Greenwich Time: From Pendulum to Quartz 1

by Ray Essen.

Timekeeping has been in the national news this year because of the proposal to do away with the leap second, which keeps Greenwich Mean Time (GMT) close to mean solar time, and this gave me the idea to write about another landmark in the history of time, namely the replacement of the pendulum clocks on which GMT was once based.

The changeover from pendulum to quartz clocks was anything but smooth. It coincided with the start of the Second World War when the Royal Observatory was being forced to leave the site it had occupied at Greenwich for over 250 years. As Britain prepared for war, the Astronomer Royal made a number of changes to safeguard Britain's national time service. This article covers these events and next month I will describe what happened during and immediately after the war. Although these events took place over seventy years ago, many of the challenges encountered then are equally relevant today. When restoring a clock, how often do we have difficult decisions, such as whether to repair or replace parts of the movement? The Astronomer Royal faced similar problems on a grand scale, whilst also having to respond to urgent demands made by the Armed Services to improve the accuracy of Greenwich Mean Time, **1**.

1. Flamsteed House, Old Royal Observatory, Greenwich, showing Octagon Room and Time Ball.

Mean Clock

The main timekeeper at the Royal Observatory between 1925 and 1942 was the Shortt free pendulum clock. It was a dual-pendulum, electric clock in which a slave clock was maintained in synchronisation with the master pendulum. The 'slave' was a standard Synchronome clock which did all the work of driving the train of wheels required to record the time on a dial and send out time signals. The 'master' was a Shortt free pendulum which was allowed to swing freely, except for a small impulse given to it once every half-minute to maintain its swing. Further information on the Shortt clock can be found in the classic account written by Frank Hope-Jones in the 1940s (a facsimile reprint of his book, *Electrical Timekeeping*, is still available). About fifty of these clocks were made by the Synchronome Company between 1925 and 1935 and installed in observatories around the world.

Five of these clocks were in use at Greenwich before World War 2: two of them measured solar time and the other three were adjusted to sidereal time, which has a day length four minutes shorter than the solar day. One sidereal clock was selected as the master and the others served either as reserves or were corrected after comparison with the master clock.

The last Shortt clock at Greenwich was being installed when the Astronomer Royal, Harold Spencer Jones, appointed Humphry Smith as the officer in charge of the Time Department. I got to know Mr Smith a few years ago when he told me about some of his earliest memories of these pendulum clocks, two of which were already ten years old when he arrived at the Observatory. 'The clocks were terribly out of date – absolutely abysmal. By 1938 their random wanderings, amounting at times to over ten milliseconds per day, became intolerable and, to minimise the effects of unpredictable rate changes in individual clocks, their results were combined to form a *mean clock*.'

The first mean clock consisted of several Shortt clocks side-by-side in the clock cellar at Greenwich but eventually it was extended to include clocks at other establishments, including the National Physical Laboratory (NPL), Teddington, the General Post Office (GPO) Radio Research Laboratory at Dollis Hill, West London, and the Royal Observatory, Edinburgh. Initially, these remote clocks were connected to the Greenwich Time Department by Post Office telephone lines but in due course the mean clock could also include data received via radio time signals.

First Quartz Clock

The concept of the mean clock was a great success, but it did not eliminate the fundamental weakness of the Shortt clock which was prone to small, erratic changes of rate. An entirely new design of clock was needed and a possible solution came to the attention of the Astronomer Royal soon after Humphry Smith joined the Observatory. It was the quartz crystal clock.

Physicists in Britain, America and Germany had been studying the electro-mechanical properties of quartz since the early 1920s. Quartz crystals possess excellent mechanical properties and also exhibit the piezoelectric effect. The word *piezoelectricity* means 'electricity resulting from pressure'. If a piece of quartz is compressed or stretched, electrical charges are developed across its surface and if the quartz is made to vibrate, alternating charges are generated. This property enables a quartz crystal to be connected, via metal electrodes, to a suitable electronic circuit and it can then be maintained in continuous oscillation at a precise frequency determined by the dimensions and mechanical properties of the piece of quartz. This raises the possibility that the vibrating quartz crystal can be used as an accurate means of recording the passage of time.

David Dye was one of the first scientists in Britain to investigate quartz oscillators. He was a highly respected physicist at the NPL (Britain's national measurement institute) where he had a particular interest in standards of time and frequency. Dye began to study the piezoelectric effect in quartz crystals whilst he was undertaking basic research for the radio industry.

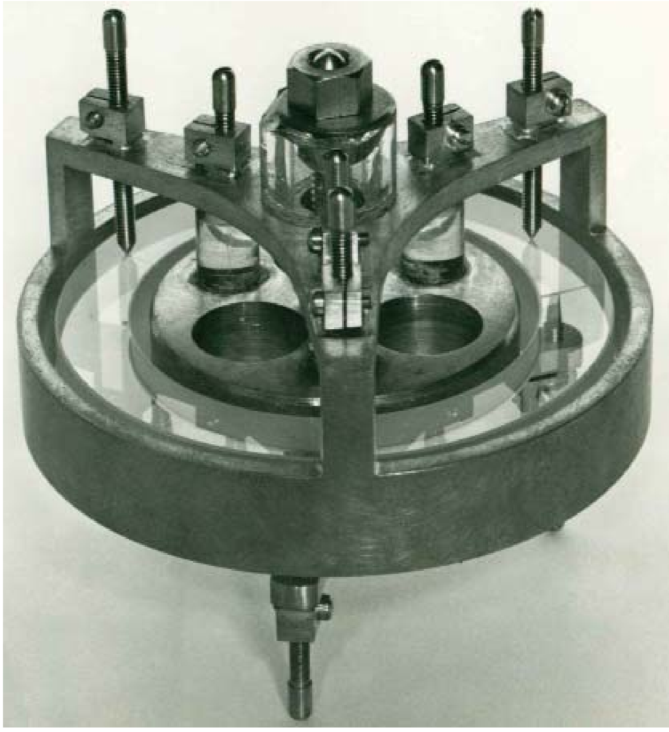
Some of the earliest crystal oscillators were cut in the shape of a bar of natural quartz but they were prone to 'end effects' which reduced the purity of the oscillator's frequency. In an

2. Louis Essen who built Britain's first quartz clock.

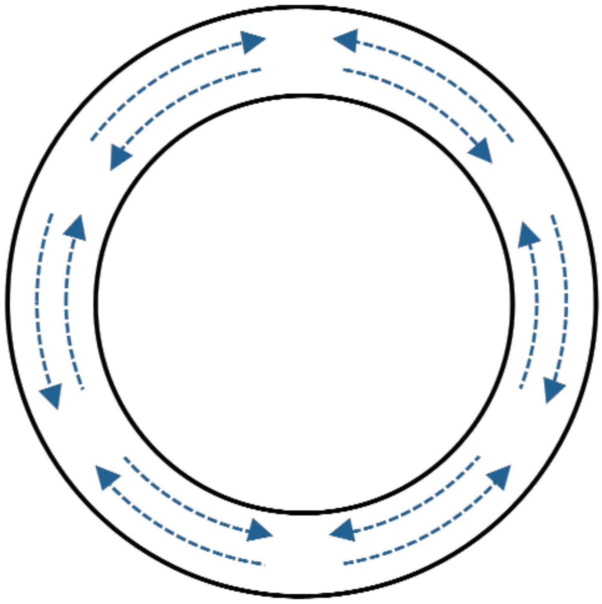
attempt to eliminate this effect Dye began experimenting with a piece of quartz cut in the shape of an annular ring which behaved like three quartz bars placed end-to-end and bent into a circle. When Louis Essen joined the NPL in 1929 he worked initially as Dye's assistant then, after his sudden death in 1932, Essen continued the work started by Dye, **2**.

Before long, Essen had produced a quartz clock based on Dye's original design. It was the first quartz oscillator to be used as a standard of time at the NPL but it was far too complicated for general use and Essen spent the next three years trying to correct its shortcomings. He found that the quality of the timekeeping depended more on the properties of the quartz than on the design of the associated electrical circuits so he concentrated on trying to improve the performance of the annular ring.

The ring-shaped oscillator possessed a number of advantages that were worth preserving in a clock, but its frequency of vibration was too low to satisfy the needs of the radio industry so Essen halved the diameter of the ring (to about 50mm) which increased its frequency to 100kHz (1kHz = 1,000 cycles per second). The exact frequency depended on the mean radius and could be adjusted in either direction by grinding the inside or outside cylindrical surface of the ring. It was necessary to grind the surface of the crystal with a very fine abrasive powder for several minutes to change the natural frequency by 1 part in 10^5, which gave a fine level of adjustment, **3**. Another difficulty with the Dye ring was that it vibrated in a radial direction which caused excessive energy loss as the ring expanded and contracted. Essen solved this problem by cutting the crystal along a different crystallographic axis which enabled him to use a different mode of vibration in which the atoms in the ring vibrated tangentially. This resulted in three regions of expansion and three of contraction around the ring so its total circumference remained constant and disturbance of the surrounding air was kept to a minimum. The crystal was supported at three points on its underside surface where there was virtually no movement, **4**.

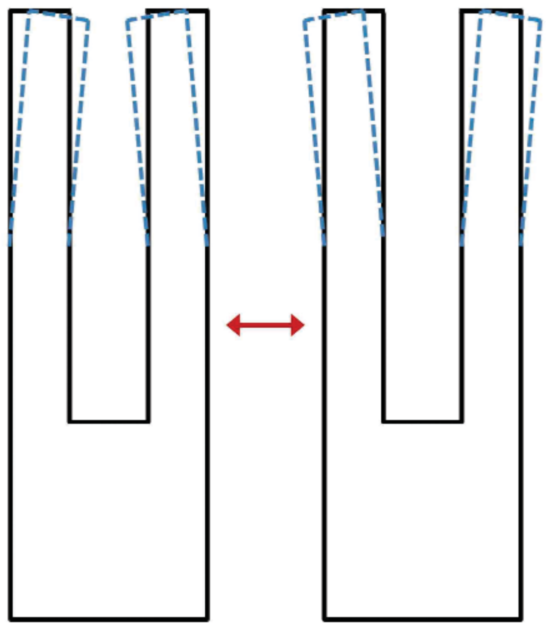


3. The Essen ring.



4. Longitudinal compressional vibrations in the form of stationary waves round the circumference of an Essen ring crystal.

It is worth remembering that many other modes of vibration are now being used for a range of different applications. For instance, a quartz crystal in the shape of a miniature tuning fork (vibrating at 2^{15} Hz, ie 32.768kHz) has become popular for low-frequency consumer applications because of its small size and low cost. A billion of these tuning-fork crystals were being produced annually for the worldwide watch market by the end of the last century, **5**.



5. Flexural vibrations of a tuning fork crystal commonly used in modern quartz watches.

Essen made a number of other modifications to the ring including operating the crystal in an overtone mode, i.e., the crystal was made to vibrate at a multiple of its fundamental resonant frequency. The result was a clock whose frequency was largely independent of temperature, pressure, electrical characteristics and, most importantly, gravity.
The Essen ring was installed as the primary standard of time and frequency at the NPL from 1936 onwards and proved to be a much better clock than the Shortt pendulums at the laboratory.
Its short term performance (as measured by its day-to-day stability over a period of a month or so) was considerably better than the pendulum clocks it replaced. Another advantage came from the fact that frequencies could be added, subtracted, divided and multiplied with great accuracy using simple electronic circuits. This enabled a wide range of frequencies to be synthesized from a suitable working standard, which was a big advantage in the 1930s particularly in the wider field of radar and radio engineering. It also made it much easier to compare the performance of one clock with another – a matter of great importance when operating a mean clock.

Sidereal Time

Essen's results were published in 1938 in a scientific paper called 'A New Form of Frequency and Time Standard'. It caused a revolution in the world of precision time measurement; three hundred years of development had gone into the pendulum clock but, in applications requiring the precise measurement of time, the quartz clock had made the pendulum virtually obsolete in less than a decade. Essen showed that the rate of his quartz clock was constant to within a millisecond a day – a ten-fold improvement in accuracy over the pendulum. In addition, the ring crystal was reasonably inexpensive, robust, portable and performed well for long periods with very little attention.
But would it make a better time standard than the existing clocks at the Royal Observatory? That was the question he now put to the superintendent of his department, E H Rayner.
The Observatory was then under Admiralty control so Dr Rayner arranged for Essen – still a relatively junior scientist at the NPL – to meet Dr Charles Seymour ('Silas') Wright, director of scientific research at the Admiralty. Wright was at the peak of his career and was effectively the chief scientist for the Royal Navy.
When the two men met on 6 January 1937 Dr Wright already knew about the top secret work being done on radar and was aware that improvements in electrical time standards could speed up the development of radar, navigation and other radio-communication systems for the military. The outcome of the meeting was very positive and Essen was asked to write a proposal to supply a quartz clock to the Royal Observatory. It took Essen less than two weeks to produce an outline specification which Rayner sent to Harold Spencer Jones on 26 January. It was already apparent to the Astronomer Royal that the quartz clock had become a serious rival to the most advanced pendulum clock at the Observatory and he was keen to gain some first-hand experience of the new technology.
The design proposed by Essen consisted of four units: (1) a crystal-controlled oscillator and associated electronics to maintain the crystal in vibration; (2) electronic frequency-divider circuits; (3) an amplifier to provide the necessary power to drive a stepping motor, and (4) the motor itself which operated the clock mechanism including the 'second' contacts. The cost of the quartz ring, including electrodes and a sealed quartz vessel, was just over £100 and the estimate for the remaining electronics was £350. For comparison, Essen's salary was £250 p.a. in 1934 when a good quality 'Austin' 5-valve radio could be purchased for 16 guineas (£16.80).
In due course, the Astronomer Royal gave his assent to the idea of a quartz clock and Essen set to work. Much of the assembly was done by outside firms working to a specification supplied by the NPL. Essen, however, was very unhappy about one aspect of the design. The Astronomer Royal had insisted that the quartz crystal be adjusted to keep sidereal time (a measure of the earth's rotation with respect to the distant stars rather than the sun) which limited its usefulness. As a result, the quartz oscillator was designed to vibrate at 99.27105kHz instead of the usual value of 100kHz.
Essen built six quartz clocks in all but this was the only one for which the crystal was ground for sidereal time (the other five crystals were adjusted to solar time). Its frequency-dividing circuits, which reduced the frequency down to 500Hz, were constructed in four stages and the final stage was used to drive a synchronous clock mechanism which generated impulses at intervals of 0.01, 0.1 and 1 seconds. The mechanism depended on a 'phonic' motor manufactured by Muirhead, a company with a considerable reputation for precision electrical and mechanical products.
As a final check, the clock destined for Greenwich was run for a couple of months at Teddington and its performance was monitored against the other quartz clocks at the NPL.

The Move to Greenwich

The quartz ring, together with its ancillary equipment, was despatched to the Royal Observatory in early 1939 where it was re-assembled in a small room with concrete floor and brick walls which was once the wine cellar in the residence of the Astronomer Royal. It was standard practice to put each new clock on long-term test to compare its performance with the mean clock. On this occasion, it was incorporated into a mean clock along with two similar clocks at the NPL. Data from the clocks at Teddington was transmitted daily to Greenwich so that the performance of the three quartz clocks could be compared.

It soon became clear to the Astronomer Royal that the experiences with the quartz clock were mixed. The advantages of the new type of clock were its considerably better short-period stability and the simplicity with which one clock could be compared with another. But Spencer Jones also realised that grinding the crystal for sidereal time had been a mistake and all subsequent quartz clocks installed at the Observatory were based on solar time.
However, the performance of the quartz clock over periods longer than a month was not altogether satisfactory. The frequency of all quartz crystals changes very slightly with time in a process known as *ageing*. Although the frequency variations are small, the greatest rate of change occurs in the first couple of months of operation. It is now known that ageing is caused by a number of interrelated factors including the presence of tiny impurities within the crystal but far less was known about it in the 1930s. The Astronomer Royal regarded the acceleration of the NPL clock as excessive (even though it was no worse than some subsequent oscillators) which resulted in a certain amount of bad feeling between the NPL and the Royal Observatory.
Eventually, it was realised that another factor was also contributing to the clock's poor performance. The form of gravity mounting for the quartz ring was not as shockproof as was first thought and there was an imperfect alignment between the grooves in the lower face of the ring and the supporting pins which were located in these grooves and on which the ring rested. Although the two quartz clocks at the NPL did not have this problem, Essen decided it needed further investigation.
But the declaration of war on 3 September 1939 halted further work to correct its deficiencies. Essen was transferred to another department that was more closely concerned with work for the military and his involvement in quartz standards stopped at that point.
The outbreak of war also put an end to most of the astronomical activity at the Observatory and the larger instruments were dismantled and moved from Greenwich for safe keeping. The Astronomer Royal took on additional duties for the Ministry of Munitions leaving Humphry Smith with day-to-day responsibility for Greenwich Mean Time.

Next month: Britain at war and the secret location of the Greenwich Time Service.

Ray Essen

Leap Second Update

On 19 January, the International Telecommunications Union (ITU) postponed the vote on whether to abolish the leap second until 2015. The ITU is the leading United Nations agency responsible for the co-ordination of radio and telecommunications worldwide. Louis Essen was an ITU member in the 1960s when he argued that the current practice of having both an atomic timescale (with no leap seconds) and an astronomical timescale (with leap seconds inserted) 'would cause endless confusion as well as involving duplication of equipment.' The first leap second was added in 1972 but Britain is now one of a minority of countries which favour retaining the leap second.

Remembering George

A celebration of the life and work of George Daniels CBE DSc FBHI was held at St George's, Hanover Square, London, on Monday April 16.
Family, friends and work associates from the UK and overseas attended to say a final goodbye to one of the world's greatest watchmakers.
During the service, readings were given by close friend David Newman, and Chairman of the BHI Richard Thomas MBHI.
Moving and humourous 'appreciations' were given by Andrew Crisford, Deputy Master of the Worshipful Company of Clockmakers; Daniels' protege watchmaker Roger Smith FBHI; and Roger Collings, Past President, Vintage Sports Car Club.
George's passion for vintage cars was recognised by the siting of his 1908 Grand Prix Itala outside the Church.
George's car and motorcycle collection will be sold by Bonhams on Friday June 29 at the Goodwood Festival of Speed. His watch and clock collection will be sold by Sotheby's in London on November 6.

WCC Masters and Apprentices

A new list of Clockmakers' Company Masters and their Apprentices, transcribed from the Atkins' list of 1931, by Jeremy Evans, is now available as a pdf link on the WCC website. A total of 157 pages of records are now available.
You can find the list at:
www.clockmakers.org/museum-and-library/clockmaker-masters-and-apprentices/