

The marine chronometer in the age of electricity

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This is a shortened version of a lecture given at two AHS meetings held at the National Maritime Museum, Greenwich. The first was a one-day symposium, 'Electric Time', held in June 2010 to celebrate the fortieth anniversary of the AHS Electrical Horology Group. The second was the AHS AGM and NMM/AHS one-day conference in May 2012. An article in German, 'Marinechronometer im Zeitalter der Electrotechnik', based on this lecture, was published in Chronometrophilia 72 (2012).

Introduction

In a letter published in the *Horological Journal* of December 2008, a retired ship's pilot, Bill MacFarlane, noted that it was the 150th anniversary of the founding of Thomas Mercer and reflected on the fate of the marine chronometer. Forty years earlier, in the 1960s, Bill had been invited by the Captain of a ship travelling from Liverpool to Portugal to 'look at something unusual'. It was 'a small quartz chronometer cased in an aluminium block and kept in the ship's chronometer box'. His description matches the B-1390 chronometer shown in Fig. 1. On the voyage, the Captain had tested the two chronometers side by side and observed that the quartz clock had no error at all whilst the detent chronometer had a small but noticeable one. In remembering this event, Bill wrote: 'Little did I realise that I was witnessing the beginning of the end of these beautiful instruments.' In this lecture you will see that the 'beginning of the end' was much earlier than Bill MacFarlane suspected, and whilst the spring detent would reach the end of a long life, the marine chronometer would continue, transformed by new technologies in the age of electricity.

Occupying the elite precision segment of the horological trade, traditional detent chronometers were subject to market conditions quite unlike the mass market for clocks and watches which generally grew with the increase in population and incomes. Mass market products are invariably replaced for reasons of technical



Fig. 1. Oscilloquartz B-1390.

improvement, fashion, or wear and tear. By contrast the spring detent chronometer was a perfected machine, incapable of further improvement in performance. It was very carefully looked after, extraordinarily long lived, and locked into the limited and unpredictable market of Naval, Merchant and passenger shipping.

Following a rise in demand for WW1, it seemed that sufficient chronometers had been made for future requirements and the interlocking craft skills used for their manufacture began to break down. Between 1942 and 1955, the Hamilton Watch Co. made over 11,000 spring detent chronometers to supply the demand created by WW2. Many of these came to the UK but

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Fig. 2. Campiche 1910 (auction image).

some were never even used, and in 1985 the MOD invited bids by tender for their disposal. That such wonderful precision clocks should be disposed of in this way might seem extraordinary, but the production of the mechanical chronometer had declined to the point where only a few were being made to special order by Kirov in Russia, Wempe in Germany and Mercer in England.

So what was being manufactured for navigation at the time of these disposals? Chronometers based on electrical rather than mechanical engineering, with technologies developed in the world of electronics and radio, had been in production from the beginning of the 1960s, but they had received very little mention in horological circles. There were, of course, piecemeal reports in technical publications announcing the arrival of new clocks and watches based on the new technologies, and of accuracy records being broken, but nothing like a joined up history.

My purpose in the following chapters is to fill that gap by revealing the changes that electricity brought about to time at sea, the type of oscillator that provided the timekeeping element, the types of movement, and the different technical solutions developed in France, Switzerland, Germany Japan and China.

3449. Campiche, H. A. Feb. 11. 1904

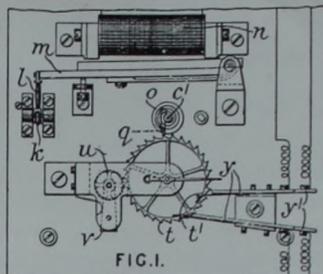


FIG. 1.

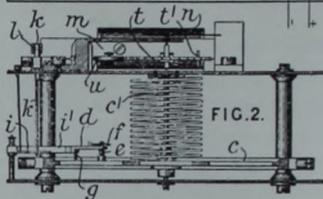


FIG. 2.

Electric clocks applicable as marine chronometers.

Fig. 3. Campiche patent 3449, 1904.

It is a privilege to give this lecture at the very home where the importance of finding longitude caused the Royal Observatory at Greenwich to be built, caused John Harrison to solve the problem in the eighteenth century, and Arnold and Earnshaw to perfect the detent escapement mechanism.

Electric marine chronometers

The earliest use of electricity in a marine timekeeper was, I believe, made by the Swiss horologist Henry Campiche of Geneva, a maker of outstanding and original electric pendulum clocks. We saw an image of his clock in the introduction (Fig. 2) and Fig. 3 is an illustration taken from his English patent of 1904. Note the words 'applicable as marine chronometers'. Once every minute, the balance wheel is given an impulse by a lever actuated by an electro-magnet. The balance, by means of a pallet attached to its staff, gathers the teeth of the index wheel. The index wheel carries a metal pin. Once in every revolution the pin wipes a pair of contacts which switches current to the electro-magnet. A second pair of contacts is wiped by the pin to allow current to flow to slave clocks. And so the cycle continues.

Paul Ditisheim, regarded by many as the most gifted horologist of his day, made

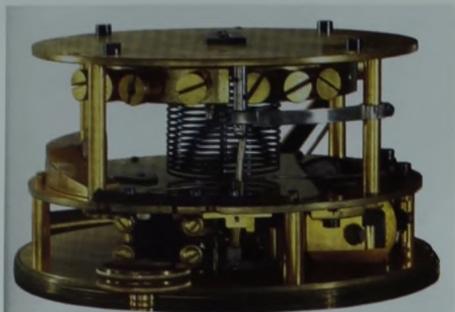


Fig. 4. Paul Ditisheim, Electro-mechanical timekeeper No. 2, 1912. (auction image).

marine timekeepers to this Campiche design (Fig. 4). These marine timekeepers, according to a contemporary account in *L'Electricien*, were not intended for navigation but to operate slave clocks on board ship. In this respect they were the forerunner of marine master clocks and synchronised slave dials that came into use about fifteen years later.

The balance wheels of the marine clocks of Campiche and Ditisheim were directly impulsed by electro-magnets. In this system the energy transferred to the balance is proportional to the current that passes through the coil of the electro-magnet. This is not ideal because the current in the system will decline with the condition of the battery, as will the energy in the balance.

A better method is to use electrical energy to wind a remontoire whose force being constant would not vary with the condition of the battery. So long as the energy available remained sufficient to wind the remontoire, the clock would receive an unvarying amount of energy and the balance would oscillate with unvarying amplitude. This concept was, I believe, first realised in a prototype marine chronometer by Louis Dubois in 1923 (Fig. 5). Dubois was a graduate of the Technicum at Le Locle, in Switzerland, where he was later appointed as Head of the Horological Engineering Department. His marine chronometer was constructed by adapting a standard detent chronometer by Thomas Mercer & Sons. The mainspring barrel and fuzee have been removed, and the train adapted to receive power from a spring remontoire cocked by



Fig. 5. Louis Dubois marine chronometer with one minute remontoire (Courtesy of M. Viredaz).

an electro-magnet. It is based on a design developed by David Perret for a pendulum regulator at the Neuchatel Observatory and used in the early twentieth century for the transmission of time signals by telegraphy to various locations in Switzerland. Most of Perret's clocks were made for the general rather than precision market and the majority of these were fitted with balance wheel escapements. Nevertheless, using the same one minute remontoire as in his pendulum regulators, these were capable of keeping very good time and showed the way forward as demonstrated in the marine chronometer by Dubois.

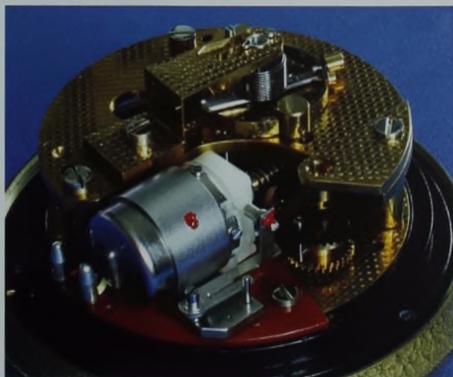


Fig. 6. Wempe Type 907 electrically wound spring detent chronometer.

Post WW2, developments in miniature electric motors enabled the electric

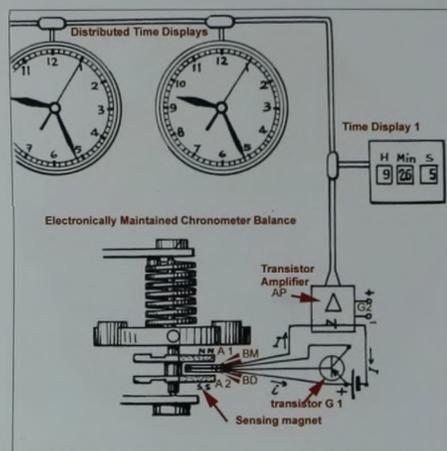


Fig. 7. Ato/Lavet patent illustration for transistorised switching.

remontoire to be simplified and exploited in the Wempe Type 907 marine chronometer, the first electrically re-wound marine chronometer made in series production in 1962 (Fig. 6). A small spring, arranged to exert constant force, is wound every $8\frac{1}{2}$ minutes by micro-motor, powered by two standard D size cells which are present in an otherwise conventional chronometer box.

Electronically maintained chronometer balance

We are now ready to move from the use of mechanical switches in electrical systems, to the use of electronics in which mechanical switching is eliminated. From the very beginning of electrical horology, the major difficulties that prevented the achievement of high precision combined with long term reliability lay in the use of the mechanical contacts needed to switch current to the system. In summary, the following three problems had to be solved:

- How to minimise disturbing the pendulum or balance wheel when causing the contact to be made.
- How to minimise the energy taken from the oscillator, normally a pendulum or balance wheel.
- How to preserve the contact surfaces from wear, dirt and oxidisation.

Over time these problems were effectively minimised, however the ultimate solution

was found by the complete elimination of all mechanical contacts through the use of electronics. This was first achieved by the use of vacuum tubes (triode valves) as electronic switches. Nevertheless, the invention of the transistor was needed in order for progress to be made from specialised and unwieldy clocks to practical portable timekeepers suited to universal use.

So far we have seen the replacement of the spring barrel and fusee by electrical means. Now, with the aid of transistors we reach the stage when the spring detent escapement is also dispensed with. All that remains of the original classic marine chronometer is the timekeeping element itself – the balance wheel oscillator. The drawing in Fig. 7 is taken from the 1953 patent that changed the world of timekeeping. It is by the French electrical engineer and horologist Marius Lavet of *Établissement Leon Hatot* and covers the use of transistors for electronic switching in horology. The patent disclosed both pendulum and balance wheel applications and also foresaw future developments in wrist watches.

Unlike mechanical switches, the transistor can operate at a switching frequency in millions per second. This fact opened the way to the manufacture of portable clocks and watches using high frequency electronically maintained tuning forks and quartz oscillators. It marked a turning point in the world of timekeeping and countless examples of clocks and watches by other makers round the world are marked Ato licence or Ato patent. Marius Lavet was not the first to use the transistor as an electronic switch which, anyway, did what had already been done with valves. Nevertheless he was, commercially, the quickest off the mark in securing a patent that defined the state of the art.

In the drawing taken from Lavet's patent we see a chronometer balance. A1 and A2 are magnets of opposite polarity attached to arms on the balance staff. The transistor G1 acting as a switch is turned on by the small voltage that appears at its base when the sensing magnet passes over the sensing coil BD. This allows a current from the battery

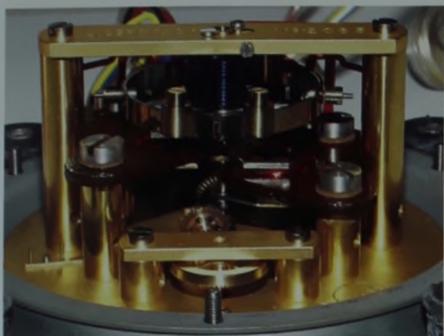


Fig. 8. Chronostat III.



Fig. 9. Chronostat III complete ship's system.

G1 to flow through the drive coil BM which acts on the drive magnet and maintains the balance in oscillation. A separate transistor amplifier AP supplies pulses to drive slave clocks using power supplied through G2.

Lavet's patent is exemplified in the Leroy Chronostat III Marine Chronometer (Fig. 8). This photograph shows the sensing and impulse coils below the compensated balance of a traditional marine chronometer. The balance is both oscillator and motor and drives the motion work through a Sully escapement working in reverse. Trials of the system were carried out during 1958 and 1959 after which Chronostat III was accepted by the French navy, the French Naval Hydrographical Service and the Merchant Marine. In October 1959, Thomas Mercer Ltd entered into an agreement with

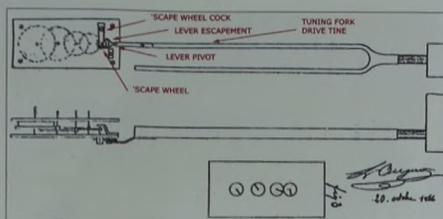


Fig. 10. Breguet patent No. 73414 dated 1866 for a tuning fork oscillator.

Leon Hatot & Leroy for exclusive sale of the Chronostat in the UK and the Commonwealth.

Fig. 9 shows Chronostat III in its final ship's form in which it went on to be used in the French Navy. It was not, however, only bought by the French. This particular Chronostat system was supplied to Shell International Petroleum and was used in the oil tanker S.S. Sivella. The Chronostat itself is in the left hand compartment of the steel box. It is kept to GMT. In the right hand compartment is a slave pilot dial to indicate the time shown on the various slave clocks in use around the ship. Above the dial are switches for changing the time as the ship passes through time zones. In the middle compartment are the electronics needed to distribute both GMT and local time to where it is needed on board. It is remarkable that this box of electronics has a classic chronometer's balance wheel as its oscillator. It goes to show that the traditional chronometer balance was a very good oscillator indeed.

Electronically maintained tuning forks

We now come to the transistor maintained tuning fork as outlined in the Ato patent with a preliminary glance at the earlier history. Fig. 10 is taken from Breguet's 1866 patent covering the use of a tuning fork as a superior frequency standard. In the patent are the words: 'We claim to make this application to the balance wheel of chronometers.' In this mechanical realisation, Breguet was proposing a tuning fork replacement of the traditional chronometer balance. His idea worked but he didn't have the enabling technology to take it further. The technique for



Fig. 11. Accutron Navigator Mark II.

maintaining a tuning fork in oscillation was perfected electronically in the radio industry using valves in the 1940s and then transistors in 1960s.

The concept of a tuning fork time-keeper was miniaturised in a revolutionary design by the Swiss engineer Max Hetzel working for the Bulova Watch Company and was introduced as the Accutron wrist watch in October 1960. It was guaranteed to keep time to plus or minus 2 seconds a day, a degree of accuracy that the traditional balance wheel watch could not match. However, this was not superior to the best performance of a chronometer balance such as used in the Chronostat III. Therefore, in order to manufacture a marine chronometer, Bulova produced the Navigator Mark II shown in Fig. 11 in which three Accutron movements were electronically interconnected to produce an average of three tuning fork frequencies. With this arrangement, a daily rate of better than one second was achieved. The movement is housed in a heavy brass tub which is sealed by O rings from water and sudden changes in pressure. Whilst the Navigator II was still in production, Bulova filed a patent for a quartz controlled version in which a tuning fork oscillator is driven by and locked to a sub-multiple of a quartz frequency. The patent and its eventual

realisation represented an intermediate stage of development and leads me to the introduction of quartz as the primary oscillator.

Marine chronometers with quartz oscillators – the Post Office and Sperry prototypes

By 1939, in the radio industry, quartz crystal control of transmitter frequency enabled stability of two parts in a million and the technology became an important component in military radio communications during WW2. These developments led to the realisation that the days of pendulum clocks as primary timekeeping standards in observatories were numbered, and from the late 1930s onwards observatories round the world began the move to quartz oscillators. The use of quartz did not at first present an opportunity for use in marine chronometers. This was because the earliest quartz clocks needed ample space for large numbers of electronic valves (vacuum tubes) to divide the quartz frequency by binary division until a low frequency oscillation was reached that was suitable for controlling the motion work and hands. Valves require high voltages for the anodes and low voltages with high current for the cathode heaters. Accommodating the valves and power supplies resulted in clocks the size of filing cabinets; considerably larger than Harrison's H1.

At the end of 1941, following the attack on Pearl Harbour by the Japanese, the USA entered WW2. A quartz marine chronometer would give a navigational advantage and although the large number of thermionic valves presented problems of size and power supplies, the US Navy placed a development contract for ten quartz chronometers with the Borg-Gibbs Laboratory. Such a machine was unheard of at that time and the specifications, perhaps inevitably, failed to be realistic. When the first chronometers went into service for evaluation they proved to be unreliable and the contract with Borg-Gibbs was cancelled.

A solution to the problem of size and portability did not become feasible until transistors made their appearance in the



Fig. 12. Post Office Development Laboratory portable quartz clock. (Replica made by Mr. John Howell).

1950s. These tiny devices not only enabled the required miniaturisation and portability but required remarkably little in terms of supply voltage and power. However the first transistors available on the market were not sufficiently reliable to satisfy critical applications such as marine chronometry and it was not until 1956 that the British Post Office showed the way forward.

In December 1956 the Radio Research Section of the Post Office Engineering Dept issued a *Radio Report* named, 'A Quartz Clock with transistor drive'. The Post Office clock was made as a research project in the Radio Experimental and Development Laboratory at Dollis Hill with the objective of proving the feasibility of a transistorised quartz clock. Only the report and a very poor image of the clock survives; the clock seen in Fig. 12 is a replica. The report summary stated:

A transportable quartz clock, with transistors in place of thermionic valves

has been constructed. Because of its low current consumption it can be operated from batteries, and may have an application as a chronometer.

The GPO chronometer was, I believe, the earliest truly portable quartz clock in the world. However, whilst it proved the feasibility of manufacturing a portable quartz clock, it was not intended as a production item but as a stimulus to show the way forward. The stimulus was shortly to be taken up by the Ministry of Defence and a development contract was placed with Sperry Gyroscope Ltd in the UK to develop a quartz chronometer for the British Navy.

Sperry Gyroscope Company Limited, the British subsidiary of Sperry Gyroscope Inc., had been formed in the U.K. in 1913 and production in Britain of the Sperry Gyrocompass in ships became standard issue. Apart from the gyrocompass business, a large amount of development work was placed with Sperry Gyroscope Ltd on a variety of technologies requiring electronics. It was not surprising, therefore, that in the second half of the 1950s and with more than thirty-five years of business with the Admiralty, the company was chosen to develop a portable quartz chronometer for the Royal Navy.

There are few references to the development of portable germanium transistor quartz clocks before 1960 and such development as there was had generally taken place in the light of open commercial and technical interest. In contrast, the Sperry contract for the Royal Navy required the level of official secrecy associated with all development work for the Ministry of Defence and, in consequence, was completely unknown except to those directly involved with the project. As with many secret development contracts for the MOD it was seen as a way of securing a critical advantage for HM forces over those of other nations, and, in this case, specifically in the field of navigation. Unlike other quartz clocks in development, the Sperry prototype for the British Navy did not use a synchronous motor for the clockwork with its inevitable sweeping seconds hand, but employed a newly developed 2 Hz stepping motor which



Fig. 13. Sperry prototype quartz chronometer for the Royal Navy.

would move the hand by half-seconds steps as preferred by navigators. As stated, the contract was secret and it is unknown in the horological literature; this account is the first to be published.

Development took place at Sperry's research establishment at Stonehouse near Stroud in Gloucestershire and from the evidence of the objects that have survived it is clear that the project had reached the stage of pre-production trials. Only two cased examples now remain and reveal a finished case design and display close to that of a conventional chronometer. A precise date cannot be reliably determined for these examples. However, the components used suggest that work did not extend beyond 1960, about the time that germanium transistors gave way to silicon.

Rapid development of silicon semiconductor technology took place when the era of germanium transistors was replaced by silicon (shortly to be followed by integrated circuits) and caused this milestone project to become out of date whilst still in development. The contract was, therefore, not completed and the small handful of prototype clocks, circuit boards and other work in progress was consigned to the MOD scrap yard at Stratton St Margaret near Swindon where the TSR-2, the Valiant, and other historic developments were later broken up. The development papers, still



Fig. 14. Sperry 'breadboard' restoration.

marked secret, were incinerated and, normally, this story would never have been known. However, a close friend of mine, the Mullard engineer who was responsible for the supply of electronic components to major companies, visited the scrap yard in 1961 and by chance saw the Sperry equipment. He gained approval to rescue what remained, which amounted to two cased trials clocks and a quantity of development parts. Enquiries made to Sperry revealed that all design, technical and contract records had been destroyed. In the absence of circuit diagrams and specifications, more than thirty years went by without any attempt at restoration until, eventually, I expressed my interest in attempting the job. The parts, minus one of the trials clocks that had been lent to a colleague and lost, then came into my possession and restoration was carried out the hard way – by tracing circuits and testing components.

The first clock was restored as a 'breadboard' in the autumn of 1997, entirely from original parts and sub-assemblies, many still carrying MOD tickets such as the one visible here (Fig. 14). The quartz oscillator is concealed in the temperature controlled oven behind the clock. The cased example (Fig. 13) was restored in early 1998. Since then the second cased clock has been found and restored by Mr. John Howell and these are almost certainly the earliest working, germanium transistor, quartz clocks with stepping motors in existence. As the earliest, and only, quartz chronometers developed specifically for the Royal Navy they are of great historical interest.



Fig. 15. Mercer M.39 chronometer.

Venner, Mercer & Oscilloquartz

Following the earlier attempts described above, successful development of portable quartz marine clocks took place more or less simultaneously in Europe and the Far East and I will now deal with these by region and maker.

The decision to scrap the Sperry contract might well have been influenced by developments taking place elsewhere. Venner Electronics in the UK had, already, developed a quartz clock based on a modular 'plug-in' design. It was announced in the *Journal of the Institute of Physics* in 1959 and Mercer became interested in the opportunity to manufacture a quartz marine chronometer. Venner's modular technology was taken up by Mercer who in 1962 announced the M.39 Crystal Chronometer and control system for marine clocks shown in Fig. 15. The Venner quartz chronometer, with its plug-in electronic modules and the synchronous motor time display, can be seen in the top half of the case and door. The ship's clocks controller and the silent slave, manufactured by Mercer are in the lower half of the case and door.

In September 1968, the Oscilloquartz Division of Ebauches S.A. in Switzerland announced the B-1390 quartz chronometer, housed in a waterproof machined metal case measuring only 137x112x2mm including battery compartment (Fig. 16).



Fig. 16. Mercer/Oscilloquartz B -1390.

It was advertised in *Broxton's Nautical Almanac* in 1969 and a trial example was tested by Thomas Mercer Ltd with a view to selling them under licence. Over seven days it had no observable error and was submitted to the National Physical Laboratory for evaluation with astonishing results. When compared by electronic means to NPL's atomic time standard the mean variation over seven days at temperatures between 4 and 36 centigrade varied between +0.003 and -0.004 seconds. Mercer duly took out an agreement with Oscilloquartz S.A. to sell the B-1390 under licence and Mercer boxed it under their own name for sale to the UK and Colonies and also through a licence agreement with Kelvin & Hughes. The B-1390 was a successful venture and chosen by the Cunard Steamship company where its use on the QE2 was much used for publicity.

Patek Philippe

In 1958, Patek Philippe began the research & development of quartz clocks for marine use. In April 1959, three years after the portable quartz clock by Post Office in the UK, (and no doubt stimulated by it) they announced *'The Smallest Quartz Clock in the World'* (Fig. 17). The oscillator was a



Fig. 17. Patek Philippe first small quartz clock.

10KHz crystal supplied by Oscilloquartz. After frequency division, the output was fed to a miniature synchronous motor of their own manufacture. It was a remarkable achievement but not a design suitable for a practical clock to be made in serial production.

During the 1960s, Patek Philippe went on to produce three grades of quartz master clock, Series E, F and G with standard specifications for daily accuracy of 0.1, 0.01 and 0.001 seconds respectively; all in steel cabinets, oven enamelled and fit for marine use. The Type ECK 24 R for ship's systems seen in Fig. 18 was first shown at the Basle Fair in 1964. Capable of driving up to fifty secondary clocks and fitted with standby rechargeable cells on float charge. The pilot dial beats seconds whilst the secondary clocks are driven by impulses every 1/2 minute. For these chronometers, Patek Philippe replaced the synchronous display with a newly developed stepping motor beating seconds. The movement was indexed by a rocking armature driving a pivoted driving anchor.

Also shown at Basle was the Chronotome (Fig. 19), a portable battery chronometer version of the bulkhead mounted marine clock but without the facilities for driving and synchronising slave clocks.

The stepping motor and circuit design principles developed for the Chronotome was later standardised for the well known Naviquartz Series E 1200 shown in Fig. 20.



Fig. 18. Patek Philippe ECK 24 ship's systems master clock.



Fig. 20. Naviquartz E 1200.

Presented in a slimmed down aluminium case and contained in a fine glazed mahogany box it successfully extended the market for a high precision quartz chronometer to include yachts and recreational ships outside the requirement of the military and merchant marine.

In the late 1970s and into the 80s Patek Philippe manufactured observatory clocks synchronised by radio as well as master clocks for many applications. However the electronics side of the business was, by then, perceived to present an image conflict with their traditional business and so, in 1988, the decision was taken to get out of electronics entirely.



Fig. 19. Patek Philippe Chronotome Type CC.

Longines, Golay Marine & Omega

Little known today, the firm of Bernard Golay S.A. in Lausanne Switzerland was one of the principal pioneers in the development of quartz marine timekeepers. Bernard Golay, who had trained as a master watchmaker, set up a business to provide a testing and quality control service for many leading watch houses. He felt that the future of horology lay in electronics and in 1964 opened a research laboratory which ran alongside his existing company. Out of this research laboratory was to emerge some of the most innovative electronic horology ever seen, much of it in partnership with the famous firm of Longines who had been involved with sports timing and navigation for many years.

The first product to emerge was the Micro-Quartz Marine Chronometer shown in Fig. 21, announced in 1964. This was not the first quartz chronometer made portable through the use of transistors, but it was by far the smallest. The Micro-Quartz chronometer was submitted to the Observatory at Neuchatel where it won 1st prize, setting a precision record for a single



Fig. 21. Longines/Golay micro quartz chronometer for ships and aircraft.

chronometer in 1964. The following year, in 1965, it beat its own performance with another first prize and also won the serial prize for the first four chronometers.

Use of proportional divider techniques enabled fewer components to be used than needed by the traditional and proven binary divider system. The entire quartz oscillator, electronic circuits and mechanical mechanism including battery is constructed using innovative modular techniques



Fig. 22. Modular construction.



Fig. 23. Chronostat IV.

(Fig. 22) and enclosed in a package advertised as being no bigger than two packets of twenty cigarettes. The quartz oscillator, electronic circuits and mechanical mechanisms are constructed using modular techniques that laid the foundations for future electronic manufacturing.

In this period, Golay and Longines were also developing a quartz ship's chronometer, Chronostat IV (Fig. 23), to the requirements of the Hydrographic Service of the French Navy (SHOM), in order to replace the transistor maintained chronometer balance of Chronostat III. Unlike the Micro-Quartz, it was to be the same size as Chronostat III and conform to a set of agreed marine specifications. It was completed in 1969 and presented at the International Symposium of Chronometry in Paris. Two sets of batteries (one set on standby) are in



Fig. 24. Micro stepping motor with jewelled driving anchor.

waterproof tubes accessed at the front of the box whilst output of the oscillator frequency is available at the socket visible on the right hand side.

The macro photograph of the stepping motor manufactured by Longines (Fig. 24) shows the driving anchor sub-assembly that indexes the wheel train of the analogue time display. A rocking coil responds to $\frac{1}{2}$ second pulses of alternate polarity and drives the wheel train through a driving anchor with jewelled pallets.

By the mid-1970s individual transistors had given way to integrated circuits in which thousands of transistors, in complex fully developed circuits, were manufactured as a single chip. The SHOM specifications for quartz marine chronometers were duly updated and in 1978 submissions invited from leading manufacturers for a new quartz chronometer based on the latest techniques. After exhaustive laboratory tests and sea trials the Omega, Caliber 1525, Marine Chronometer (Fig. 25) was chosen. Each chronometer was first tested at the Observatory of Neuchatel before issue, and provided with a certificate of performance. Deliveries started in 1980 for use on all the ships of the French Navy. By that time, bearings could be taken by means of satellites. Nevertheless marine regulations still required an independently operated timepiece on board so that, in combination with a sextant, the ship's position could be determined by 'astro' navigation.



Fig. 25. Omega Cal. 1525.

Western and Eastern Germany – Wempe & Glashütte

Shortly after WW2, the Allied Control Commission for Germany approved the establishment of a new agency, the German Hydrographic Institute or DHI for short. Because of the cold war split between West and East Germany, two DHI organizations came into being; one for the Federal Republic based in Hamburg and another for the German Democratic Republic (DDR) based in Rostock. I will deal first with Western Germany and the Wempe Chronometer Works.

During WW2, Wempe Chronometerwerke produced clocks in sixteen different places around Hamburg to avoid the danger of getting bombed. However, the main factory in the centre of Hamburg was totally destroyed in July 1943. After a very difficult



Fig. 26. Wempe Marine-Quarz Type 904.

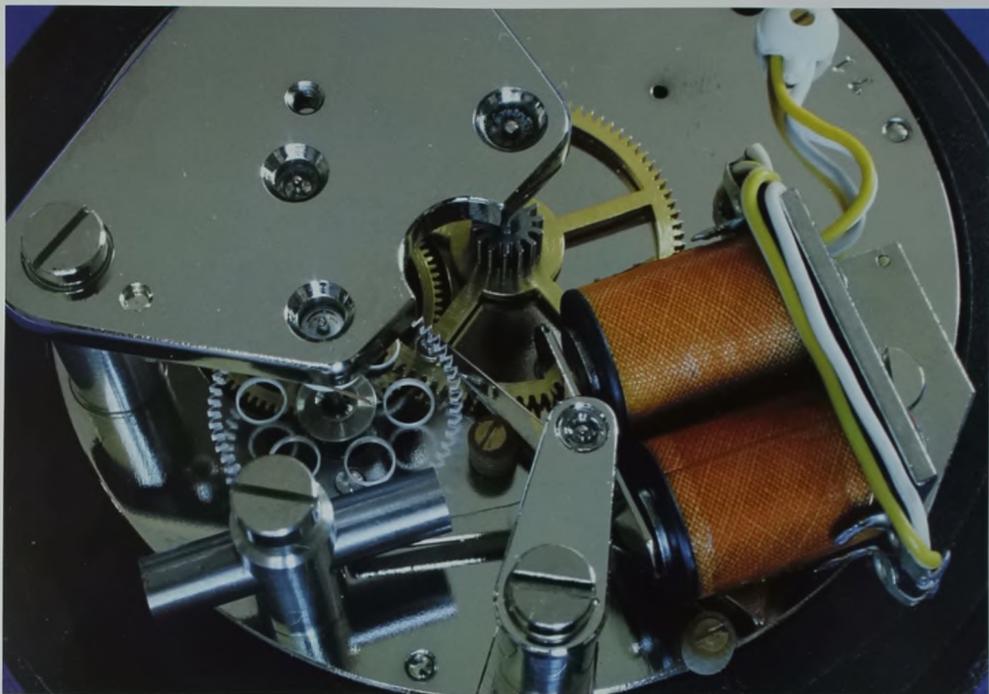


Fig. 27. Wheel train and stepping motor of the 904 movement.

post-war restart the first chronometers went into production in 1962 with the Type 907 spring detent design with electric remontoire mentioned earlier. Then, to enter the quartz market, the company bought in established electronic techniques to marry with their own expertise in movement design. The traditional size for the movement and dial and box were retained together with subsidiary seconds moving in $\frac{1}{2}$ second steps as preferred by navigators. Wempe's first quartz chronometer, Type 904 (Fig. 26), reached the market about four years after quartz chronometers in Switzerland. This can be explained by the fact that the Swiss chronometers emerged from companies that had not been destroyed by war, and with an established history of electronic research.

The movement of the Type 904 is a first class and innovative design. An armature rocks to drive the transparent index wheel by a driving anchor fitted with sapphire pallets. The efficiency is outstanding because the two electro-magnets are wound so that for any direction of current flow, the pole pieces have opposite magnetic poles

on their faces. At the same time the armature is polarised as a constant north by a rod shaped magnet that is seen at the bottom left in Fig. 27. This arrangement means that, as the $\frac{1}{2}$ second alternating pulses pass through the coils, one wing and then the other of the armature is attracted at the same time as the other is repulsed, which makes for the greatest torque for the smallest power. Moreover, the sensitivity is adjustable by careful positioning of the rod magnet which is held firm by the clamping screw visible on its post.

I will now deal with Glashütte in Eastern Germany. During WW2, all production in Glashütte was concentrated on the production of marine chronometers for the navy and wristwatches for pilots, however, many of the main factories were destroyed by Russian bombs. Post war, Glashütte found itself in the eastern part of a divided Germany where the Communist government placed all industry under State ownership. In 1951, famous names, such as Lange, disappeared from the dials of clocks and watches to be replaced by GUB



Fig. 28. Glashütte Quartz Marine Chronometer.

(Glashütte Uhrenfabrik Betrieb) or simply Glashütte. Nevertheless, the skills of watch-making families that had been passed down through the generations, managed to survive. When the highest level of quality was required, as for marine chronometers, it could still be delivered as demonstrated by the instrument shown in Fig. 28. I bought this shortly after the wall came down and deck watches and chronometers made in East Germany for the Communist Bloc began to appear on the market. It was manufactured in the old Glashütte chronometer factory with engraved dial, solid gold hands and typical top quality wheel work with jewelled bearings. The Glashütte quartz chronometer was in production from 1971 until re-unification of East and West Germany in 1990. The box markings show it was made to the 1st Quality specification whilst the dial carries the DHI references of the Hydrographic Institute in Rostock including the letters DSRK which means Deutsche Schiffs-Revision Klassifikation. The quartz crystals were supplied to GUB by the Japanese firm DNK, an approved supplier of frequency standards to the National Space Development Agency of Japan.

Fig. 29 is an image of the stepping motor. Once every second, an impulse from the electronic circuit reaches the impulse coil and a balanced armature closes in order to

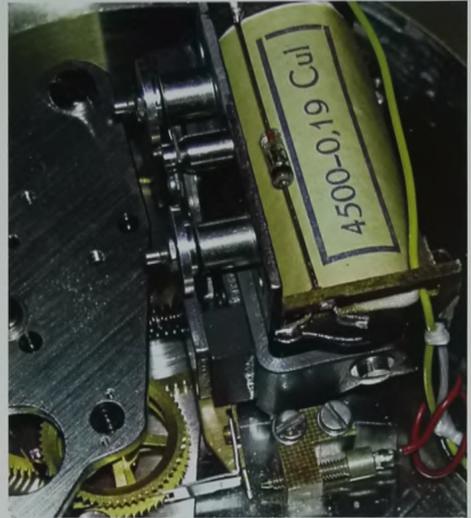


Fig. 29. Impulse coil and indexing mechanism.

index the wheel train. As the armature closes, a stirrup is used to pull the index wheel by one tooth on each impulse. Micrometer control of the position of the indexing carriage is adjusted by an eccentric screw. The duration of the seconds impulse is controlled by closing a mechanical switch at the moment the indexing completes. This is the only example of mechanical control of pulse width in electronics that I have ever seen and allows the mechanism itself to 'decide' when the pulse has done its job. This design is hardly the easiest way to convert electronic pulses into rotary motion but it is, nevertheless, a very effective and efficient electro-mechanical design. After the collapse of the Soviet Union and the re-unification of Germany in 1990, a new independent legal entity owned by shareholders came into existence and is now part of the Swatch Group.

Japan and China - Seiko and Yantai Polaris

Finally, chronometers made in Japan and China. In Japan, during the years 1922 to 1927, Hattori, the holding company for Seiko, retailed spring detent chronometers made by Mercer. Then, during WW2, chronometers were manufactured in house as exact copies of the Swiss chronometer by Ulysse Nardin. In 1964, the Epson



Fig. 30. Seiko 951.



Fig. 31. Seiko 951 temperature compensation.

Division of Seiko provided the sports timers for the Tokyo Olympic Games and a portable crystal chronometer, shown here, was introduced at the same time. It is the Seiko 951 (Fig. 30). The circuit to oscillate the crystal is simple compared with those developed in Switzerland, and without electronic temperature compensation, yet an average daily rate of 0.2 of a second was claimed.

The method for doing this astonished me when I first restored one of these chronometers. To compensate for variations in temperature, Epsom in the twentieth century turned to John Harrison who, in the eighteenth century, had invented bimetallic temperature compensation. In Fig. 31 we can see that a bimetallic coil is used to move the vanes of a variable tuning



Fig. 32. Seiko 951-II Crystal chronometer.



Fig. 33. Seiko QM-20.

condenser in order to adjust the tuned oscillatory circuit of the quartz bar against the affects of temperature variation.

Later in the 1960s, the 951-II (Fig. 32) was introduced with improved quality of manufacture and in a waterproof case. In this form it was used by the Japanese navy, on Eastern merchant ships, and in Europe by the Swedish Navy. As touched on already, an inherent problem in using synchronous motors to drive the wheel train of a precision clock is that an accurate instantaneous start is not possible because the motor must first be spun (by mechanical or electrical means) and then be locked synchronously to a sub-multiple of the quartz frequency.



Fig. 34. Chefoo, China in the 1930s (Courtesy of US Naval Historical Center).

In consequence the synchronous display will always be in error with respect to GMT in spite of trying to start the clock on a precise time signal. This is not actually too important in a marine chronometer because navigators have always worked known error into their calculations. Nevertheless it is irritating and, therefore, a mechanical means for adjusting the seconds – after starting the chronometer – was provided in the original design. The motion work contains a planetary gearbox which allows adjustments of a $\frac{1}{5}$ of a second by use of push buttons whilst the motor is running. It was an extraordinary mechanical achievement and unique to Seiko.

Although the 951-II was a very successful marine chronometer, its use of a synchronous motor for the time display and the need for its mechanical adjustment whilst running was a dead end. In the late 1970s it was superseded by the QM-10 using integrated circuits and a $\frac{1}{2}$ second stepping motor to be followed in 1986 by the QM-20 shown in Fig. 33, a chronometer which for oscillator stability and overall quality was their finest product and selected for use by the Dutch Royal Navy.

Yantai Polaris – China

Lastly, I will deal with China. Whilst Japanese products are extremely well known in global markets, those of China in the time of Chairman Mao are virtually unknown. The modern Chinese timepiece industry was created in 1915 in Yantai; a treaty port universally known as Chefoo,



Fig. 35. Yantai Polaris SY2.

that was extensively used by international shipping and was also 'home' for the US Navy's Asiatic Fleet (Fig. 34). The need to service every aspect of the shipping industry led to Yantai becoming the birthplace in China of modern industrial manufacturing. In 1957, the Yantai Timepiece research department completed designs leading to production of a spring detent marine chronometer to fill their domestic needs.

Ten years later, in 1967, research was completed for the production of a quartz observatory clock, the SY1, after which the SY2 quartz chronometer shown in Fig. 35 went into production. The name on the dial of the SY2 is Polaris, the navigating star that was chosen as the trademark for Yantai timepieces. The Proletarian Cultural Revolution under Chairman Mao was in progress when this was made and the Yantai Timepiece Industry was a closed book as far as the west was concerned. References to this chronometer do not exist (as far as I know) outside of China.

Examination of this instrument has revealed that it is very well constructed and, with its sweeping seconds, clearly a close copy of the Seiko 951, particularly with respect to the design of the synchronous motor.

There is, however, an additional feature, not provided by Seiko, that overcomes the lack of precision in a synchronous display. The wheel train of the synchronous motor and the movement carry electronic sensing coils shown in Fig. 36 from which an output circuit provides frequencies at a socket on

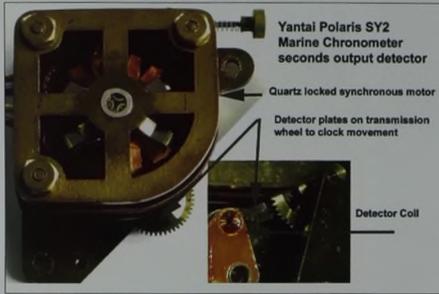


Fig. 36. Seconds output detection system.

case of the chronometer. I have photographed the sensing arrangements disassembled so that the details are clear. With this addition, ships fitted with the Yantai instrument have frequencies available for monitoring exact seconds – not possible on the face of a sweeping seconds dial - as well as facilities for controlling ships clocks.

These images of chronometry in China in the time of the Cultural Revolution bring my lecture to a close. Yantai Polaris today operates in a free market and manufacture their own satellite controlled ship's clock systems both for national use and export. It is interesting, however, that they also still manufacture a stand alone ship chronometer, currently type SY-5.

Conclusion

The death of the ship's chronometer has been predicted since the transmission of time signals by radio in the first decade of the twentieth century and, more recently, since the last stage of the global positioning system was put in place in 1994. However, positioning systems can fail from multiple causes including technology failure and human error. They are also easy to jam. Moreover, the GPS and the satellites on which the system depends are, for the most part, under the control of a single global power. In time of war the GPS could be turned off or sabotaged. It is appropriate, therefore, that whilst GPS is now universally accepted as the primary method of position determination, the US Navy's navigation policy states

Every platform/user with a validated requirement shall have a primary and at

least one alternate means of position determination. The alternate means must be independent of the primary.

The chaos that would be caused by GPS failure had been understood for many years. As long ago as 1999 George Kaplan of the US Naval Observatory and an advisor on this subject wrote:

As our defense forces rely increasingly on GPS, it is important that this dependence does not become a single-point-failure risk for military operations. Independent alternatives to GPS are needed and are required by official policy. Imaginative application of available technology can ensure that celestial navigation has as much of a role to play in the future as it has in the past in helping to provide safe passage for our military forces worldwide.

These words proved to be prescient. In April 2014, Satellites of the GLONASS network (the Russian equivalent of GPS) experienced a half-day outage when bad data was uploaded to spacecraft causing a GLONASS receiver at Harwich in the UK to give corrupted position fixes that were off target by more than 50km. The relevant authorities agreed that it was a timely reminder that alternatives to satellite navigation are essential.

Professor David Last, a consultant engineer and past president of the Royal Institute of Navigation was interviewed on the BBC News and said:

What we saw last week was many people being affected by the GLONASS failure even with receivers that were also picking up GPS. The lesson that comes out of this is not just that satellite-navigation systems are vulnerable, but that you don't get a protection by simply plugging in a second satellite-navigation system. You need something that is different and doesn't share common modes of failure.

It would seem sensible to preserve terrestrial based precision timekeepers and the skills of the human navigator.