How Accurate is a Radio Controlled Clock?

by Michael A Lombardi.

The advertisements for radio controlled clocks and wristwatches often make sensational claims about the accuracy of the products. One overly enthusiastic writer penned this memorable bit of ad copy:

'We're still perfecting Einstein's theory. We must apologize that our Atomic Watch loses 1 second every 20,000,000 years. Our scientists are working diligently to correct this problem…'

While this particular advertisement contained more hyperbole than most, it was not alone in referring to a radio controlled clock (RCC) as an atomic clock, a claim made in nearly all sales pitches and product literature. The claim, of course, is false. The oscillator found inside an RCC is based on the mechanical vibrations of a quartz crystal, typically counting 32,768 vibrations of the crystal to mark one second. A true atomic clock oscillates based on the energy transitions of an atom and 'ticks' much faster. For example, the second is defined internationally as the duration of 9,192,631,770 energy transitions of a cesium atom.

Although advertisers are wrong when they call an RCC an atomic clock, they are correct in stating that an RCC benefits from atomic timekeeping. An RCC periodically synchronizes its quartz oscillator to a real atomic clock by receiving a time signal from one of the radio stations listed in **Table 1**. Some RCCs are capable of receiving just one station, and must be within the coverage area of that station in order to work. Others, including many wristwatches, are now capable of receiving all of the stations in **Table 1** and will synchronize to the signal from the nearest station[1].

Now that we've established that a RCC is not a real atomic clock, but simply a quartz clock periodically synchronized by radio, can we determine its true accuracy? The answer is yes, but at least four questions first need to be answered:

· How accurate is the time kept at the radio station?
· How long does it take for the radio signal to travel from the station to the RCC?
· When the signal arrives, how accurately is the RCC's display synchronized?
· How accurate is the RCC's quartz crystal oscillator between synchronizations?

We'll look at each question in turn, using the U.S. radio station WWVB, **Figure 1,** as an example.

1. Aerial view of NIST time signal station WWVB.

### Q1. How accurate is the time kept at the radio station?

Time signal stations synchronize their clocks to Coordinated Universal Time (UTC), the international standard for timekeeping. No clock keeps UTC exactly because UTC is an average time, calculated with data collected from hundreds of atomic clocks located around the world. The calculations are performed by the Bureau International des Poids et Mesures (BIPM) in France. Laboratories such as the National Institute of Standards and Technology (NIST) in the United States keep local versions of UTC that closely agree with the BIPM's calculations. The NIST version of UTC, called UTC(NIST), is generated by averaging an ensemble of cesium beam and hydrogen maser clocks. The ensemble is periodically calibrated using a cesium fountain clock called NIST-F1, which serves as the primary time interval and frequency standard for the United States[2].

Figure 2 shows the time difference between UTC(NIST) and UTC over a one-year period with the data points taken at five-day intervals[3]. During the year, UTC(NIST) never varied from UTC by more than 20 nanoseconds (0.000 000 020 s). Thus, while there is technically a difference between UTC(NIST) and UTC, the difference is miniscule and for all practical purposes can be ignored.

The time signal stations listed in **Table 1** are located some distance away from the timing laboratories that control them, typically in rural areas where there is enough space for their antennas. For example, the NIST timing laboratories are in the city of Boulder, Colorado, and WWVB is located in a rural area about 78 km away. Therefore, UTC(NIST) in Boulder is not directly connected to WWVB. Instead, WWVB has its own

Station Call Sign	Frequency (kHz)	Country	Controlling Organization
BPC	68.5	China	National Time Service Center (NTSC)
DCF77	77.5	Germany	Physikalisch-Technische Bundesantalt (PTB)
JJY	40, 60	Japan	National Institute of Information and Communications Technology (NICT)
MSF	60	United Kingdom	National Physical Laboratory (NPL)
WWVB	60	United States	National Institute of Standards and Technology (NIST)

Table 1. Time Signal Stations used by RCCs.
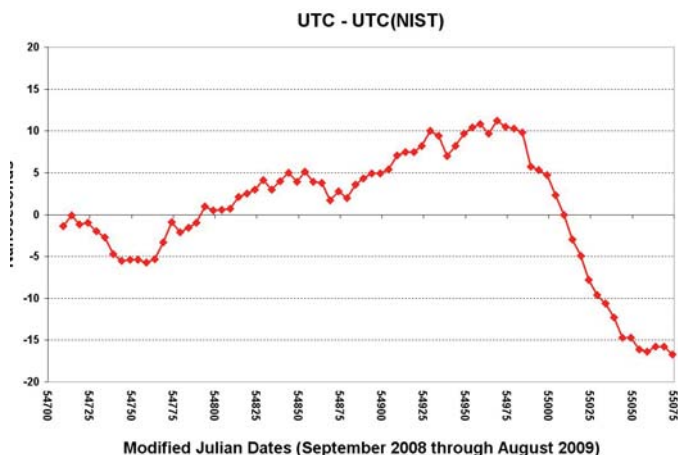
2. UTC(NIST) Time Scale compared to Coordinated Universal Time.
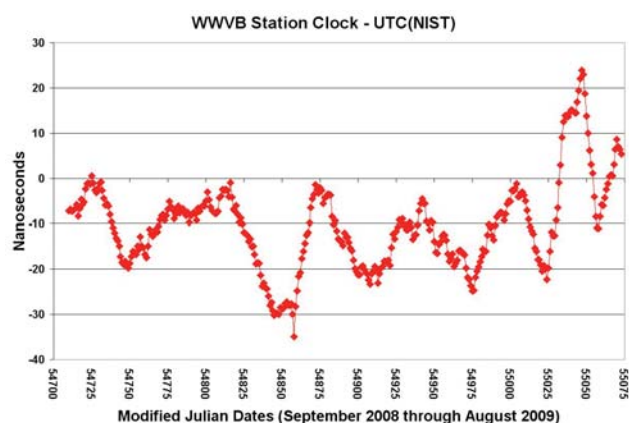
3. WWVB Station Clock compared to UTC(NIST) Time Scale.

clock, actually a group of cesium beam clocks, that are steered to agree with UTC(NIST) in Boulder by making time comparisons using satellites[4].

Figure 3 shows the difference between UTC(NIST) and WWVB station time over the same one year interval shown in **Figure 1** (here the data points are at 1-day intervals). Note that the station clock never varied from UTC(NIST) by more than 35 nanoseconds (0.000 000 035 s). Again, for all practical purposes, the differences are so tiny they can be ignored. In fact, the frequency offset of the station clock is less than 1×10^{-15}. If this frequency offset were held constant, it would take more than 30 million years before the accumulated time error reached one second. If the advertising writer was referring to the station clock, and not the RCC, you could actually argue that they were being conservative.

Q2. How long does it take for the radio signal to travel from the station to the RCC?

The exceptional accuracy of the station clock becomes a moot point once you start to consider the problem of path delay. There is some path delay before the signal even leaves the radio station. Once the time signal is generated from the station clock, it passes through a transmission system that includes the radio transmitters, the antenna feed lines, and the antennas themselves.

At WWVB this delay is about 0.000 017 s[5] or about one thousand (10^3) times larger than the time difference between the station clock and UTC. Even so, it is still too tiny to matter to RCC users, so the station does not advance its signal to compensate for the transmission delay.

Once the signal leaves the transmitter and enters free space, it travels at the speed of light to the RCC, approximately 0.000 003 336 seconds per kilometer. If you know the location of your RCC and the location of the time signal station, you can calculate the distance between the transmitter and the receiver, and estimate the amount of this delay. For example, a 3000 kilometer path would delay the time signal by about 10 milliseconds (0.01 s). This assumes, of course, that the signal travels along the ground and covers the shortest possible distance between the station and the RCC.

For the low frequencies used by the time signal stations in **Table 1,** a groundwave path can be assumed for short distances, perhaps up to 1500 km, but at longer distances the signal might bounce off the ionosphere (skywave) and take slightly longer to arrive. Even so, it is safe to assume that the path delay will be less than 20 milliseconds (0.02 s) because the signal will rarely be usable at distances of more than 5000 km, and any additional delays introduced by skywave will be relatively small. However, for RCCs located on the east and west coasts of the United States the path delay is roughly 0.01 s, or about one million times (10^6) larger than the time difference between the station clock and UTC.

Q3. When the signal arrives, how accurately is the RCW's display synchronized?

The time signal stations in **Table 1** send information using a very simple modulation scheme. For example, WWVB broadcasts a continuous 60 kHz sine wave signal, but drops the carrier power by about 98% (17 dB) every second, restoring it to full power a fraction of a second later. This power drop serves two purposes. Its first purpose is to send bits of a binary time code, as the length of time that the power is held low determines whether a bit is a 0, a 1, or a frame marker. A complete time code is 60 bits long and thus requires 60 s to transmit. The second purpose of the power drop is to send an on-time marker (OTM) that is synchronized with UTC(NIST). The OTM is the first 60 kHz cycle that is sent at reduced power. For example, when the power is held low for 0.2 seconds to signal a 0 bit, 12,000 cycles are transmitted at low power, but only the first of these reduced power cycles is the OTM. In theory, an RCC should be able to synchronize to within one half of the period of 60 kHz, or within ±0.000 008 s of the OTM.

In practice, there are other problems. One is that the quartz crystal oscillator inside an RCC runs at a frequency of about half of the incoming radio signal (32.768 kHz), and thus even if the correct OTM were found, the quartz crystal could still be synchronized only to within half the period of its own frequency, or to within about ±0.000 015 s.
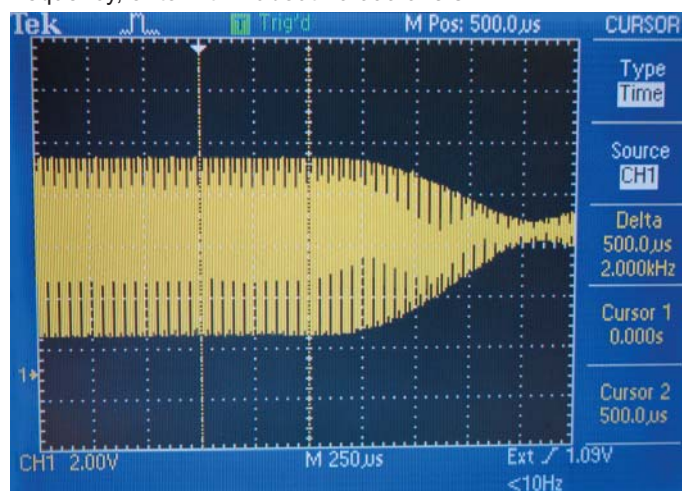
4. WWVB OTM as seen on an oscilloscope.

As it turns out, that doesn't matter because it is very difficult for the RCC to find the correct OTM. The WWVB waveform (Figure 4) has a long exponential decay that is related to the period of the antenna bandwidth. This makes it very difficult to determine exactly where the carrier power drop began. The actual OTM is located in the flat part of the waveform, before a noticeable drop in amplitude can be seen on an oscilloscope. Finding the OTM becomes even more difficult when the signal is weak or noisy, or when both groundwave and skywave signals are received. Therefore, the OTM synchronization accuracy is probably limited to about 1 millisecond (0.001 s), although the actual accuracy will depend upon the quality of both the received signal and the RCC's digital signal processing (DSP) firmware.

Processing delays also occur while the RCC's display is being synchronized to the right time. These delays include DSP software delays, the time required to retrieve the data from the microprocessor unit and to process and output the data, and the response time of the stepping motor used by analog clocks or the LCD display used by digital clocks. The processing delays can exceed 100 milliseconds (0.1 s), but the RCC manufacturer normally takes them into account, and advances the display to compensate. Even so, the amount of delay compensation will not be perfectly estimated, and a synchronization error of 10 milliseconds (0.01 s) is probably not uncommon.

Table 2 summarizes the accuracies discussed in the answers to the first three questions. Based on this analysis, it seems reasonable to expect that an RCC will be accurate to within 30 milliseconds (0.03 s) at the time of synchronization, with the path delay and synchronization errors the only two factors that really matter. However, a much larger time error is likely to accumulate during the interval between synchronizations, as will be seen in the answer to question 4.

Source of inaccuracy	Seconds
Radio station clock	0.000 000 050
Transmission system delay	0.000 017
Path delay (worst case)	0.020
OTM selection	0.001
Synchronization errors	0.010
RCC inaccuracy at time of synchronization	~0.03

Table 2. Sources of RCC synchronization inaccuracy.

Q4. How accurate is the RCC's quartz crystal oscillator between synchronizations?

Some RCCs schedule only one synchronization attempt per day, at 2 am, for example. If the synchronization attempt fails, they will wait 24 hours before trying again. Others are designed to schedule multiple attempts (at 2, 3, 4, and 5 am, for example). Some RCCs will attempt synchronization during each of their scheduled times, synchronizing again at 3 a.m. even if the 2 am attempt was successful. Other RCCs will skip the remaining attempts on the schedule after synchronization is achieved and wait until the next day to try again. For these reasons, the interval between synchronizations is typically either 24 hours, or just a few hours less than 24 hours.

It might seem reasonable to receive the radio signal more often because the signals are always being broadcast, and a synchronization attempt could be made at any time. However, the number of attempts is limited for several reasons. One reason is that the signal is much stronger at night and synchronization attempts during daytime hours are far more likely to fail. A second reason is that many RCCs are battery powered, and fewer synchronization attempts means longer battery life. The most important reason is simply that one synchronization per day is usually all that is needed to keep an RCC accurate to within a fraction of a second of UTC.

NIST has published guidelines recommending that RCCs keep time between synchronizations to within ±0.5 s of UTC(NIST). If this requirement is met, the time displayed on an RCC will always be correct when rounded to the nearest second[6]. At least one manufacturer of RCCs specifies the accuracy of their quartz crystals as ±15 s per month, which is essentially the same thing as ±0.5 s per day. This type of accuracy is now commonplace in low cost quartz oscillators[7]. It translates to a frequency offset of about 6×10^{-6}, more than one billion (10^9) times less accurate than the station clock!

While ±0.5 s per day is a reasonable benchmark, synchronization to within ±0.2 s is more desirable and achieved by many RCCs. An 0.2 s error is unlikely to be noticed by the human eye if an RCC is checked against an independent time reference, whereas a 0.5 s error might be. Of course, an accumulated time error of 0.2 s between synchronizations is still much larger than the other factors listed in Table 2. This means that an RCC will be most accurate immediately after a successful synchronization and will become less accurate from that point forward until the next synchronization.

To demonstrate this, the accumulated time error of an analog radio controlled watch was measured between synchronizations. A sensor was used, Figure 5, that could record the beat rate of the watch's stepping motor pulses. At the time of synchronization, it is assumed that the time error was 0, although in reality the synchronization accuracy is limited by the factors shown in Table 2. The assumption had to be made because the second hand stops during synchronization attempts, which in turns stops the sensor from collecting data. However, since the watch was operating near WWVB (the path delay was about 0.000 26 s), it was probably accurate to within 0.01 s of UTC(NIST) at the time of each synchronization.


5. Measuring an analog radio controlled wristwatch between synchronizations.

The measurement results are shown in Figure 6. The watch synchronizes five times daily, at midnight, 1, 2, 3, and 4 a.m. The midnight synchronization occurs after the watch has run for about 20 hours without adjustment and the amount of the correction is about 0.45 s. The other four synchronizations occur after the watch has run unadjusted for about one hour, and the correction is slightly larger than 0.02 s. This particular

watch narrowly meets the requirement of always remaining within ±0.5 s of UTC(NIST). Its performance can be considered typical of many RCC products.

This brings us back to our original question: How accurate is a radio controlled clock? The short answer is they should always be accurate to within one second of UTC, assuming that they synchronize at least every other day and that their quartz oscillator is of reasonable quality. The key, of course, is successful synchronization to a time signal station, because without that advantage an RCC is just a run of the mill quartz clock. Instead of the '20,000,000 years' mentioned by the ad writer, the watch measured in **Figure 6** would lose a second in about two days if it were unable to receive a radio signal and synchronize.
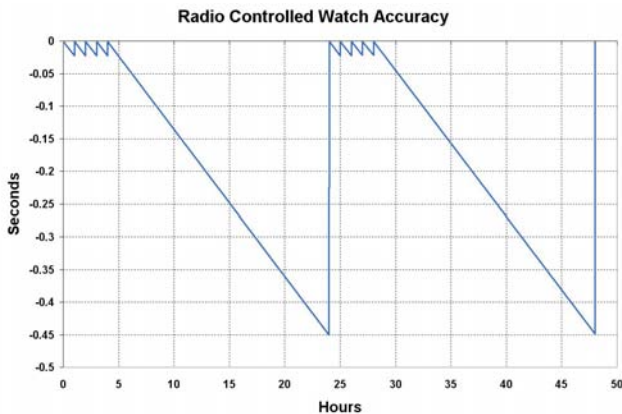
6. The performance of a typical radio controlled wristwatch.

On the other hand, if a RCC could miraculously be made to run for '20,000,000 years' and was somehow able to synchronize once every 24 hours, it would *never* lose a full second. Such are the benefits of atomic timekeeping.

Notes

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Author Notes

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Michael is currently in charge of the remote time and frequency calibration programs at NIST. He also works on numerous other time and frequency projects, including a time network that continuously compares the time standards of North, Central, and South America. He has published over 80 papers related to time and frequency. A member of IEEE, and an associate editor of *Measure: The Journal of Measurement Science*, Michael lives in Colorado with his wife and two daughters.