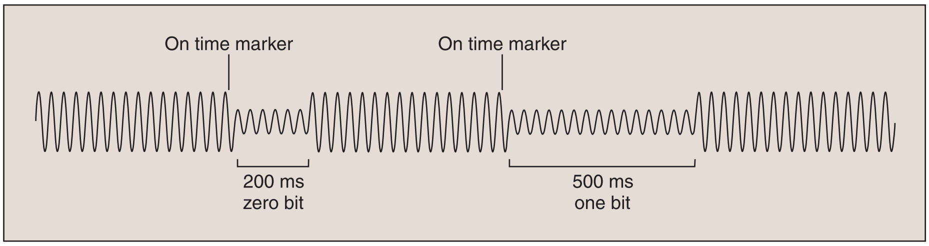


Fig. 6. Pulse width modulation by reduced carrier transmission.

Digital time codes contain hour, minute, and second information in addition to an on-time marker – everything necessary for an RCC to set itself from the airwaves without human intervention. The National Bureau of Standards (NBS) began the first digital time code service in the United States from shortwave radio station WWV in 1960 [18]. The code was not broadcast during every minute and found few applications. RCCs that received WWV were eventually sold but were never common, probably because shortwave signals are hard to reliably receive without a large outdoor antenna.

Low frequency (LF) signals were better suited for digital time codes, and NBS added a time code to its 60 kHz WWVB broadcasts on July 1, 1965. Designed by David Andrews, the first application of the new time code was to add time markers to strip chart recordings, particularly for the timing of seismic events [19]. Within a few years, clocks appeared that could automatically decode and display WWVB time. The first "automatic RCC" was probably a WWVB clock, most likely the Develco 3391, which was providing accurate time for the electric power industry by 1969 [20]. Other models followed, and some hobbyists began building RCCs in the early 1970s. For the most part, however, these clocks were unknown to the general public, and their use was limited to scientific and industrial applications. Another decade passed before they finally entered homes and offices.

Low Cost RCCs for Homes and Offices

RCCs first appeared in homes and offices about eighty years after the first time signal broadcasts. The new generation of low cost RCCs was made possible by the invention of the microprocessor, the miniaturization of antennas and electronic components, and sophisticated manufacturing techniques. The first consumer-oriented RCCs appeared in Europe in the late 1970s and early 1980s and tuned to the German station DCF77 on 77.5 kHz, which began broadcasting a digital time code in 1973 [21]. DCF77 was also the timing source for the first radio controlled watch, the Junghans MEGA 1 (Fig. 4), which debuted in 1990 with an antenna inside the wrist band [22]. Countless other RCC products followed in Europe, the United States, and Asia, and many millions of radio controlled clocks and watches are now sold annually.

The LF time signal stations are operated by the organizations responsible for keeping the official time in their countries. The primary time stations are BPC in China, MSF in England, DCF77 in Germany, JJY in Japan, and WWVB in the United States. These stations use different time code formats, but it is now common for RCCs to work with more than one station because the frequencies and modulation schemes are similar. For example, the watch shown in Fig. 5 can synchronize to signals from all five of the countries listed above.

Most recent developments in radio have involved microwave frequencies, so the low cost RCCs are definitely "retro". They receive signals in the 40 to 80 kHz range, the same part of the spectrum once used by early stations such as FL and NAA. The technology is old, but it works well for time signals. Very little bandwidth is required to send a time code, and LF signals can cover a wide area with relatively low power. The long wavelength signals can also pass through buildings and walls and be received indoors, which provides an advantage over the time signals broadcast by satellite.

To illustrate how they work, consider a clock that synchronizes to WWVB. Located in Fort Collins, Colorado, WWVB broadcasts a 70 kW signal at 60 kHz that reaches the entire United States during the nighttime hours. The signal originates from a group of cesium clocks that keep time within a few nanoseconds of the national time standard. The binary time code is generated by simply lowering and raising the power of the carrier. The carrier power is dropped by more than 90 % at the start of each second. This power drop is the on-time marker. The power is held low for 0.2 s to send a binary zero or for 0.5 s to send a binary one (Fig. 6). This form of modulation is sometimes called amplitude shift keying but is more properly referred to as pulse width modulation by reduced carrier transmission. This is because the information contained in the signal is demodulated by looking at the pulse widths (duration) rather than the amplitude. The bits are sent at the glacial rate of one bit per second, and a full minute is required to send a complete time code. The time code is amplified and transmitted through an immense antenna array that covers about 30 acres of land area and is suspended from towers more than 120 m tall.

A WWVB controlled clock contains both a quartz clock and a miniature receiver. The clock keeps time with a small quartz oscillator that operates at 32768 Hz, the same type of device found in a quartz watch. The receiver is permanently "tuned" to WWVB with a second quartz oscillator that matches the 60 kHz frequency of the broadcast. A small antenna is hidden

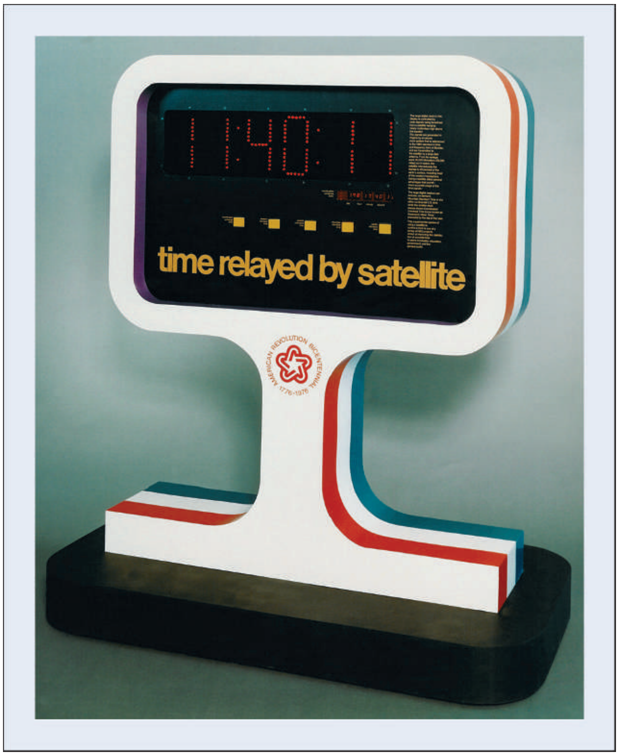


Fig. 7. A satellite clock built for the U. S. Bicentennial in 1976.

inside the clock case. The case is normally made of plastic, because a metal case could prevent the signal from reaching the antenna. The antenna must be small enough to fit inside the case (some are less than 20 mm long) and is typically a ferrite bar wrapped with a thin coil of wire. The receiver sends a string of bits to a processing unit that decodes the message and then synchronizes the quartz clock. The time code is in Coordinated Universal Time (UTC) format, so the hour differs from the local hour. The processing unit converts UTC to local time, based on a time zone setting selected by the user.

The clock is normally synchronized once every 24 hours, typically at night when the LF signal is easier to receive. The quartz oscillator is normally within a fraction of a hertz of its nominal frequency, so one synchronization per day is usually enough to maintain one second accuracy. Accuracy at the time of synchronization is usually within a few hundredths of a second [23].

Satellite Clocks

Satellite time signals now dominate the high accuracy timekeeping world. The first automatic RCC that received signals from satellites was built at NBS in 1976. Designed by a team led by Dick Davis, the clock used the 4-bit Intel 4004 as its central processing unit, which is generally regarded as the first microprocessor. It received a time code that was relayed from a ground clock through the geostationary GOES satellites at a frequency near 468 MHz. Fig. 7 shows a version of an early satellite clock that was built to commemorate the U. S. Bicentennial [24].

GOES clocks could do something no previous RCCs could do: they could compensate for path delay, or the time required for the signal to travel from the reference clock to the RCC. The satellites broadcast a message that included their position in addition to the time. If the user keyed in the coordinates of the GOES clock antenna, the clock could calculate the distance between the ground station and satellite and between the satellite and the receiver and convert these distances to path delays. The received time was then advanced by the amount of the path delays. This made GOES clocks accurate to within 100 µs. This was considered impressive for a few years, but GOES clocks were eventually made obsolete by Global Positioning System (GPS) satellite clocks.

The importance of GPS to timekeeping is hard to overstate. GPS has become not only a globally available navigation system, but also the main system used to distribute accurate time signals. The GPS constellation includes as many as 32 satellites in semi-synchronous orbit. Each satellite carries atomic clocks that are referenced to the USNO, the same organization that controlled the first radio time signals over a century ago. The satellite clocks are required to be exceptionally accurate in order for GPS to meet its requirements as a navigation system. To illustrate this, consider that the maximum acceptable contribution from the satellite clocks to the positioning uncertainty is about 1 m and that the satellites can receive time corrections from Earth only once or twice per day. Because light travels at a speed of about 3×10^8 m/s, the 1 m requirement means that the satellite clocks need to stay accurate to within about 3.3 ns for periods of up to one day.

The satellites broadcast on several frequencies, but most GPS clocks only receive the L1 carrier at 1.57542 GHz. Time is recovered from the satellites through a series of range measurements that first determine the receiver's position. Then, by using the travel time of the signal and the exact time when the signal left the satellite, time from the satellite clocks is transferred to the receiver clock. This time difference between the satellite and receiver clocks, when multiplied by the speed of light, is a distance called the range. However, it is not the true geometric range but rather the pseudorange. The pseudorange (p) is calculated as

$$p = \rho + c \times \left(dt - dT\right) + d_{ion} + d_{trop} + rn \qquad (1)$$

where c is the speed of light, ρ is the geometric range to the satellite, dt and dT are the time offsets of the satellite and receiver clocks with respect to GPS time, d_{ion} is the delay through the ionosphere, d_{trop} is the delay through the troposphere, and rn represents the effects of receiver and antenna noise [25], [26].

The GPS time code includes the number of weeks, seconds, and leap seconds since January 6, 1980, the day the GPS time scale originated. This information can easily be converted to hours, minutes, and seconds and displayed by a clock. GPS clocks are far more accurate than the satellite clocks that preceded them, because the satellite clocks are very tightly controlled, and because the pseudorange data makes it possible to compensate for path delay with uncertainties of just a few nanoseconds. The largest factors that limit accuracy are receiver and antenna cable delays and antenna coordinate errors. However, even an uncalibrated GPS clock should be accurate to within 1 μs, and calibrated clocks are typically accurate to within 0.1 μs.

The first experimental GPS satellite was launched in 1978. The first receiver used as a clock was developed by Stanford Telecommunications and delivered to the USNO in 1979 [27]. This receiver and other early models used for timekeeping [28] could track only one satellite at a time. Today, GPS receiver circuits that cost just a few dollars can simultaneously track twelve or more satellites and are small and inexpensive enough to be embedded inside many types of clocks.

Disciplined Oscillators

A disciplined oscillator is a more sophisticated variation of a radio controlled clock that serves as a standard of both time and frequency. A simple RCC periodically corrects the time of a clock, although it does not adjust the frequency of the clock's oscillator. In contrast, a disciplined oscillator continuously adjusts its frequency to agree with the radio reference, typically with a combination of hardware and software that functions as a phase locked loop. The first step is to compare the local oscillator phase to the phase of the incoming radio reference signal. Then, based on the results of this comparison, the local oscillator is adjusted to keep it phase locked to the reference. The best devices can output standard frequency signals, typically 10 MHz, with a stability that rivals a cesium clock. Most disciplined oscillators also function as very accurate RCCs and provide a digital time display.

The idea of a disciplined oscillator was probably first suggested by John Pierce of Harvard University. A recognized radio expert, Pierce measured the performance of quartz and atomic clocks with very low frequency (VLF) and LF radio signals for a number of years. He noted the "obvious relation between the measurement of a frequency of an oscillator and the automatic control of that frequency," and described four different methods of measurement and control in a 1957 paper [29]. Pierce's work was influential, and LF disciplined oscillators were commonly used as laboratory frequency standards until time signals began to be broadcast from satellites.

We noted at the beginning of this article that a group of clocks cannot keep exactly the same time. However, some telecommunication networks require groups of thousands of clocks to continuously keep time to within one microsecond of each other, and they often need frequency accurate to within 1 × 10^{-11}. Cesium clocks (discussed in Part 3 of this series) could easily meet the frequency requirements but not the time requirements, because they cannot synchronize themselves. Even if they were all individually synchronized, they would still be unable to indefinitely keep time to within one microsecond, and the cost of installing thousands of cesium clocks would be prohibitive. GPS disciplined oscillators were the perfect solution for network providers and hundreds of thousands of units have been installed in the United States alone. As a result, GPS is usually the time reference for what has become the most common RCC of all, the mobile telephone.

Fig. 8. Mobile phones include a radio controlled clock (Courtesy of HTC).

Mobile Phones and their Effect on Timekeeping

As we all know, mobile phones are now more than just phones: they function as text messaging systems, cameras, web browsers, navigation devices, music players, book readers, video games, FM radios, and even as televisions. Buried somewhere inside of all that functionality, a mobile phone is also a radio controlled clock! The clock on a mobile phone is usually accurate to a fraction of a second, even though it typically displays only hours and minutes (Fig. 8). Phones that are part of Code Division Multiple Access (CDMA) networks receive time signals from base stations that keep time to within one microsecond, thanks to GPS. Although additional delays occur as the signals travel from the base station to the phone, the received time is still accurate to within a few microseconds. Not all mobile phone networks are synchronized to GPS, but most still deliver very accurate time. Mobile phones can also get time from sources other than the phone network. For example, they can display web clocks or run clock applets that synchronize through the Internet. Some phones have embedded GPS capability and can display time directly received from GPS.

As you might guess, the success of the mobile phone has taken its toll on the wristwatch. Because our mobile phones are always with us, some of us have stopped wearing watches. A United Kingdom survey estimated that one out of seven people no longer wear a watch, and that this figure is twice as high among fifteen to twenty year olds [30]. Of course, watches are fashionable dress and jewelry items, and billions already exist, so they won't disappear anytime soon. However, unless your watch is radio controlled, your mobile phone probably keeps more accurate time.

The recent proliferation of radio controlled clocks is one of the more significant events in the history of time measurement. A century of gradual progress has fulfilled Hope-Jones's vision: we have taken away the independence of clocks by forcing them to agree with each other. Thanks to radio control, clocks with sub-second accuracy are no longer a novelty. In fact, we now take them for granted.

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