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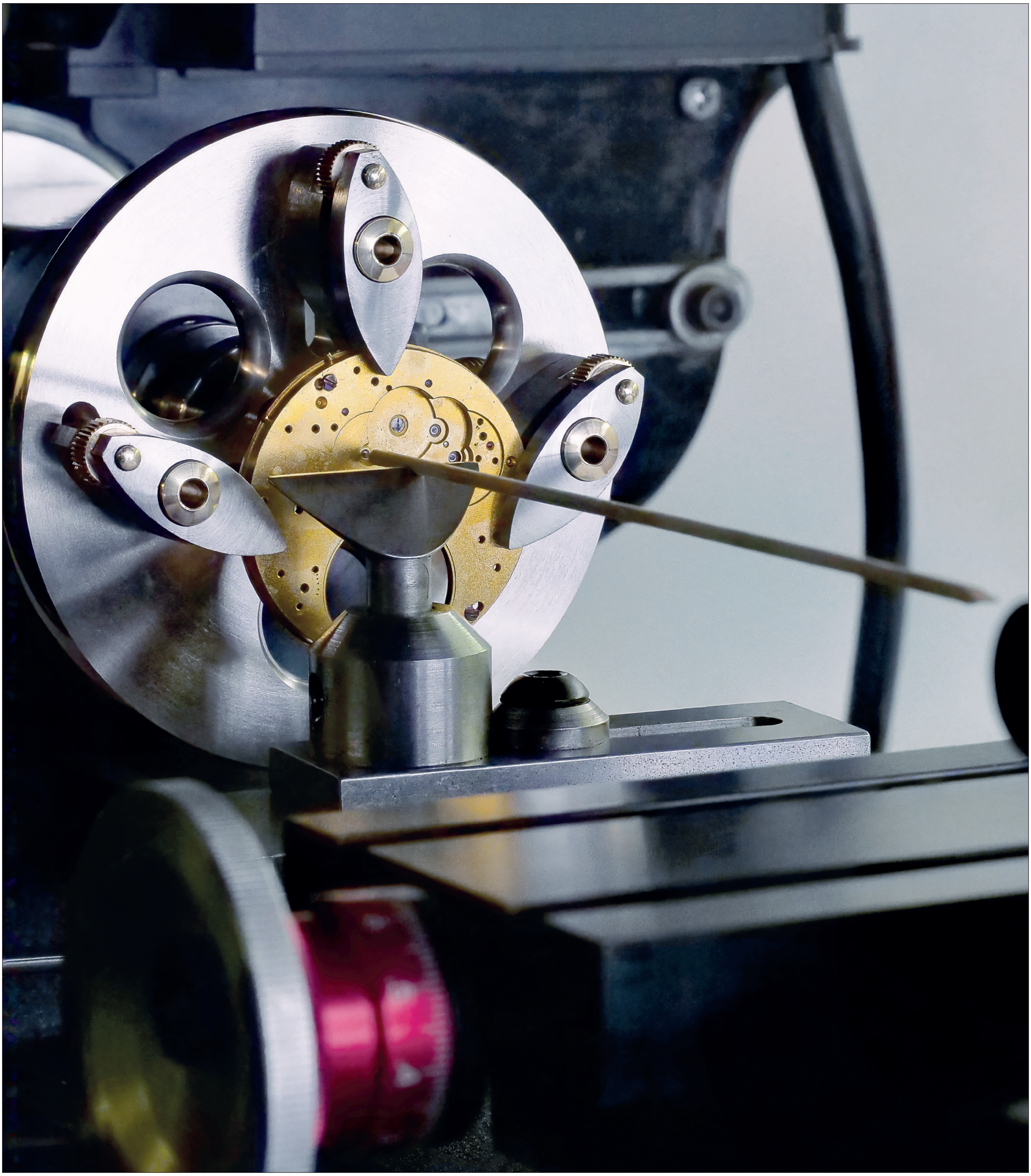


The Magic of the Twin Quartz Watch

Two Wrongs Make a Right

Malcolm Pipes FBHI

Introduction

Ideally, a quartz watch will keep a perfect rate, irrespective of external effects such as temperature, ageing and shock. This article highlights temperature changes as being the most significant cause of rate error, and discusses a compelling method to almost eliminate such errors using two similar quartz crystals in the same watch.

A Parabolic-Shaped Frequency Relationship

There are many different ways to 'cut' a quartz crystal, which will give different relationships between temperature and the associated frequency/rate variation when used in quartz electronic oscillators.

The vast majority of quartz watches use a single 'tuning fork cut' quartz crystal vibrating at a nominal 32,768 vibrations every second (32.768 kHz) as their frequency reference, and with very good reason.

This relatively low frequency is easy to divide by two just fifteen times (using a fifteen stage binary counter in the watch electronics) to produce one pulse per second, itself highly suitable to drive the stepper motor connected to the seconds hand of a watch.

The low frequency of the tuning fork cut crystal, with its associated divider electronics, allows the watch to operate with very low power consumption from the necessarily small physical size and amp-hour capacity battery. For example, a single CR2032 lithium battery can drive a watch for ten or more years. Tuning fork cut crystals (which are indeed tiny tuning forks within a sealed container) are relatively easy to produce in their millions at very low cost, which may be reflected in the low price of the watch.

As a piano tuner's metal tuning fork generates a particular fixed frequency, so the crystal tuning fork vibrates as a tiny mechanical tuning fork – but using the piezoelectric effect. This is where electrical energy from the watch battery can be converted into kinetic or mechanical energy due to crystal deformation, and vice-versa.

In several respects, quartz is an ideal material for the job: it is abundant, cheap, has a low coefficient of expansion and a very high 'Q' (a measure of oscillator steadiness), requiring very little energy to continue oscillation.

However, despite a very low coefficient of expansion and stiffness with temperature of a tuning fork cut quartz watch, with a battery providing energy, it has a characteristic parabolic-shaped frequency relationship with temperature, as shown in **Figure 1** (see Author's Notes).

What we really want, and the ideal relationship, is a horizontal straight line for which the frequency – and hence rate of the watch – are constant and unaffected by temperature. However, this variation of crystal frequency with temperature is unavoidable and typical of almost all quartz watches using a tuning fork cut crystal. This causes errors, as any change in temperature will cause the rate of the watch to deviate.

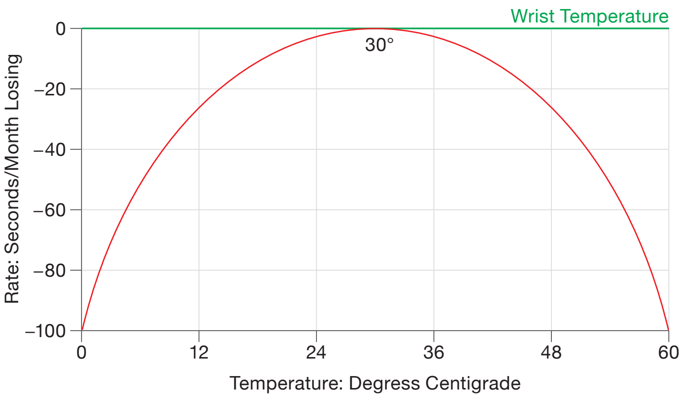
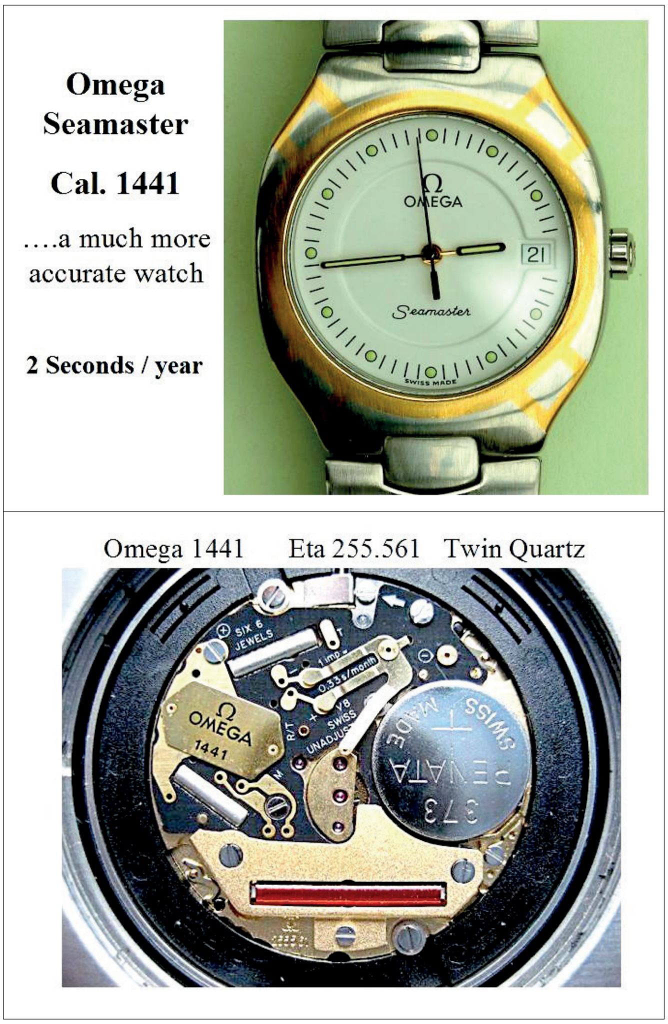


Figure 1. Typical watch rate/temperature for tuning fork cut quartz crystal. Adjusted for correct rate at wrist temperature.

However, the peak of the frequency parabola can be caused during crystal manufacture, to peak at about 28°C, which is around the (fairly stable) temperature of the watch if worn on the owner's wrist. Temperatures either cooler or warmer than this will cause the watch to lose time, and at an increasing amount the further the departure from this temperature.

The change in watch rate with temperature is relatively low around this 28°C temperature because, as can be seen, the gradient of the graph (turnover point) is then near-horizontal. This is why watch manufacturers may suggest their watches (without temperature compensation) are worn on the wrist for perhaps twelve hours daily, rather than left in a cold room or in a hot car, when both situations would cause the watch to lose relatively to the rate at 28°C. Although perhaps not ideal for the wearer, the longer the watch remains on the wrist the more stable and uniform the watch rate will be, especially if the case is in direct contact with the wrist.

Watch manufacturers are often concerned with creating highly accurate and sophisticated mechanical watches with tourbillons, high beat movements (although far lower than a quartz watch), fusees and free sprung balances, with very sophisticated mechanical temperature compensation than may be provided by some equally expensive watches with common non-thermally compensated quartz movements.



Figures 2A and 2B. The Omega Cal. 1441 showing twin quartz crystals and digital pulse inhibition contacts.

Purchase price may bear little relationship to quartz watch accuracy, but there are some reasonably priced quartz watch exceptions whose rate will comfortably far surpass the rate stability of any mechanical and most quartz watches using clever and novel techniques.

One example is the Omega Calibre 1441 wristwatch movement, which has two quartz crystals, and was used for a relatively short time in some Seamaster and Constellation models, and in similar watches by Longines in its VHP (Very High Precision) watches, see **Figures 2A and 2B**, as well as the Seiko Twin Quartz.

All of these watches are easily capable of maintaining a rate of ten seconds per year or better, even when exposed to significant temperature variations. For example, my Omega 1441 Seamaster keeps constantly to two seconds per year, summer and winter, and without any interference whatsoever apart from battery changes (it is never placed in a uniform temperature environment). The Longines VHP performs similarly.

Two Perform Better Than One

How can two very similar quartz crystals in a watch perform far better than one? Manufacturers can be understandably secretive about the methods used for creating their high accuracy watches, but by using two quartz crystals of similar, but necessarily subtly, different characteristics in the same watch circuit it can be done.

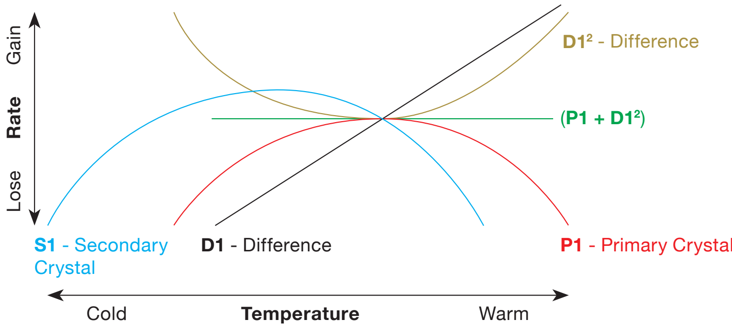


Figure 3. The use of two quartz crystals of tuning fork type to vastly reduce temperature dependance.

Figure 3, which is a schematic, shows how this can be achieved. Just take a deep breath and follow the five coloured lines on the diagram in the order below…

1. Both crystals, a primary and secondary, are of common 'tuning fork' type and, importantly, have the same so-called parabolic co-efficients, which means they have the same frequency (or rate) relationship with temperature 'curvature' as shown on **Figure 3** lines P1 and S1. However, intentionally, they will not have the same fundamental frequency of oscillation.
2. The primary crystal (line P1) may have a frequency of 32.768 kHz at 30°C, and the secondary crystal (line S1) has a higher frequency at low temperatures, but as already mentioned, they must both have the same so-called parabolic co-efficient. This means that while they will have the same frequency against temperature 'curvature' – as shown in **Figure 3** – they will intentionally not have the same fundamental frequency of oscillation, as mentioned: the secondary crystal having the higher frequency of the two crystals at lower temperatures.
3. By using the simple watch electronics, which was easily achieved even fifteen or so years ago, to subtract the two different parabolas with the same curvature, a new 'straight line' relationship is created, as shown (line D1), which will not (and intentionally must not) be horizontal.
4. By further using the watch electronics to 'square' this straight line, D1, to become a curved line ($D1^2$) another parabolic rate/temperature relationship is formed opposite to that of the primary lower frequency crystal line P1 (and is a mirror image of it).
5. Now all that is needed is to add these two parabolas together – again in the watch electronics – to obtain the straight horizontal line ($P1 + D1^2$) to create a fixed watch rate or frequency relationship independent of temperature, which is fed, as usual, to the frequency dividing electronics in the watch to provide one second (1 Hz) steps, and then to the stepper motor driving the watch hands.

Other Considerations

Shock, such as dropping a watch, can easily permanently affect its rate. Any minute debris left within the crystal encapsulating chamber can become attached to the crystal and change its rate. Ageing may also affect the rate, normally but not invariably to cause a loss; this rate change diminishes with time, and after a year will normally fall by an order of magnitude in the following year.

The use of a 'trimmer capacitor' to adjust the overall watch rate may become unreliable and cause the watch rate to change. Its rotation also causes a non-linear rate change. The later 'pulse inhibition' method (where the crystal is intentionally set to run very slightly fast and then certain pulses ignored/removed by the watch electronics) is vastly superior and reliable.

There are other methods to improve quartz crystal frequency stability with time, and electronics can allow the use of temperature compensated oscillators (TCXO).

Higher frequency crystal cuts, such as AT, BT or SC, have quite different frequency temperature characteristics. They may be used in timing machines, and the Seiko 8F32 watch for example, with a frequency of 196,608 Hz, and a few others in the MHz range – but may tend to use more battery power.

Although matchbox, not watch size, I have built a small, battery operated, double oven encapsulated SC cut quartz crystal oscillator (an OCXO – ex satellite equipment), which outputs a 10 MHz sine wave, and deviates by less than one part in a billion (1 in 10^9). Being previously 'aged' in use, it is now very stable with time.

This highly accurate standard can be used to calibrate other equipment, such as timing machines, and at far lower cost than GPS or Radio 4 carrier transmission receivers, although I have experimented with both of these, and built an Anthorn MSF receiver, to show a single LED flash, and beeps exactly on each and every second (and exactly on the minute a longer flash is produced) – all of which are disciplined by atomic time standards.

A basic MSF receiver can be bought for a few pounds and the electronics modified for even less.

Author's Notes

The Parabola

A parabola is a simple mathematical curve, which can be produced by cutting through a cone, and is called a 'conic section'. The shape is commonly found in car headlight reflectors, and satellite dishes, etc. This pleasing shape can be drawn by plotting a simple graph of $y = x^2$ where y is the vertical axis, and x the horizontal axis. For example, if the 'x' value is equal to minus three, (or plus three), then 'y' equals plus nine. This shape can seen on the graph of frequency/temperature shown previously.

Establishing the Rate

It is quite possible to establish the rate of a watch or clock to high accuracy without a commercial timing machine by using a compact digital camera set on video mode. It can be used to compare the seconds hand of the watch under test with the seconds hand of a radio-controlled clock, which may receive a time signal from the Anthorn MSF signal (now in Cumbria and itself linked to atomic time clocks).

By taking a hand-held video clip of the two second hands in the same image and playing it back frame by frame on the camera or a computer, the initial difference between the watch and radio clock can be established.

Most compact cameras play back recorded video at 30 frames per second (and optionally much higher), so if 15 frames have to be 'stepped-on' before the watch hand meets the same dial division as the radio clock, then the watch is exactly half a second slow. When using this method it is best to wait until the radio clock has recently received a radio correction signal, typically on the hour, or when the battery has been removed/replaced, as the MSF correction from Anthorn by the clock typically takes place 'on the hour'.

Using an LCD radio controlled clock is not ideal as the digits do not change instantly and fade in and out comparatively slowly, unlike a mechanical analogue clock such as a Junghans RC2 for example (in my opinion among the best I have found), where the seconds hand can be found to increment virtually instantly on the second. As mentioned above, another option is to use a MSF receiver (at remarkably low price) which can be modified and used to flash an LED, and/or sound a beeper precisely on the second, every second.

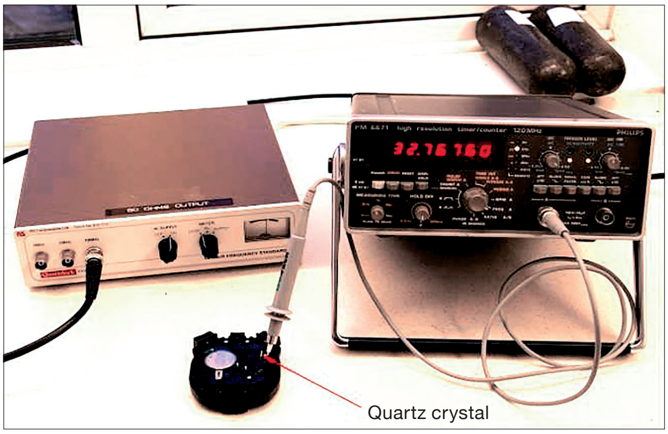


Figure 4. An off air standard and frequency counter with quartz watch. Losing one second per day.

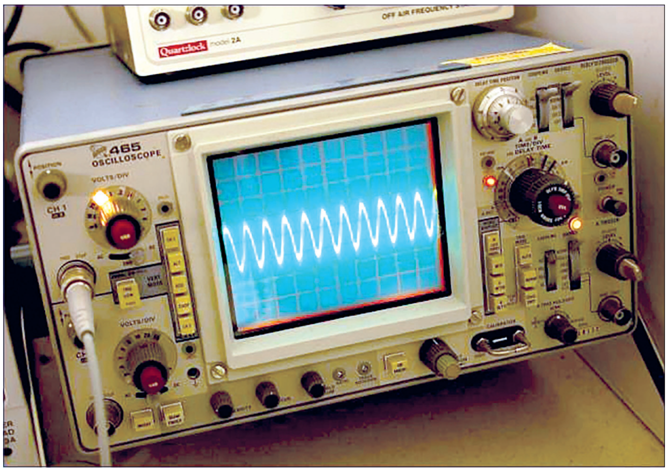


Figure 5. An oscilloscope trace of a quartz crystal in a stop watch.

In an ideal world we would find exactly the same difference anytime later, however by repeating such tests, the new difference can be seen and the watch rate found.

I have found the above methods particularly useful in establishing the rate of precision quartz watches. The watch in the photo has an Omega 1441 calibre 'temperature-compensated' movement, which has achieved an average rate of +2 seconds per year for several years, and with negligible variation. The comparison method outlined above allows the rate of this exceptionally accurate watch to be found relatively quickly and its rate then adjusted, whereas a conventional watch timing machine would be unsuitable as its rate would almost certainly be far less accurate than that of the watch.

Very few watch timing machines are capable of achieving the required accuracy, and those typically use a GPS signal as a frequency standard/reference at considerable expense.

Figure 4 shows a frequency counter monitoring a quartz stopwatch, where the counter itself is controlled by an 'off air' frequency standard, linked to atomic clock signals. The stopwatch has a crystal frequency of 32,767.60 Hz, so is very slightly slow compared with the ideal of 32,768.00 Hz.

Figure 5 shows an oscilloscope trace when connected to a quartz stop watch. By using a double beam oscilloscope to compare two signals – one trace provided from an atomic clock-generated signal for example – there is no practical limit to the accuracy which can be achieved by monitoring the relative horizontal movement of the two traces.

Acknowledgements
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