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Synopsis

Some aspects of precision time measurements, controlled by means of piezo-electric-vibrators, as deployed in Germany prior to 1950.

For several centuries, time was controlled by means of mechanical clocks and chronometers which were, themselves, controlled by astronomical observations. In this country, Greenwich deployed one of the world's most important chronometers. Soon after the introduction of wireless in the early nineteen hundreds, special time signals were transmitted the impulses for which were derived from the best chronometers in the country.

Since the mid nineteen twenties, it has become possible to control clocks by means of piezo-electric-vibrators. For several decades following, those so-called quartz clocks were of a rather bulky nature and were mainly employed by astronomy centres to control their own time and frequency standards.

Though the scientific knowledge and technology of quartz was rather limited in the early days, it is very interesting to follow the improvements in quartz-clock technology and its specifications during the first half of the past century.

This paper describes the quartz-clocks designed by the German Bureau of Standards and the revolutionary quartz-clock invented by Rohde and Leonardt, of the Rohde and Schwarz company, in 1937. Also described is a very particular time measuring apparatus which was invented and designed by the Telefunken company specifically to check the range calibration of their radar equipment.

Introduction

Time is a rather mysterious quantity, whose physical existence nobody has ever seen and/or touched. But nearly every human being is, to some extent, aware of its phenomenon and has, from moment to moment, a rather subjective experience of it.

Even in physics it is not known what time really is, the only thing we can do is to construct apparatus with which we can compare (and so create) the time intervals. The “second” is the unit of time interval which is used in physics and which is the 86400 th part of the (average) daily rotation of the earth (24 x 60 x 60). These reference equipments were, in the past, often pendulum clocks which were succeeded, after about the end of the nineteen twenties and early thirties, by quartz controlled time standards. The first pendulum clock was patented (in Holland called octrooi) on 16 June 1657 and was invented by Christiaan Huygens. He probably wasn't the first one who worked in this field but it was he, without doubt, who brought the idea to maturity. (1)

Since about the mid 1950s we have been able to use, for this purpose, so-called atomic-clocks or frequency standards. However, for many decades previously, the electrical time-impulses were derived from the steady and cyclic movement of a pendulum which triggered an electrical (switching) contact. Those pendulum clocks were themselves compared with astronomical clocks as were, for instance, employed by the famous observatory in Greenwich. They probably used the world's best pendulum chronometer made by William Hamilton Shortt, the deviation of which was estimated at . 1.5 x 10^{-3} seconds per day. (2)

After wireless allowed the transmission of reliable time signals, most observatories in the world compared their time standards by radio. The accuracy of the time measurements could thus be increased to up to 10^{-8} (or even better). A disadvantage was that quite a long time interval was necessary, for even up to several months, to correlate the time data to obtain a sufficiently precise resolution.

From Lapis electricus to piezo-electricity

For this paragraph I am mainly indebted to the introduction chapter of Cady's famous book "Piezoelectricity". (3)
In 1703 a Dutch merchant stationed in Ceylon, reported in a letter to Holland a phenomenon:
- when a tourmaline stone was placed in hot ashes it first attracted and then repelled the ashes. This phenomenon was already known for many ages in India and neighbouring territories. It was sometimes called the "Ceylon magnet". In 1747 Linnaeus gave this phenomenon the scientific name "lapis electricus". Aepinus in 1756 noted the opposite polarities at the two ends of a heated tourmaline crystal. Brewster introduced the word "pyroelectricity" in 1824, after he had observed similar effects on various crystal types as well. (Cady, p. 1,2)

However, we had to wait until the brothers Pierre and Jacques Curie published, in 1880, their famous papers in the proceedings of the "Comptes rendus de l'Académie des sciences" in France.

1. Développement, par pression, de l'ectricité polaire dans les cristaux hémièdres à faces inclinées. (2.8.1880)

2. Sur l'electricité polaire dans les cristeaux hémièdres à faces inclinées. (16.8.1880)

(we have ignored the publications after 1880) (4)(5)(6)

They had observed that crystals (quartz and tourmaline) when compressed in particular directions showed positive and negative charges on certain portions of their surfaces, the charges being proportional to the pressure and disappearing when the pressure was withdrawn. It was Hankel who proposed (introduced) the name "piezo-electricity". (piezo is the Greek word for to press) (Cady, p. 2,3)

Many scientists were fascinated by pyro- or piezo-electricity. It was the German (Prof.) Voigt who became, in 1910, most famous for his monumental *bible* “Lehrbuch der Kristallphysik”. (Cady, p. 5,8) According to Cady, Voigt proved (in his book) the differential equations for the elastic vibrations of the piezo-electric-vibrators. Many scientists were searching for a technique to explore the elastic vibrations in quartz crystals, though none of them had so far designed a working circuit.

Nonetheless, a decade later Walter Guyton Cady proved that the piezo-electric phenomenon could really control frequency stability.

Cady applied for an American Patent on 28 January 1920 which was granted on 3 April 1923 under number 1,450,246. He claimed a *Piezo electric resonator,* his second patent 1,472,583 claimed a *method of maintaining electric currents of constant frequency*, which was granted on 30 October 1923. Probably due to legal obstructions these patents were (had to be) re-issued (registered) in 1929. (7)

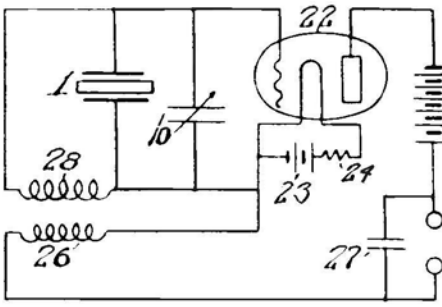

Fig. 1: Cady's first quartz oscillator application

On 1 October 1925 Cady filed another patent in this was claimed: *method of mounting piezo electric resonators for the excitation of various overtones.* Which was classified on 18 November 1930 under the patent number 1,782,117.

The wold’s first quartz filter (circuit) application is shown in fig. 2 which was, apparently, covered by Cady’s first patent as well.

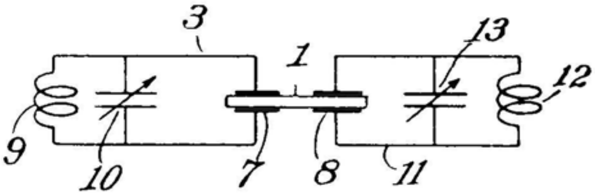

Fig.2: Cady's first quartz filter application

From now on it became possible to ensure frequency stability. However, its scientific nature wasn’t yet fully understood.
The second important patent was filed, in the name of George Washington Pierce concerning an “Electrical system”, on 25 February 1924 and which was classified 1,789,496. The two relevant circuit components were a quartz crystal and an oscillator valve. Originally Pierce placed the

quartz between the anode and the grid of the valve. Miller modified its circuit (also called modified Pierce or Pierce-Miller circuit) and placed the quartz crystal between ground and the grid.

Terry attacked in a paper (1927) the conditions for stability of frequency of piezo oscillators. In the years that followed numerous papers covering other treatments of the theory appeared, each containing simplifying assumptions. One of the most thorough was that of Vigoureux (he died recently), who derived formulas for frequency and currents in terms of the crystal, valve, and circuit parameters. These were in good agreements with experimental results. (Cady, p. 506, 507)

We have seen, in the previous paragraphs, that the early technologies to explore the piezo-electric phenomenon mainly originated in the United States.

In closing this chapter we should also not forget the names of - Marrison, Mason, Hansell and others who played, for decades, a significant role in various American institutions. Pierce later turned his scientific attention mainly to the field of “magneto-striction”.

Germany’s contributions

The German Bureau of Standards which was officially known as “Physikalisch- Technischen Reichsanstalt” (or abbreviated PTR) was probably the first scientific centre in Germany which responded to Cady’s paper concerning his quartz resonator experiments published in the Proceedings of the Institution of Radio Engineers of 1922 .

Giebe and Scheibe of the PTR accepted the challenge of this new technology and became leaders in Germany, in the field of frequency and time standards. In the 1920s and 1930s their patents were widely perused even in this country.

Their first (main) attempts were carried out with quartz bar resonators. These quartz bars, or rods, were longitudinal vibrators whose long-axis was parallel to the X- or Y-plane of the quartz crystal. (Cady p. 463) Their first important innovation was to place a quartz bar (which had either a rectangular or sometimes circular cross section) inside a glass envelope incorporating a mixture of **Ne**on and **He**lium at a pressure of only a few millimetres of mercury (Hg). Assuming that the quartz crystal is mounted in an appropriate manner (with low damping) the local strains can become so strong that the piezo-electricity can ionize the Neon and Helium mixture which produces a visible glow (like an aura) around the centre(s) of action. For those cases where no high accuracy was required these luminous crystals were used as a secondary frequency standard and became, in the late nineteen twenties and in the early nineteen thirties, very popular. Its simplicity of operation is evident. It could load an inductive link or be connected by a small capacitor onto the antenna of a transmitting system. Its power consumption was very low and did not result in detuning of the (feed) source. Soon, several quartz bars were placed inside one envelope so that more than one frequency could be controlled or measured. However, a special phenomenon could manifest itself during luminous effects. The luminous quartz device could generate a squinched kind of tone modulation. This erratic behaviour was dependant upon the surrounding pressure and the mixture of the Neon and Helium gas. (8)

In the early days they used rather low, fundamental, quartz frequencies for luminosity purposes. An advantage was that its behaviour, at overtones, could be observed very well. As we have previously mentioned, the damping of a quartz resonator is an important parameter. Giebe and

Scheibe became masters of the so-called “wire cord mountings” in which the quartz bars were bound or fixed at their nodal points in a very particular (probably patented) manner. They used for these structures silk or equivalent wire cords. The electrodes were capacitively coupled with the quartz bar, thus not touching its surface so as to enhance the Q -factor of the quartz resonator. (see later fig. 4 a-b)

Giebe and Scheibe’s efforts were carried out on behalf of the PTR, but these luminous or so-called “Leuchtquarze” were (probably for legal reasons) manufactured by the Radio-Frequenz GmbH, which company was a subsidiary of the Loewe-Radio company. In the 1930s Loewe became the major supplier of these luminous devices. However, due to political implications in the “Third Reich”, the affiliated brand name “Opta” also appeared at a later date.

The first British reference to the luminous quartz devices which I have been able to trace was published in Experimental Wireless & The Wireless Engineer of November 1926 (p. 658-660). It describes the Berlin Wireless Exhibition of that year quite extensively. Photographs of luminous quartz resonators, excited in various overtone modes, were shown even encompassing the 21st harmonic.

In the 1920s it became necessary to compare the frequency standards and measuring methods of the national institutions of standards in the civilised world. In 1926/27 the American BOS (Bureau of Standards, as it was named by Giebe and Scheibe, probably this institution is equal to the well known NBS later named NIST), and the NPL in this country, the TM in France and the IE in Italy started to cooperate in this field. Dellinger was also involved in the international group of frequency standardisation on behalf of the BOS in the US. Some of the standard devices and/or apparatus were sent to their fellow centres in the rest of the world. A funny detail in their paper is: - that the Germans sent their “quartz plate (probably bar) number 15” from Germany to America and then it went via England - France to Italia and back home. Whereas, the quartz plate number 16 travelled in the reverse direction. (9)

The Germans were not only focussing on quartz bar resonators but were also experimenting with quartz plates. Their aim was to enhance the quality of their frequency and time standards.

The Quartz-Clocks

Marrison of the Bell Labs had started to work already, in 1924, on the development of a quartz controlled clock which culminated (in 1929) in a mature quartz-clock. Its short term frequency stability was estimated at . 5×10^{-8} and it showed an average daily time deviation of .5×10^{-3}. According to Petzhold, these details were based on Marrison’s paper “The crystal clock”, in the Proceedings of the National Academy of Science of the United States, July 1930.

In September 1932 Scheibe and Adelsberger gave a paper called “Eine Quarzuhr für Zeit- und Frequenzmessung sehr hoher Genauigkeit”, at the German annual Physics meeting. (10) Which can be translated: -A highly accurate quartz-clock for time and frequency measurement. (Giebe died in early nineteen thirties)

They explained that, after an experimental period, their first quartz-clocks (model I and II), at the PTR, had been running since January/February 1932. Their time base, as this is called today, used a 60 kHz longitudinal quartz resonator which was housed in an evacuated glass envelope. (see also fig.4) They explained: - that to keep the daily time deviation of the clock within " 1 ms the temperature stabilisation had to be controlled at " 0.002° C. This was done by using a double temperature controlled housing, the quartz crystal being kept at 39 °C (some others at a different temperature).

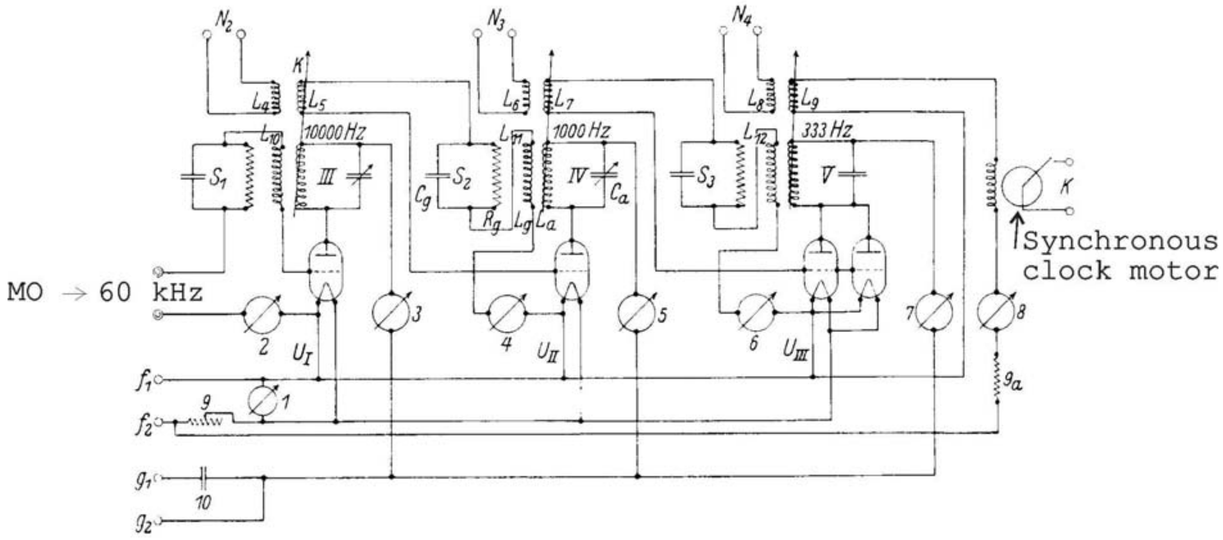

Fig.3: The divider circuit of the PTR clocks (1934)

The frequency of 60 kHz was first amplified and then fed onto a factor 6 divider stage making it 10,000 Hz; this was followed by a factor ten divider stage producing a 1000 Hz signal; this signal was then divided by 3, resulting ultimately in a 333 Hz signal.

Those dividers were of the so-called reactive type. An inductively coupled generative feed-back stage was phase-locked by the in-coming signal from a higher frequency order. Those divider types were widely used in those days but were a bit difficult to operate due to the delicate tuning required to obtain stable synchronisation.

The 333 Hz signal was fed onto the synchronous motor of a clock which also generated the 1 second (= 1 Hz) time (interval) impulses. These time impulses could be compared with the astronomical signals which were sent by the wireless stations of, for instance, Nauen, Greenwich and the **B**ureau **I**nternational de l'**h**eure in Paris (after late 1987 BIH was renamed in BIPM which stands for **B**ureau **I**nternational des **P**oids et **M**esures) It soon proved that even these highly respected institutions didn't supply coherent time signals. We will cover this point later.

These early quartz-clocks were rather bulky instruments though their specs were very good for those days. After an observation period of six months clock number I showed an absolute time deviation of 2 ms which was equal to a frequency deviation of . 2 x 10^{-8}. However, comparison of the time or frequency constancy, over the same time period, for both clocks I and II showed a time difference of . 0.3 ms which is equal to . 4 x 10^{-9} (Hz).

The rotation of the clock (spindle) system showed daily deviations of " 0.0003 s which is equal to a frequency tolerance of 4 x 10^{-9}. Statistically (absolute Gangkonstanz), those clocks were better than " 1 ms which is equal to a frequency deviation of 1 x 10^{-8}. (Adelsberger and Scheibe, p.

839) We still have to consider that the only available time references, world wide, were the astronomical chronometers and, consequently, the wireless time signals which were transmitted by them.

In 1934, Scheibe and Adelsberger published a paper in a well respected German technical magazine entitled: - Die technischen Einrichtungen der Quarzuhren der Physikalischen-Technischen Reichsanstalt, which can be translated as: The technical installation of the quartz-clocks of the PTR. (11)

Their explanation of the quartz resonators which they had used was quite detailed. The quartz bar was 91 mm long, 3 mm width and its thickness was 1.5 mm. The bar orientation was parallel to the X-axis and its width was parallel to the Y-axis (zero-angle cut). The quartz bar and its electrodes are shown in fig 4a. Fig. 4b shows an example of the wire cord mounting.

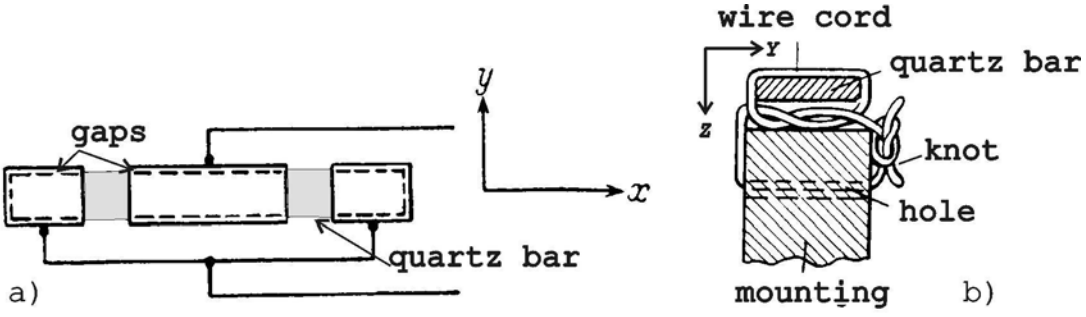

Fig.4: a)The quartz bar and its electrodes
b)Giebe's and Scheibe's wire cord mounting

In the meantime (1933/34) they had constructed two new clocks numbered III and IV the latter one being slightly different in design (in fact all showed differences due to modifications). Their quartz resonators and accompanying thermostats had also been improved as well. The switching intervals of the inner as well as outer thermostats were monitored by (ordinary) mechanical “telephone counters”. The clock outputs were each fed on to an electrical time recorder. For their statistical survey it was very important to compare the time data which was generated by the astronomical centres with that of their own systems.

The (divided) signals of 10,000 - 1000 and 333 Hz (see fig.3) were available at their measuring outputs. The 10,000 Hz signals were also used to compare the output signals against the other quartz-clocks so as to generate beat notes which were caused by the phase drifts between the quartz-clock frequencies. By this means it was easy to create, and calculate, statistical time and/or frequency deviation graphs.

The first statistical proof of the deviations of the daily earth rotation

In 1936, Scheibe and Adelsberger published their quite revolutionary paper(s) called: “Schwankungen der astronomischen Tageslänge und der astronomischen Zeitbestimmung nach der Quartzuhren der Physikalischen-Technischen Reichsanstalt”. Translated: Deviations of the astronomical length of the day and the astronomical time measurements using the quartz clocks of the PTR. (12)

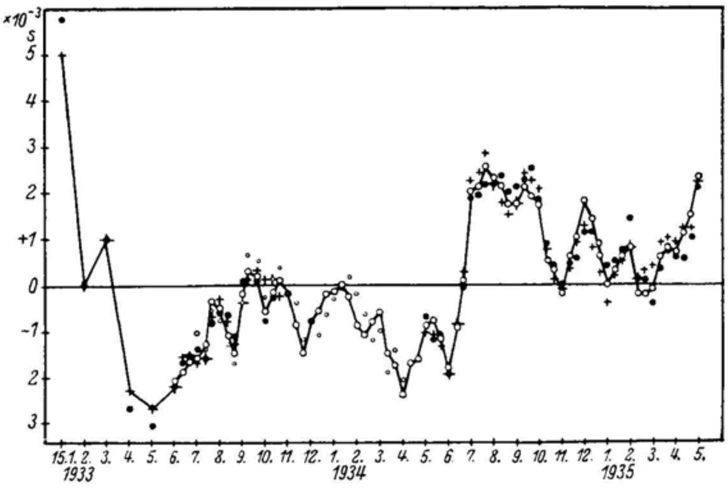

Fig.5: Deviations of PTR quartz clocks versus astronomical time

After explaining all kinds of particular system details, they proved, in figure 5, that the long term time deviations (January 1933 up to May 1935) of the three compared quartz-clocks showed only marginal mutual deviations in contrast to those of the astronomical time signals. This was a very important pre-condition to show that, when time differences were being measured between the astronomical centres and that of their own systems, these deviations (differences) could not be originating from their own systems.

Fig. 5 shows clearly that there were significant time deviation peaks around the months of May and lesser time deviations in the autumn periods.

Stoyko, in a controversial polemic claimed in his paper: - "Présion d'un Garde-Temps Radio-Electrique à Quartz" (13), - the assumption that the astronomical time generated by the pendulum chronometers would not be entirely correct was not valid. What he meant was, that the quartz-clocks were not as good as the astronomical clocks. We are not going to pursue Stoyko's assumptions. Adelberger made it clear that Stoyko's presumptions were not cogent, because Stoyko compared the results of only one astronomical clock (presumably that of the Bureau International de l'heure in Paris) against the time registrations of fellow astronomical centres. Challenged by Stoyko's statements, Scheibe and Adelsberger decided to seek to prove the real existence of deviations in the daily earth rotation. Up until then the time registrations were based upon the observations of the sun, or fixed stars, when these were crossing a particular meridian (longitude). These observations were, among other factors, subject to errors caused by the observer.

One of their conclusions was: - that their comparison of the quartz-clocks and the chronometers (chronographs) of the astronomical centres indicated that the quartz clocks, over a 30 day period, had a daily deviation of only " 0.0002 s, which was about 4.5 times less than that of the, average, astronomical controlled pendulum chronometers (. 1 ms). Which latter value wasn't denied in Stoyko's paper.
We will not go into details about Scheibe and Adelsberger's proof concerning the stochastic deviations of the daily earth rotations.

Lothar Rohde's revolutionary "portable" quartz-clock

The General Radio (GR) company built their first commercial frequency standard type "Class C-21-H" somewhere in the nineteen thirties. Its designs showed a more or less similar system philosophy to what we have noted with the quartz-clock apparatus deployed at the PTR.

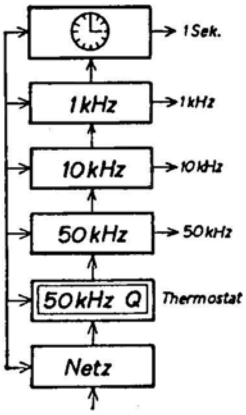

Fig.6: Block diagram of GR's pre-war quartz-clock (Rohde)

GR used a 50 kHz reference oscillator whereas the PTR used a 60 kHz one. (14) Nonetheless, there is strong evidence that they had deployed (optional) a 100 kHz quartz reference as well (type 676-A). Its quartz (bar) mounting was less sophisticated than that of the post war type 1190-A. (see hereafter)

In the late nineteen forties GR built their modified type 1100-A. Its circuit concept still followed their previously described formula though, they had changed to a 100 kHz quartz crystal. A very interesting detail is that, although they used deposited silver electrodes, the quartz crystal was mounted by means of springs. Around the quartz bar was a particular wire cord construction which showed some similarity with that of Giebe and Scheibe's wire bounding. According to the manual: *The mounting is a spring suspension, holding the quartz bar at the corners only of the long faces, in a manner such as to introduce the least damping. .. The spring tension maintains the mounting conditions essentially constant over long periods. Because of the mode of vibration, there are two nodal regions and supports are placed at each. (Operating instructions for Type 1100 -A Frequency Standards, General Radio, p. 5)*

This support method showed some similarity with that designed by Giebe and Scheibe in the 1920s. An interesting detail is that the quartz bar is not mounted in a vacuum envelope and that very near to its faces (at both ends) there were placed two baffles (so-called ultra sonic reflector plates) to reduce the energy radiated from the ends of the quartz bar. (15) (15a)
In a later chapter we will come back to GR's particular interest in aspects of the wartime PTR clock designs.

However, a great disadvantage was that both the PTR and the GR quartz-clocks were rather bulky instruments which could hardly be regarded as being "portable".

Rohde's revolutionary quartz clock design

We have previously learned that PTR, as well as General Radio in the US, built quartz-clocks which employed quartz controlled time bases. These latter circuits were followed by several divider stages to obtain, ultimately, a frequency by which synchronous clock motors could be made to run in a stable (reliable) manner. The frequency most often used was 1000 Hz (the PTR used 333 Hz to drive their clock motors). The clocks which were driven by synchronous motors derived the 1 second time impulses by means of electrical switches. This was the state of the art up until about 1937.

The friends Rohde and Schwarz both got their Ph.D. in 1931 at Jena Technical University and established in 1933 a small design lab in Munich for RF measurement equipment. This company became later very well known as Rohde & Schwarz (R&S). (16) (17)

On 7 July 1937 Rohde applied for a German patent which became classified on 9 May 1940 under DRP Nr. 691 848. (18) He claimed: “a Piezoelectric controlled time standard”. Although his name is solely mentioned on this patent application, we may presume that Richard Leonhardt was involved as well.

The associated patent drawing was of a rather cryptic nature and is, on first viewing, not easy to understand. I have made a considerable study of all sorts of patents, but the German patent claims can often be the most puzzling ones.

We will rely mainly on Rohde's explanations in ENT of 1940 (19), this paper was called: “Quarzuhr und Normalfrequenz-Generator”, which translates to “Quartz-clock and Standard frequency generator”.

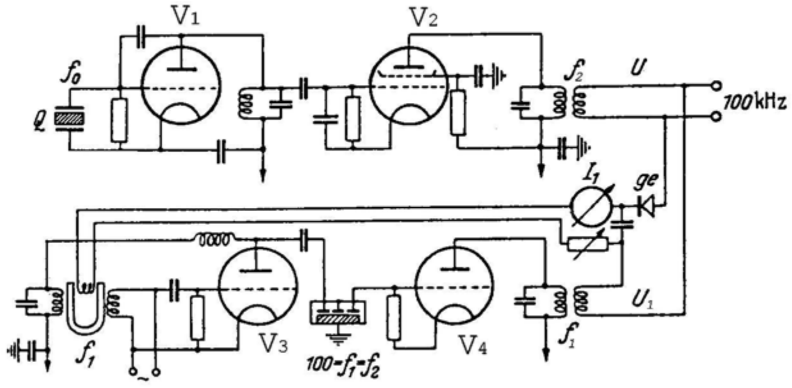

Fig.7: Rohde's way to control the freq. of the tuning fork

The quartz oscillator valve V_1 is, in this circuit, followed by a buffer stage, which valve was omitted in the modified version. Its signal was fed onto the RF transformer which was tuned on the quartz frequency f_2 at 100 kHz. A tuning fork oscillator of conventional design was tuned at a frequency of 1000 Hz; its output signal, at V_3, wasn't of a sinusoidal nature but contains considerable harmonics of which the 100 th was selected by means of a narrow quartz band-filter (flexural type). Its signal was, after amplification, being fed onto V_4 and then to the transformer tuned at f_1. Both signals will interfere by means of vector summation when linked together. We call the output signal of the tuning fork U_1 and the output of the quartz oscillator U_2, which will result in the modulus u.

$$u = U_1 \cos (\omega t + \boldsymbol{n}) + U_2 \cos \omega t \tag{1}$$

Practically, we can assume (which was estimated to be valid for this circuit) $U_1 = U_2 = U$ We may consider:

$$u = 2\, U \cos (\boldsymbol{n}/2) \cos (\omega t + \boldsymbol{n}/2) \tag{2}$$

It is evident that when $\boldsymbol{n} = \pi$ the resulting $u = 0$, and that for $\boldsymbol{n} = 2\pi$ the resulting output is at its maximum. For the regions where (argument) $0 < \boldsymbol{n} < \pi$ we get instability and no phase locking will occur. In practice the angle $\boldsymbol{n}$ will vary for only about 10 %, which results in a phase shift error of . 5 x 10^{-7}. This can, according to Rohde, be neglected with respect to the 100 kHz reference frequency.

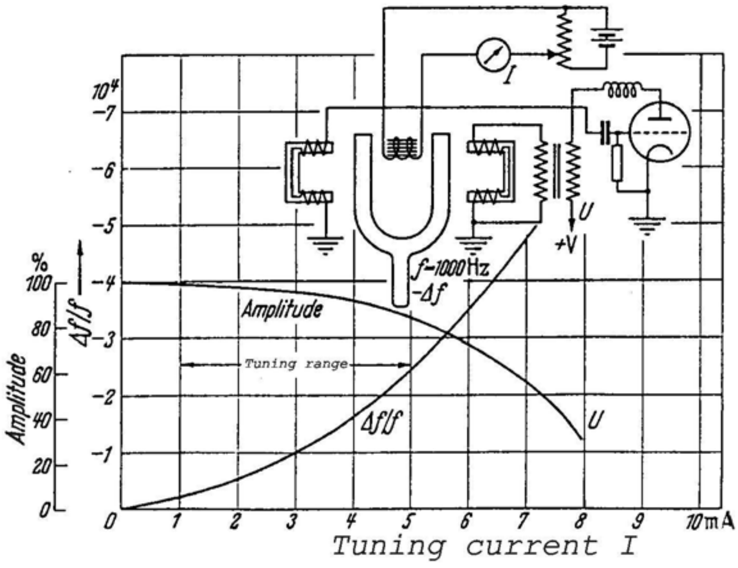

Fig.8: The parameters of the tuning fork control

The response curve of the tuning current versus the detuning $\Delta f / f$ of the tuning fork is shown in figure 8, which was obtained by means of an electro-magnet placed between the two fork legs. Increasing its magnetic flux slows the fork oscillations and in consequence decreases its output frequency. Of course, the inverse will occur when the magnetic flux is being reduced. It is evident that when the frequency is being decreased this also will lower the Q factor of the vibrating tuning fork. If we estimate that the bandwidth of a tuning fork is 0.1 Hz at 1000 Hz, then the Q will be 10,000. A damping of the Q factor of the tuning fork, due to its magnetic loading, obviously decreases its output voltage. The voltage swing of the tuning fork oscillator (output) can be estimated for a maximum of about 15 % (which didn't caused any technical problems).

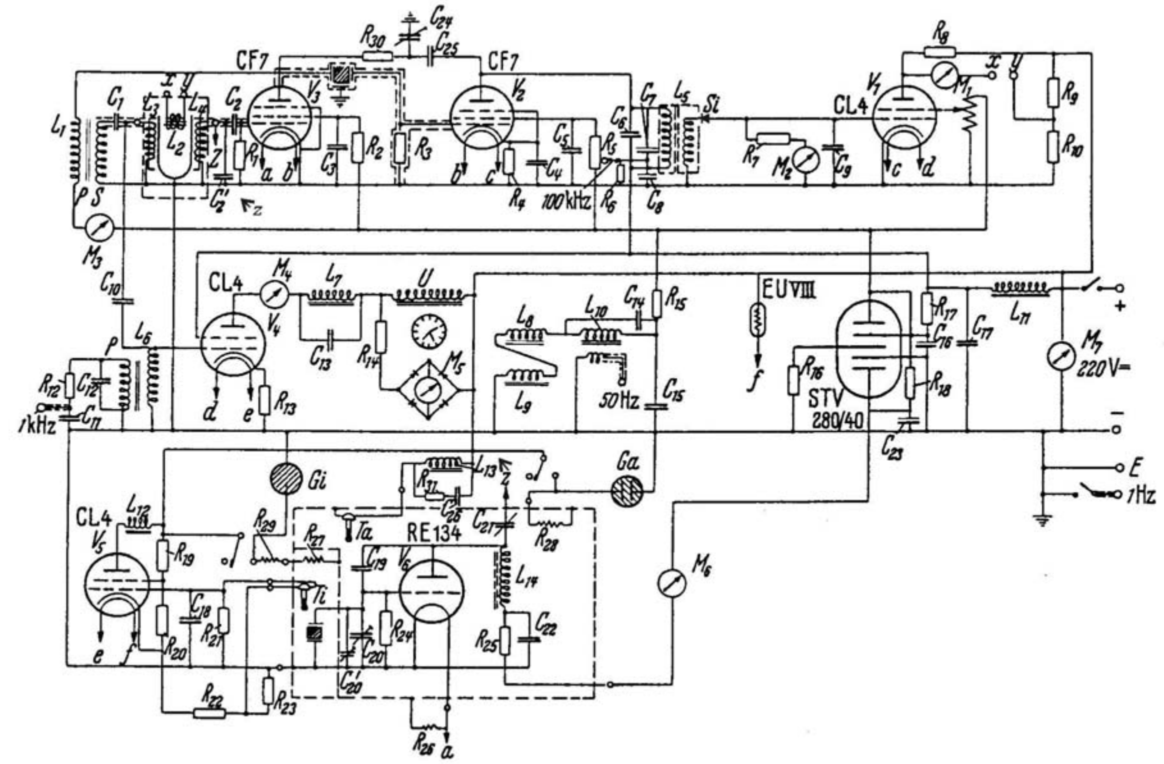

Fig.9: Simplified diagram of the quartz-clock type CFQ (R&S)

Shown here is a, slightly simplified, electrical circuit diagram of the famous Rohde and Schwarz quartz-clock type CFQ. The tuning fork oscillator valve is V_3. The 100 kHz quartz reference oscillator valve is V_6. If we keep figure 7 in mind, then it is obvious that the output of the tuning fork signal and that of the 100 kHz quartz reference oscillator have to add their mutual signals by means of vector summation (modulus).

The output signal of V_6 is fed, via line '*Z*', onto the grid circuit of the tuning fork oscillator valve V_3, which circuit was especially designed to generate harmonics of high order. The later oscillator valve acts, by this means, as an additive mixing circuit as well. Its output at the anode contains a wide signal spectrum of which the 100 kHz region is selected by means of a narrow band quartz-filter QF (the modulus of the 1 kHz x 100 and the 100 kHz reference signal, notice equation 1 and 2). The great advantage of this circuit is that when the signal is following the same signal path (delay) then their mutual phase deviations are (all) kept equal.

The resulting signal is, after amplification in V_2, fed onto the tuned circuit of L_5. Its signal output is, after rectification in diode S_i, fed onto the dc amplifier V_1. The output signal, at the terminals *x* and *y,* is linked onto the (de)tuning control coil L_2 (between the tuning fork legs).

The 1000 Hz signal for the synchronous clock motor was amplified by V_4. The filter circuit L_7 and C_{13} was (presumably) tuned at the second, or eventually third, harmonics of the original fork frequency. The principle diagram of the synchronous clock module is shown in figure 10.

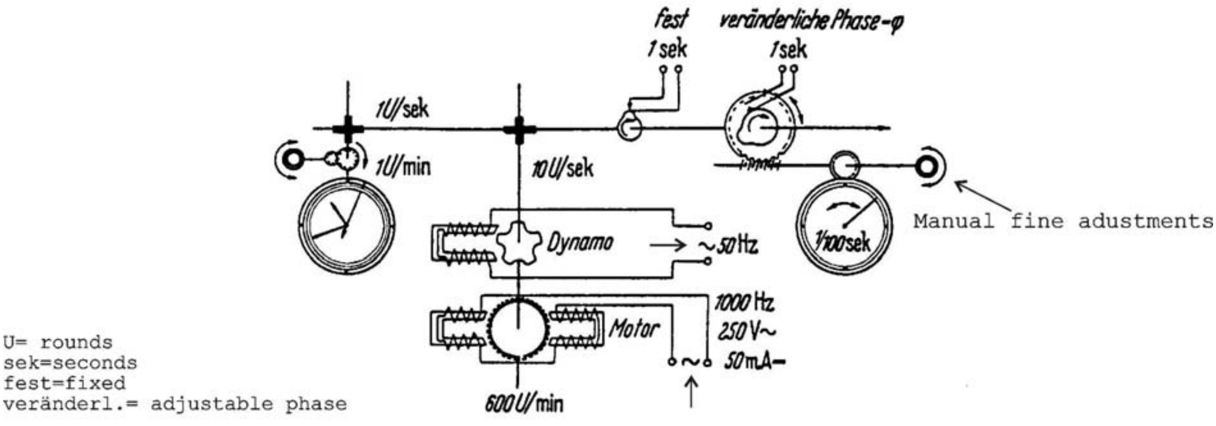

Fig.10: The principle of the synchronous clock module

The synchronous clock motor employed 100 poles which consequently resulted in 10 rounds per second which corresponds with 600 rpm (the rotor was damped by means of the, adjustable, flow of mercury). The drawing is self explanatory.

The quartz resonators which were used by R&S for their early quartz-clock designs were of (more or less) similar design to the ones which were used by the PTR (both employed longitudinal quartz bar resonators). The quartz bars were similarly fixed by a silk wire cord (later artificial silk) (see fig. 4a-b). (20) This information was confirmed, in a fax message, by Mooser, one of the former employees of R&S. He stated that the early quartz (clock) references were manufactured by the firm Loewe and that the quartz bar was fixed in the envelope by means of two special knots. This demanded very special skills (work of art) to ensure that the wire cord didn't change its configuration during long term operation. Unfortunately, after Loewe's specialist had died there was no one left who was capable to continue this skilful job. As a result they modified the crystal resonator type and used CT cut quartz resonators. (21)
However, in contrast to the fundamental mode operation used by PTR, the R&S quartz-clock crystals were excited at the second harmonic frequency.

The Temperature coefficient was at 39° C (which was the working temperature) about $1 \cdot 10^{-7}$ K^{-1}, the crystals were kept in a nitrogen filled glass envelope at a pressure of about 0.1 mm Hg.

The reference quartz at 100 kHz and its oscillator valve V_8, including the tuning fork oscillator were placed inside the inner, thermostatically controlled, cabinet and kept at 39° C within 0.01° C.

Quite remarkable was the fact that the oscillator valve used a relatively low emission current of only about 800 µA. Normally this can "poison" the cathode - grid area of a thermionic valve. Due to this annoying phenomenon, they employed a directly heated valve (RE 134) which proved to be a good choice. It could run continuously for many years without replacement! (As long as the filament voltage had been properly adjusted!)

During the war years R&S modified their CFQ clocks slightly and replaced the CF 7s valves by four, so-called, "metal encased valves" type EF 12.

According to information which was passed on to me by Gerd Langloh, during a meeting in the R&S head quarters in December 1999, they produced a total of 107 CFQ clock instruments.

The advantages of using a tuning fork as frequency divider device can perhaps best be explained by quoting from the conclusions which were expressed in the Allied report which was published in the late 1940s. (22)
... A point of considerable interest is the comparative freedom from stoppage of the Rohde and Schwarz equipment. This probably constitutes the only evidence so far available concerning the long time reliability of the type of dividing circuit used and the results suggest that this and other time discrimination methods of division described recently by F.C. Williams and T. Kilburn should be considered for the possible application to quartz clock equipments. In the United Kingdom the frequency division is usually effected by the multivibrator type of circuit and this has on the whole been found satisfactory, unbroken periods of over a year having been obtained. The Rohde and Schwarz method using a tuning fork as an intermediate oscillator has one considerable advantage however. Owing to the inertia of the system, control of the tuning fork by the quartz oscillator can be maintained in spite of transient impulses which might be induced in the circuit by, for example, a momentary breaking of the circuit; whereas with electronic division such transient would almost certainly disturb the phase relationship between the quartz oscillator and the dividing circuits. On the other hand there is some "hunting" of the tuning fork frequency and consequently some loss in the precision of the time impulses. This can be overcome by the use of a special circuit arrangements by which the tuning fork impulses serves as a "gate" for the appropriate impulses from the standard itself. .... It is noteworthy that all the quartz oscillators used as time standards in Germany were made by a commercial firm. In the United Kingdom, on the other hand, oscillators of the necessary precision have so far been made only in Government laboratories. (Such as by the GPO at Dollis Hill, AOB).

Consider photo at the next page

R&S quartz-clock type CFQ serial number 106 (by courtesy of Rohde & Schwarz)

The measuring of frequencies with extreme accuracy

The Deutsche Seewarte in Hamburg was the main institution in Germany, which supplied the time impulses (signals) for the wireless and broadcasting stations. According to the Bias report (23) this institution could be regarded as a subsidiary of the Deutsches Hydro-graphisches Institut which is also known as DIH.

Here we will mainly rely on Rohde's contribution in Fortschritte der Hochfrequenz-Technik. (24)

As we have seen in previous paragraphs, the time signal impulses were compared with those of their associated time controlling centres. The main German time signals were sent by the station Nauen, on various frequencies, at 01:00 and at 13:00 central European time (MEZ). These time signals were transmitted according to the European "Onogo-signal" standard. (25)

The broadcast stations were also transmitting time signals. These time signals were tone modulated bursts and were based on the morse signal codes as well. **The first edge** of a particular impulse represented the time reference. Much effort had been put into enhancing this technology so that the tone bursts were started (triggered) at the correct (appropriate) momentum. Increasing the tone burst frequency, consequently, enhanced its accuracy.

It can be easily understood that the astronomical observatories which generated the time impulses had to be linked by means of telephone trunks with the keying circuit at the transmitter sites. These (time) signals were commonly being transferred via several exchange and amplifying centres before reaching their keying circuits. The velocity of electrical signals in telephone cables is far less than that in free space. In telephone cables we estimate an average velocity of . 2 x 10^8 m/s; in free space this is 3 x 10^8 m/s. (theoretically in vacuo) Consequently, there was considerable signal delay (= time delay) between the time generating circuits and the signal which was, ultimately, being transmitted (due to many sorts of more or less erratic time delays). One of these erratic deviations was caused by the changes in the (local) temperatures of the cables and their auxiliary equipment. These deviations could be of several milliseconds and this simply couldn't be tolerated. Subsequently, efforts were made to counter these most serious disadvantages.

Without resorting to the actual proof, we will follow Rohde's explanations. (26)

The daily pace of the synchronous clock (*G*) is dependant upon the frequency deviation of the frequency reference standard (*f*) (internal time base or frequency generator), where *s* is in seconds and $\Delta f / f$ is the comparative (relative) frequency deviation in respect to its nominal value.

$$\frac{\Delta f}{f} = \frac{G\,(s)}{8.64 \; x \; 10^4} \qquad (3)$$

It is evident that when we increase the period over which we carry out the measurement that we will subsequently enhance the accuracy of the measurement. We have to consider that we measure time in respect to the time base frequency and the frequency in respect to the generated time.

If we consider that the deviation of the frequency of the time base f_0 is changing linearly in respect to the time, then we may express the momentary reading of the clock versus the real time: -

$$\Delta\, t = \Delta\, t_0 - 8.64 \; x \; 10^4 \; [d \cdot \frac{\Delta f}{f} + \frac{n^2}{2} \, \Delta \, \frac{\Delta f}{f}] \qquad (4)$$

$\Delta f/f$ is the comparative frequency deviation in respect to its nominal value

$\Delta\,\Delta f/f$ is the comparative frequency change per day

$\Delta\,t$ is the standard deviation of the quartz-clock

d is the observation interval in days

Let us consider, for this occasion, the following conditions:

$\Delta f/f = 0$, $\Delta\,\Delta f/f = +10^{-9}$, and d = 7

Thus, in seven days the quartz clock has been changed by $\Delta\,t = 2.1$ ms when we assume that $\Delta\,t_0 = 0$.

Consequently, the frequency has been changed, after an observation period of 7 days, by: $\Delta f/f = +7 \times 10^{-9}$

Early efforts on electronic BCD counters

A few years ago, Leonard Hunter brought to my attention the book entitled “German Research in World War II, an analyses of the conduct of Research”, by Leslie E. Simon published in 1947 (Colonel Simon was, at the time, in the Ordnance dept. and was US Army director of the Ballistics Research Lab.). This most interesting survey describes in detail the wartime German Army and Air Force research and development centres. Due to Simon’s comprehensive knowledge about the state of the art in both the US and the German research establishments, he passes on to the readers a most thorough inside view of what was going on. I became fascinated by his description of an electronic chronograph which he came across at the German Army proving ground at Hillersleben. This must have been an unique piece of equipment. If similar equipment had been available on the allied side I am sure he would have mentioned it!

This device had been manufactured by the Berlin(er) Physikalische Werkstätten at Immenhausen. I have researched the background of this company which, as far as I could find out, was established a long time ago and produced mainly laboratory instruments for educational purposes. However, this firm’s name appears on some patent applications relating to more sophisticated apparatus as well. There is evidence that this company became the contractor for various “secret” projects. It was established in Berlin W 35 in the Woyrchstrasse 8. But adding the term “GmbH” suggests that it was either owned or affiliated to another company (due to its limited legal liability).

Let us follow Simon’s comments integrally.
The counter chronograph, or, properly counter chronoscope, is an electronic device for counting electric cycles with extreme rapidity. A fixed frequency, say 100,000 cycles per second, is supplied by a crystal oscillator. The counter starts at a signal such as the passage of a bullet through

a pick-up screen, and stops on a similar signal. In simple form, the counter is equipped with a vaccum-tube circuit which functions as *follows: on receipt of the first cycle after the start signal the circuit causes the first of a series of small neon lamps to glow; the second cycle extinguishes the first lamp and excites the next one; the third cycle again excites the first lamp; the fourth cycle extinguishes the first lamp and the second lamps and excites the third, and so on. Successive lamps, when glowing, represent 1, 2, 4, 8, 16, 32@@@@*2^{n-1} *cycles, and the total numbers of cycles in any recorded period is equal to the sum of the numbers corresponding to the lamps found glowing at the end of the time interval. In some counter chronoscopes the lamps are arranged in groups of four and the circuits are designed to reset each group to zero after the ninth count in order to give numbers in the decimal system.*

Unfortunately, I was unable to unearth more information concerning this quite revolutionary apparatus.

The Rehbock (Roebuck), a very revolutionary radar-range-calibrator

It is known that the piezo-electric phenomenon in crystals can convert a mechanical force in to an electrical energy (emf) and that an electrical energy can be converted in to a mechanical force. When we excite a piezo-electric-resonator electrically this will create a deformation of the crystal at resonance. (neglect for the moment the particular mode of excitation).

Telefunken's clever idea was to use this piezo-electrical effect to create a RF signal transponder.

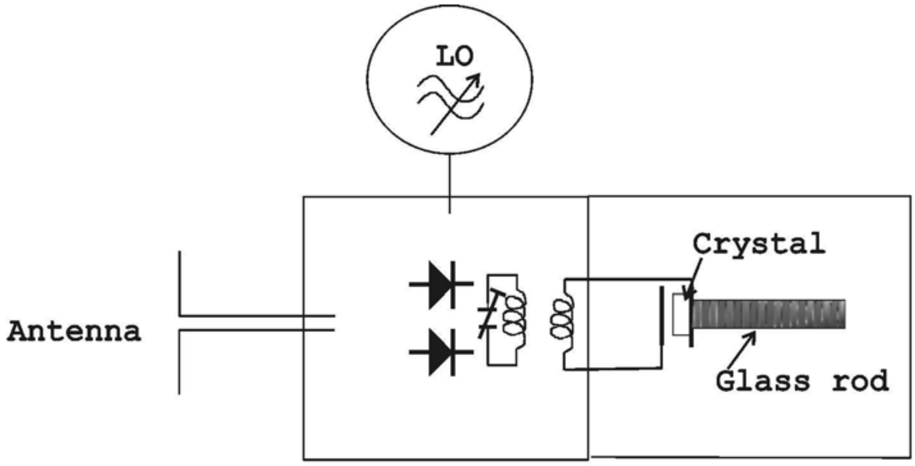

Fig. 11: Principle diagram of the Rehbock apparatus

We will follow the route of the radar signal (stimulus) after it has been received by the antenna circuit. This signal is passed onto a balanced mixer circuit. The local oscillator was tuned at 25 MHz below the receiving frequency (this was dependent upon the particular frequency of the crystal-delay-line device, which sometimes could be at about 26 MHz). Let us assume that the radar signal (RS) is transmitted on 560 MHz and that the intermediate frequency (IF) is 25 MHz then the local oscillator (LO) had to be tuned on 560 - 25 = 535 MHz. The IF output was loaded (tuned) by an inductively coupled band-filter. This band-filter was itself, on its secondary side, loaded by the (transponder) crystal device onto the axis of which was mounted a glass delay-line. The ultra sonic vibrations, due to the prf of the radar set, caused a sonic wave pattern travelling inside the glass rod towards its opposite end. These sonic waves were bounced back towards the (quartz or tourmaline) crystal. After this sonic vibration reached its face of origin it excited the crystal at its correct (mechanical) mode. This, consequently, produced the RF signal at the appropriate intermediate frequency. This signal is then being mixed up in frequency and passed on, now in reversed direction, towards the radar set (IF + LO = RS).

These sonic waves were, due to some mechanical mis-match, not entirely absorbed at the inner surface of origin. But were partially (attenuated) bounced back towards the other end of the glass delay-line again. This process was repeated several times. I have determined that its 5 th reflexion could be very well received by the radar set under test. Each time interval was slightly delayed in respect to its previous one. Due to this phenomenon an individual calibration chart had to be constructed for every Rehbock apparatus.

All seems to be very simple, though this wasn't the case. First, we have to consider that quartz crystals were commonly being made for the fundamental vibration mode up to about 10 to 12 MHz. For higher frequencies commonly the, so-called, overtone mode had to be used or, multiplier stage(s) had to be employed.

In 1931, Straubel introduced the first high frequency tourmaline oscillator. (27)

On 2 April 1931 a patent application was filed in the name of Carl Zeiss Jena, which became classified under the number: DRP 612 997. Its aim was a: Piezo-electric oscillator or resonator by means of tourmaline. This patent was certainly based on Straubel's work. Tourmaline quartz oscillators could be made for . 400 MHz regions. (28) A disadvantage was that these, so-called, ultra high frequency resonators were very difficult to produce because of the thickness which was often < 0.01 mm! In my opinion, this was the main reason why the optical firm Carl Zeiss became involved in this field. The Germans produced those kinds of tourmaline crystals, generally, for frequencies up to about 40 MHz (fundamental mode) (see hereafter). The disadvantage of the increased power loss of tourmaline resonators was compensated for by the simplicity of its circuit design. No multiplying stage(s) was necessary to obtain high frequency output. Tourmaline plates, of equal thickness, resonate at about 35 % higher frequency and were in some respects easier to manufacture.

Zeiss produced tourmaline crystals with rather good results. However, it is known from allied surveys shortly after the end of WW II, that the Zeiss company also manufactured quartz crystals up to rather high frequencies. According to the interrogation, on 30 November 1945, of (the famous) Mr. Gerber who worked for Carl Zeiss in Jena and which was issued in the FIAT Final Report No. 641, (p. 9) (29): -
In response to questions regarding the Zeiss technique of thin-quartz grinding, Gerber stated that quite a large number of plates of 49 ° cut had been produced at 60 MHz by very careful handwork by very skilful workmen. The laboratory made a very few at 100 MHz, but the reported 200 MHz was projected research only...............Tourmaline crystals were made as high as 400 MHz by skilful handwork. These were 7 mu thick.....

The tourmaline (or eventually quartz) crystal and the glass delay-line can be seen in the right hand section of figure 11.

The first attempts to get this transponder device working satisfactorily were hampered by a considerable amount of generated (signal) noise, which was transmitted back towards the radar receiver. They finally discovered that this noise was originating from inside the glass delay-line itself. It was found that the sonic signal path wasn't travelling in a straight line towards the reflecting (inner) surface of the glass rod, but that a dispersion of the (ultra) sonic waves took place. The solution, to counter this disadvantage, was found by frosting the surface of the glass cylinder. The stray sonic waves were thus absorbed and couldn't be reflected.

After a long search I have recently traced, in the British Library, a Telefunken (secret) patent application which claimed: - a crystal in conjunction with a delay-line device to convert electrical signals into ultra sonic waves and its re-conversion into an electrical signal". This application even claimed an echo (noise) reducing technique as well. (30)

Allied post war investigations

The Allies showed considerable interest in the German technical and scientific achievements. Groups of specialists were arriving, sometimes a few hours after the Germans had surrendered (or after they had withdrawn at particular sites) to investigate places of interest. Their aim being to capture as much valuable apparatus and documents as possible and to interrogate the leading members of staff.

One of the reports (31) which was published concerning these interrogations dealt with the use of the quartz-clocks which were maintained by the major time controlling institution Deutsche Seewarte in Hamburg. This institution maintained clocks which were produced by both PTR and R&S.

The second party, on behalf of the U.S. Technical Industrial Intelligence Committee, investigated (in June 1945) the PTR clocks which were employed in Heidelberg (after this institution had been moved from a site which was, until recently, under Russian control). (32)

According to Jucker's additional information (33): *On pressure of members of the U.S. Technical Industrial Intelligence Committee (Melville Eastham, President of General Radio and Dr. Don Sinclair, Vicepresident of General Radio) the PTR site Zeulenroda/Thuringa was moved out of the Russian occupied zone into the US zone at Heidelberg.*
I would add, that it is most likely that this would have been managed before the Russians could lay their hands on the possessions of the PTR. All the Allies tried to keep, for themselves, what ever they could lay their hands on. Not even all U.S. investigation reports, concerning German technology, were shared with their closest ally Britain!

If we remember that the pre-war General Radio quartz-clocks were of more or less similar design to those of the PTR in Berlin, it is no wonder that they were showing distinct interest in the state of the art of the PTR clocks.

The Americans allowed the remaining PTR body to continue operation after the surrender of the Third Reich. According to one of the reports they recommended: *"It is believed that this group is an important potential aid to rehabilitating the German equivalent of the Bureau of Standards, and should be tied in to whatever Government Institution is established to look towards the economic technical rehabilitation of Germany".* (32)

On 10 September 1946 the U.S. Department of Commerce issued its final FIAT Report No. 895, called: *"Progress in time and radio frequency measurements at the PTR Heidelberg".* This report describes extensively several aspects of time and frequency measurements which were employed by the German Bureau of Standards prior to 1945. (In the meantime, **all** the PTR quartz-clock apparatus had been removed from the Heidelberg site and had been sent to Greenwich (UK) and to the U.S. for investigation thus leaving no remaining quartz-clock in Heidelberg!)

Evaluation

We have learned that quartz-clocks, in the 1930s and early 1940s, were becoming quite accurate time and frequency generating instruments. That the short term stability could be estimated for . 1 x 10^{-9}, for some good clocks even up to 10^{-10}. Longer running (good) quartz- clocks could reach values of 10^{-9} a day. This latter figure was mainly due to the typical aging of the quartz resonators. For quartz controlled oscillators, even for today, this is a reasonable value. According to Rohde (34) the long term frequency accuracy of the PTR clocks, in the early 1940s, was estimated at 1 x 10^{-9}.

According to Hans Jucker's additional information which he recently passed on to me: - the typical deviation of a clock, controlled by means of a BVA quartz oscillator (Swiss brand name which is very well known for its excellent products), **with no offset** after 90 days can be observed as follows:-

- Aging drift 90 x 2 x 10^{-11} = 1.8 x 10^{-9}
- Accumulated time deviation ½ x 90 x 86400 x (1.8 x 10^{-9}) = 7 ms

The typical deviation of a clock controlled by an atomic frequency (Rubidium) standard **with no offset** after 90 days has, for comparison figures of the order:-

- Aging drift 90 x 10^{-13} = 9 x 10^{-12}
- Accumulated time deviation: ½ x 90 x 86400 x (9 x 10^{-12}) = 35 µs

The specifications of modern frequency standards are much better than those which were achieved by the early quartz controlled clocks and frequency standards. But, the technology has been improved tremendously over the years. However, comparing today's technology with that of the early days of the quartz-clocks, their parameters weren't too bad, but the early, bulky, quartz-clock systems required much effort to maintain those devices. In contrast the time standards of today are very handsome devices which are very easy to operate.

Acknowledgements

Without the enthusiastic support of many who are committed to recording and evaluating the history of technology, I never could have started to work on this paper.

Hans Richter supplied me, several years ago, with historical papers concerning the early work done by Giebe, Scheibe and Adelsberger at the PTR in Berlin. Hans Jucker passed a variety of quartz related papers and details on to me. Klaus Blankenburg of Rohde & Schwarz in Munich managed, very kindly, to arrange an afternoon meeting at their head quarters with the retired employees Gerd Langloh and Ludwig Mooser, who had been involved in quartz-clock design and related technology. We were even allowed to investigate their last remaining CFQ clock artefact from inside! Blankenburg supplied me with copies of all the required records and papers which were available in their archives. Rohde & Schwarz very kind fully prepared, especially for this occasion, a series of beautiful photographs.

Heinz Claus in Sindelfingen had previously, very kindly, supplied me with considerable numbers of quartz references of all kinds.

Tom Going, was, as ever, of great support to me concerning our surveys in the various London archives. He showed me, some years ago, the way to approach the Patent Reference Library; which recently has been integrated in the (very beautiful) British Library and its, marvellous, Micawber street depot and, the Science Museum Library at Imperial College - thanks Mr Carter!

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I also have to thank the late Hans Widdel who, several years ago, brought to my attention the detailed information concerning the quartz-clock which was used in the early days of his institute.

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