The Accuracy and Stability of Quartz Watches

by Michael Lombardi

Quartz wristwatches are neither as intricate nor as intriguing to many collectors as their mechanical counterparts, but with very few exceptions, they do a considerably better job of keeping time. At least one manufacturer of low-priced quartz watches specifies their accuracy as ±15 seconds per month, suggesting an accumulated error of just a few minutes per year. This type of accuracy is sufficient for most people, who are generally happy if their watch remains within a minute or two of the correct time. In fact, many quartz watch owners set their watches only a few times per year – typically when they change the battery, change time zones, or switch to and from daylight saving time. Unless their watch is broken or the battery is dead, its timekeeping accuracy is never in question.

But for those among us who view even the cheapest quartz watch as a precision scientific instrument, rather than as a piece of jewellery or as a disposable consumer item, some questions remain. For example, exactly how accurate is a 'run-of-the-mill' quartz wristwatch? Can they really keep time to within ±15 seconds per month? Does their accuracy vary over time? This article attempts to answer those questions. It characterises the performance of four low-cost quartz wristwatches by applying some measurement and data analysis techniques that are normally reserved for laboratory type frequency standards.

The Watches Under Test

The four quartz watches chosen for the test, **1-4**, are members of the author's pedestrian collection. While none of them will make a watch enthusiast's heart beat faster, they do have the virtue of being common; and similar watches have found their way on to many wrists. **Watch A** is an 'official' Mickey Mouse watch, purchased at Disneyland in California several years ago for about $35 USD. **Watch B** is a Rolex 'replica', purchased from a street vendor in South America for about $15 USD, and somewhat surprisingly, still running some two years later. **Watch C** is a 20-year old dress watch that originally sold (mid-1980s) for about $100 USD, and was worn everyday for more than a decade. **Watch D** is a typical discount store watch, a new (2007) Timex that sells for approximately $30 USD.


1-A


2-B


3-C


4-D

Like nearly all quartz watches, the four devices under test use 32.768 kHz (2^{15} Hz) quartz crystals as their oscillator. The quartz watch industry standardised on 32 kHz crystals in the early 1970s due to their reliability, their compatibility with existing electronic circuits, their small dimensions, and their low power consumption.[1] Since their introduction, watch manufacturers have continued to improve the timekeeping performance of quartz watches. Most of the advances have been related to crystal and mount miniaturisation, better electronics, better manufacturing techniques, and most importantly, making the crystal frequency less dependent on temperature.[2]

Accuracy versus Stability

The performance of a timekeeping device is usually stated in terms of its accuracy and stability, and measuring both characteristics was the goal of this test. Accuracy is related to the difference between a measured value and an ideal value. For example, a 'perfect' watch would agree exactly with Coordinated Universal Time (UTC), the international reference for time, time interval, and frequency. If a watch was synchronised to UTC and then found to be 1.3 seconds fast one day later, its time is said to be accurate to within 1.3 seconds per day. Frequency accuracy refers to the difference between the measured frequency of an oscillator and its nominal frequency, or an ideal frequency with zero uncertainty. For example, if a crystal with a nominal frequency of 32768 Hz is measured at 32768.5 Hz, its frequency is said to be accurate to within 0.5 Hz. Both time accuracy and frequency accuracy are normally expressed as dimensionless values by using the equations $\Delta t/T$ and $\Delta f/f$, respectively. The two equations produce equivalent answers when applied to the same device. Thus a time accuracy of 1.3 / 86400 (seconds per day) and a frequency accuracy of 0.5 Hz / 32768 Hz both result in a dimensionless accuracy value of about 1.5×10^{-5}.

Stability indicates how well a device can produce time or frequency with the same accuracy over a given time interval. It doesn't indicate whether the time or frequency produced by a device is accurate or inaccurate, but only whether it stays the same. In contrast, accuracy indicates how well a clock has been set on time or an oscillator has been set on frequency. To understand this difference, consider that an inaccurate device can be stable, and an unstable device can be at least temporarily accurate. For example, a quartz watch that gains exactly 10.5 seconds every day is very inaccurate, but very stable. It might be possible, then, to adjust the frequency of the crystal and make the watch both accurate and stable. In contrast, a watch that fluctuates within a range of ±5 seconds of the correct time is unstable, but on occasion would have the correct time and be considered accurate.

The Allan deviation (ADEV) is a statistic used internationally to estimate frequency stability.[3] It differs from the conventional standard deviation because it does not use the average accuracy of a device as a point of reference. Instead, it compares the frequency accuracy of the device under test during a given measurement period to its frequency accuracy during the previous measurement period. This reveals how an oscillator's frequency is changing over time due to effects such as frequency drift and aging. ADEV is regularly used to estimate the stability of devices ranging from high-performance mechanical watches[4,5] to the world's best atomic oscillators, and will be applied here to estimate the stability of the quartz watches under test. ADEV, expressed mathematically as $\sigma_y(\tau)$ is computed as

$$\sigma_y(\tau)=\sqrt{\frac{1}{2(M-1)}\sum_{i=1}^{M-1}(\bar{y}_{i+1}-\bar{y}_i)^2}$$

where the y_i series contains estimates of the frequency accuracy of the device under test, M is the number of values in the y_i series, and the data are equally spaced in segments τ seconds long.

The Measurement Method

To estimate their accuracy and stability, the watches were measured with a commercial watch analyser, **5**. This versatile device can simultaneously measure the frequency of both the quartz oscillator and the stepping motor pulses. The watch analyser sensor can automatically detect the quartz frequency through several available methods. If the watches have metal cases, as did all of the watches tested here, the mechanical quartz oscillations are acoustically recorded. The device can also capacitively record the stray electrical field from quartz oscillators with open movements or with cases made of synthetic material. It is also possible to derive the quartz frequency from the supply current if the analyser is providing power to the watch.[6]

5

The Watch analyser (with watch D resting on the sensor)

To get a true picture of the timekeeping capability of an analog quartz watch, simply measuring the quartz frequency is not adequate. It is also necessary to measure the stepping motor pulses, because many watches correct the frequency of the stepping motor to compensate for the frequency offset of the quartz oscillator. This correction system, sometimes called inhibition compensation, can be implemented in several different ways. One common way is to design the oscillating circuit so that the quartz crystal runs at a frequency slightly higher than nominal. To compensate for this intentional frequency offset, a programmable number of quartz oscillation pulses are suppressed before they are sent to the frequency divider that drives the stepping motor. This removes the frequency offset, and makes time derived from the stepping motor more accurate than time derived from the free running quartz. The duration of the inhibition period, usually 10 or 60 seconds, is automatically detected by the watch analyser. Quartz pulses might also be added or suppressed to compensate for the aging rate of the quartz crystal, or for temperature changes.

The watch analyser displays measurements of both the quartz frequency and the stepping motor with a resolution of 0.01 seconds/day. The measurements are referenced to the time base oscillator inside the watch analyser, and to support this resolution, the time base oscillator must have a frequency accuracy of better than about 1.2×10^{-7}. The watch analyser was calibrated before and after it was used to measure the watches under test. The calibration was done by locking a synthesised signal generator to the United States national frequency standard, and then deriving a reference 32768 Hz signal from the signal generator that was accurate to parts in 10^{13} or better. When this reference signal was applied to the watch analyser sensor, it was correctly found to be within 0.01 seconds/day. This indicated that the watch analyser was accurate enough to support its measurement resolution.

The watches under test were each measured for a period of at least 30 days. During the test, the watch analyser produced readings every minute for both the frequency of the quartz oscillator and the stepping motor. It also produced a temperature reading with a resolution of 1 °C. The watch analyser was interfaced to a computer through its RS-232 port, and all of the readings were stored for later analysis.

The readings returned by the watch analyser were expressed as seconds per day. This was converted to dimensionless frequency offset (accuracy) using the equation $\Delta t/T$. Average frequency accuracy was computed by simply averaging all of the 1 minute samples collected during the entire test. Frequency stability was estimated by use of the Allan deviation as previously described. The dimensionless frequency offset values served as the y_i data series. Because a new value was obtained every minute, the base averaging time, τ_0 was equal to 1 minute.

Measurement Results

Table 1 shows the measured accuracy of the watches under test, both as dimensionless frequency accuracy, and as time accuracy (seconds per day). Due to inhibition compensation, all of the watches are accurate to much better than 1 second per day. In response to our initial question, only one of the watches under test failed to meet the ±15 seconds per month specification that was discussed earlier. That was Watch C, the oldest watch in the test, and it missed by only a few seconds per month. The quartz oscillators in watches **A**, **B**, and **C** are not particularly accurate, with frequency offsets (perhaps intentionally introduced) ranging from 5.9 to 10 parts in 10^5. In contrast, the quartz oscillator in Watch D was a stellar performer, with an average frequency offset of just 8×10^{-7}, or less than 1 part per million. The accuracy of Watch D's stepping motor was nearly identical to the accuracy of its quartz oscillator, so it is not clear if inhibition compensation is used in the design. However, the watch analyser detected an inhibition period of 10 seconds, as reported in **Table 1**.

The stability estimates for the four watches are summarised in **Table 2** and illustrated in **6**. The eight lines on the graph show the stability of both the quartz oscillator and the stepping motor for each of the four watches. The graph is an 'all-tau' graph, meaning that it shows stability estimates for all possible values of τ, ranging from 1 minute to 1

Watch	Inhibition Period (seconds)	Dimensionless Frequency Accuracy		Time Accuracy (seconds per day)		Temperature during test (° C)	
		Stepping Motor	Quartz Oscillator	Stepping Motor	Quartz Oscillator	Range	Average
A	10	5.3×10^{-6}	7.9×10^{-5}	0.46	6.79	22 to 25	23.3
B	60	2.1×10^{-6}	5.9×10^{-5}	0.18	5.09	21 to 25	23.8
C	60	6.7×10^{-6}	1.0×10^{-4}	0.58	8.76	22 to 26	23.9
D	10	7.8×10^{-7}	8.0×10^{-7}	0.07	0.07	22 to 26	23.3

Table 1: The accuracy of the watches under test.

Watch	Stability (Allan deviation)							
	1 minute		1 hour		1 day		1 week	
	Motor	Quartz	Motor	Quartz	Motor	Quartz	Motor	Quartz
A	2.9×10^{-8}	4.6×10^{-8}	1.5×10^{-8}	1.3×10^{-8}	2.2×10^{-8}	1.8×10^{-8}	2.6×10^{-8}	2.2×10^{-8}
B	4.1×10^{-8}	8.4×10^{-8}	1.3×10^{-8}	1.3×10^{-8}	2.9×10^{-8}	3.2×10^{-8}	4.0×10^{-8}	4.0×10^{-8}
C	3.4×10^{-8}	6.7×10^{-8}	2.3×10^{-8}	2.0×10^{-8}	2.9×10^{-8}	3.1×10^{-8}	4.8×10^{-8}	5.4×10^{-8}
D	2.5×10^{-8}	6.6×10^{-8}	1.2×10^{-8}	1.1×10^{-8}	2.9×10^{-8}	1.7×10^{-8}	2.2×10^{-8}	1.6×10^{-8}

Table 2: The stability of the watches under test.

week (in 1-minute increments). It is interesting to note that the watches were most stable at τ = 1 hour, when all of the devices were stable to within less than 2.5×10^{-8}. At τ = 1 day, all of the devices were stable to at or near 3×10^{-8}, suggesting that their accuracy will vary by only a few milliseconds per day.

The Allan deviation graph for the watches under test

While inhibition compensation dramatically improved the timekeeping accuracy of three of the four watches (**Table 1**), it seemed to only significantly improve the stability at short averaging times. At longer averaging times, the stability of the stepping motor was about the same or worse as the stability of the quartz crystal. The crossover point where the stability of the quartz oscillator began to meet or exceed the stability of the stepping motor occurred at less than 25 minutes for watches **A** and **C**, and near 1 hour for watches **B** and **D**.

As might be expected, the variation in frequency for watches **A**, **B**, and **C** was larger at one week than it was at one day, due to the effects of frequency drift and aging. Frequency drift is generally attributed to factors *external* to the oscillator, including environmental factors such as temperature, vibration, and humidity. These factors were reasonably well controlled in the laboratory environment, and the watches were certainly subjected to fewer environmental changes than they would have been during normal use. However, it should be noted that the laboratory temperature during the tests (**Table 1**) was lower than optimal. Quartz watches are optimised to work best at a temperature that reflects the expected temperature of the watch in normal operation. If the watch is worn as intended, this means about 16 hours on the wrist, and about 8 hours off the wrist each day. If the watch is left off the wrist for extended periods, its accuracy can be expected to degrade. The angle of cut of the crystal resonator used in wristwatches is such that the zero temperature coefficient is usually in the range of 25 °C to 28 °C (27 °C is typical), which is warmer than the laboratory temperature during the test.

Aging is the systematic change in frequency with time due to *internal* changes in an oscillator. All quartz oscillators age, but the aging rate often depends upon its surface area to volume ratio of the crystal; and in theory, small, low frequency crystals will age slowly.[7] The results seem to support this, as the crystal in the watches under test all were stable to within about 5×10^{-8} or better at τ = 1 week, and watch **D** was nearly as stable at one week as it was at one day. The frequency stability of watch **D** suggests that its timekeeping accuracy would change by less than 2 milliseconds per day over the course of a week. Thus, in response to one of our questions, quartz watches do change their accuracy slightly over time, but the change is small and will probably not be noticeable to the owner of the watch.

Summary

Based on these tests, it seems likely that even the humblest quartz wristwatch can maintain time accurate to within less than 1 second per day with the aid of inhibition compensation. And due to the surprisingly good stability of 32 kHz quartz crystal oscillators, the accuracy of quartz wristwatches can be expected to change by only a small amount over time.

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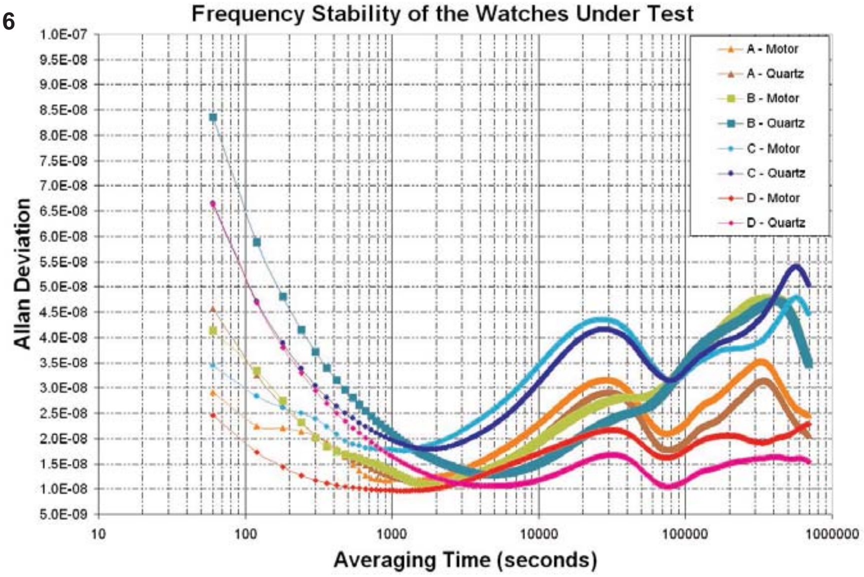
6



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