Variations and Combinations

Invention and Development of Quartz Clock Technologies at AT&T

Shaul Katzir

Quartz clock technologies played a central role in twentieth century timekeeping, telecommunication and society at large. This article explores the process of the invention and construction of the first quartz clock by Warren Marrison and his associate researchers at AT&T, who needed the clock to monitor the corporation's self-maintained crystal-controlled frequency standard. The frequency standard was deemed essential for the needs of electronic telecommunication in the 1920s. Based on research notebooks and contemporary publications, this article examines the origins of the technology in the corporation's earlier tuning-fork-frequency-standard, which included the first electronic clock. Providing a detailed examination of the various electronic methods used by Marrison and his colleagues and their origins, the article examines the way the modern, scientifically educated inventor, working within a large industrial laboratory and enjoying its rich material and intellectual resources, collected, combined and adjusted the resources at his disposal to produce novelty.

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In the early 1920s, American Telephone and Telegraph Company (AT&T) decided that it needed a new reliable and accurate system for measuring the high frequencies used in radio and telephone communication. Such a system had to be based on a highly regular oscillator, i.e. an oscillator that vibrated at a constant rate and could thus serve as a primary frequency standard for measuring oscillations via comparison. Newly developed quartz crystal resonators, vibrating stably at tens of thousands cycles per second (Hz), were considered the best choice for such an oscillator. A technical obstacle, however, prevented using the quartz oscillator as a primary frequency standard. Since frequency and time are inverse aspects of the same physical phenomenon, a comparison to a clock, the most exact measuring standard at the time,

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was deemed necessary to assure the stability of the frequency standard. To compare its oscillations to a timekeeper, one had to connect the crystal resonator to a clock mechanism, thereby fabricating a quartz clock. Yet since no clock mechanism could be driven by such a high frequency oscillation, the quartz resonator could not be used as a primary frequency standard so long as there was no method to produce a vibration whose frequency was an exact known fraction of the crystal's frequency. To solve the problem of contriving a method for dividing high frequency oscillations, managers at AT&T's research branch, set the task to a group of their researchers headed by Warren Marrison. Over a period of more than two years, Marrison and his team employed, modified and combined state-of-the-art electronic methods and devices using scientific and technological knowledge to reach a useful technique that enabled them to construct the first quartz clock, a technology which revolutionized timekeeping.

Marrison and his collaborators worked in the most important place for technological innovation of their time: the industrial research laboratory. In the aftermath of the First World War, if not earlier, the corporate laboratories replaced independent inventors as the main source of innovation and as the public symbol for advanced technology. 'Research and development, began to replace "invention" in everyday language'.[1] Independent inventors could follow opportunities to choose problems that suited their knowledge, skill and invention style. Industrial researchers like Marrison hardly enjoyed similar freedom.[2] Their supervisors assigned them problems primarily according to the needs defined by the corporation and only secondarily according to the knowledge and expertise of the researchers.

The industrial laboratory confined its researchers, but at the same time, it put richer social, intellectual and material resources at their disposal, which led to modified methods of invention. The most famous of the new tools at industrial researcher's disposal was scientific research in relation to technological questions. It led among other things to improved incandescent lamps, vacuum tubes and to the transistor. Still, most research and development in industrial laboratories did not include the scientific exploration of natural phenomena. Inventions like the frequency divider arose from the combination and modification of known methods, devices and ideas, rather than from new findings. Principal among the methods and devices in use at the AT&T laboratories were methods of vacuum tube electronics.

The strategy of varying and combining extant techniques was nothing new. It was common also among independent inventors,[3] but the larger and richer research laboratory provided better means for its implementation. The present article examines the process of invention within industrial research laboratories by exploring the cognitive and experimental steps that enabled a group of AT&T's researchers to solve an important technological problem assigned to them. It focuses on the way modern, scientifically educated inventors working within a large industrial laboratory collected, combined and adjusted the rich resources at their disposal to produce novelty.

New electronic methods of radio and multiplex telephony required high accuracy in frequency determination, levels of accuracy unprecedented in technology up to that point. Moreover, exact knowledge of frequencies became imperative for AT&T's monopolistic strategy of providing an 'interdependent, intercommunicating, universal system'. In practice, this 'universal system' was a highly complex network consisting of sub-systems using different devices and methods which required the ability to coordinate and transform messages from one device to the other. To control such a network, the corporation required a common standard for measuring the various electric oscillations in use, which ranged from hundreds to millions of hertz. Its research directors first adopted a frequency meter based on an electronically maintained tuning-fork as the basis for the company's frequency standard. The tuning-fork technique had been invented and developed by the French and the British in their research on improving radio communication for military needs during the First World War.[4]

The quartz oscillator was invented in 1921 and promised more regular vibrations and a simpler way to reach high frequencies than the tuning-fork method, but in order to use a quartz oscillator as a primary frequency standard, Marrison and his colleagues needed to invent a method to divide its frequency by about 50 to 100 times. Marrison's wasn't the only team working on the problem. A similar interest in coordinating wireless communication – for purposes of regulation rather than control – led British and Italian national laboratories to develop their own methods for dividing the frequency of quartz oscillators, which allowed the construction of clocks. Academic, commercial and military interests led three other groups in the United States, the Netherlands and Japan to develop frequency dividers that could be used to drive a quartz clock. These, however, lie beyond the scope of the present article.[5]

While the quartz clock thus emerged from the needs of electronic communication, it later transformed timekeeping and significantly contributed to the spread of 'clock discipline' in society at large. The quartz clock was the first to compete with and later exceed the accuracy of the pendulum clock, which had been improved for 250 years. From its beginnings as a laboratory device, the quartz clock ultimately reached virtually everyone in the affluent world. Today, its precision accompanies and shapes daily life in clocks of many forms, mobile phones and virtually any electronic gadget. Moreover, quartz clock technology allowed broadcasting to expand and allowed therefore for the distribution of precise time signals by radio. Consequently, the knowledge of precise time became central to an increasing number of activities.[6]

While the present technical history of the quartz clock at AT&T does not explain the broad consequences that the new technology had, it is needed for understanding the process by which modern technology is developed.

In developing its frequency measuring and standard system, AT&T built on advancements in the field made during the First World War. Its researchers first modified the tuning-fork-based system for the corporation's needs. This system served as a starting point and a model for its later quartz standard. The first, shorter, part of the present article, therefore, discusses the research at AT&T on the tuning-fork frequency standard. Walter Cady's 1921 invention of a method for controlling the frequency of electronic circuits by the steady vibrations of piezoelectric quartz resonators transformed the field. By late 1924, AT&T deemed the new technology to be a viable and superior alternative for the tuning-fork standard, and Marrison's team was tasked with driving a clock mechanism with a quartz oscillator. The second part of the article discusses Marrison's various suggestions for dividing the high frequency of the quartz resonator, the construction of the full quartz-based frequency standard of AT&T, and the steps made to improve its exactitude.

THE TUNING-FORK STANDARD

In early 1921, managers at AT&T concluded that 'refinements of [the] methods [of electrical communication] have reached a point where it is imperative that determinations of the frequency of any . . . alternating currents may be made with an accuracy considerably higher than has been possible hitherto'.[7] These refinements followed the introduction of the triode, an electronic vacuum tube with three electrodes, the central device beyond radio and electronics in general before the advent of the transistor in the 1950s. Resembling an incandescent lamp, the glass surface of an electronic vacuum tube encloses a space of low-density air ('vacuum') and two or more electrodes: cathode that emitted electrons, anode that absorbed them, and in the case of a triode a 'grid' that enhanced or obstructed electric current ('discharge') according to the relation between its electric potential and that of the cathode. Invented by Lee de Forest for receiving radio signal in 1906, in 1912 a few individuals found ways to utilize the triode for amplifying electric signals and as an oscillator for emitting electromagnetic waves. AT&T bought rights for using the tube as an amplifier, which it needed for long-distance telephone, and embarked on a research and development project for its improvement. As an oscillator the triode turned out to be highly efficient for transmitting continuous radio waves, allowing wireless transmission of voice and music. Attracting expanding attention shortly before the war, the improvement of triodes and their circuits for amplification and oscillation received larger human and material resources during WWI, becoming the central component of the expanding radio communication, which was suggested also as a complement for the wire telephone network.[8]

For connecting new wireless radio-telephony systems to the older wired system, and for sending multiple calls on the same cable (see below), AT&T needed a better method to measure frequency. Its technical heads envisioned a new accurate and reliable frequency standard that would 'cover the entire range between a few cycles per second and several million', and whose 'absolute value . . . is known to one part in 100,000'. They considered this aim feasible due to the development of the tuning-fork-based method for frequency measurement during the First World War and its aftermath. The tuning-fork method promised more stable oscillations and thus more accurate frequency measurement than those using a resistor, coil and capacitor (RLC) circuit. In the new method, electromagnets (i.e. coils) connected to a triode RLC circuit generated vibrations of a magnetized tuning-fork. The tuning-fork, which vibrated at its resonant (natural) frequency, produces an alternating electromagnetic field, which under suitable conditions forced the electronic circuit to oscillate at the same frequency. Made for acoustics, tuning-forks oscillated at frequencies considerably lower than those used for radio. To use a tuning fork for measuring high frequencies, therefore, the French physicists Henri Abraham and Eugène Bloch, employed another device that they invented during the war: the multivibrator. Consisting of two tubes in which the the grid of each was connected to the anode of the other through a capacitor, manually tuned by comparing its oscillations with that of a tuning-fork circuit, the multivibrator generated oscillations at exact integral multiplications of the tuning-fork's frequency. Following the way that the oscillations appeared (and were heard) in acoustics, researchers on periodic phenomena dubbed such oscillations 'harmonics'.

The task of constructing a measurement standard for AT&T was assigned to a group headed by Joseph Warren Horton,[9] at the research branch of AT&T – then a part of the engineering department of Western Electric.[10] From 1925, the research branch merged with a few smaller units, formerly belonging to other arms of the corporation (also referred as 'the Bell system'), to become Bell Telephone Laboratories. 'Bell Labs', officially an independent company, was however still totally owned by AT&T. The organizational changes did not affect the researchers, like Horton and his associates, already working at the Manhattan offices of the former research branch.

Born in 1889, Horton joined Western Electric in 1916, after studying physics and chemistry at MIT. When the United States joined the First World War, Horton left for the Navy underwater laboratory in Nahant, Massachusetts. He regarded that period as part of his education because he worked with notable scientists from General Electric and AT&T. After the war, he returned to the research department of AT&T to work on advanced problems in electrical communication. 'Almost the only problem which was wholly under [his] control while at Bell Labs had to do with the measurement of frequency.' 'In general, these problems [on which he worked at AT&T] called for the utilization of existing knowledge rather than for the acquisition of new knowledge.'[11] Still, important parts of this knowledge had been recently acquired, if mostly by researchers outside the Bell system. By December 1922, Horton headed a group of twenty-five employees, most of them probably with a first degree in physics or engineering, divided into four subgroups, one of them under his direct responsibility. Only one or two of the smaller groups under Horton worked on frequency standards. Norman H. Ricker, a fresh PhD in physics, headed one of these groups from summer 1921 to his departure from AT&T at the beginning of 1923. A young subordinate who had already worked on tuning-fork standards, Warren Marrison, succeeded Ricker.

Born in 1896, Marrison had earned a BSc in 'engineering physics' and used his experience as a radio amateur in the services of the Air Force of his native Canada, before working at Western Electric for the summer of 1920. In September 1920, he registered for graduate studies in physics and mathematics at Harvard, where he chose courses on a subject of much interest for AT&T: electric oscillations and their applications to radio. After he had attained a Master's degree, he returned to AT&T in September 1921.[12] Eight months later, he joined the study of tuning forks, continuing the experimental work of one J. C. Davidson who had left the group. The quite easy replacement of one researcher by another is a mark of the team approach of the group and AT&T's laboratory in general. Although individuals often worked alone, or with one assistant or co-worker, the research was ultimately teamwork. Problems and questions were discussed in both official and informal meetings and questions were allocated from one individual and even from one unit to another.[13]

When Horton returned to Western Electric, he developed a means for transmitting multiple messages on a single cable simultaneously, which was known as multiplex telephony (or telegraphy). The financial benefits of being able to send multiple messages down a single line were obvious, as it would obviate the need for the multiplication of expensive copper wires. As the largest telephone company in the world, with a monopoly in inter-city lines, AT&T had high stakes in the development of a multiplexer. In the version on which Horton worked, a regular electric current produced by a telephone transmitter was added to an electric oscillation of a higher frequency through a triode in a process called modulation. At the receiving end of the call, a similar circuit 'demodulated' the current and yielded the original wave. Both the transmitter and receiver needed to agree on the frequency of the oscillator, which set the frequency range of the transmission.

While the principles of multiplexing were well-known at the time, a few technical difficulties hampered its swift introduction into use. The production of many known frequencies from a basic frequency was one of the technological challenges of multiplexing. In 1920, Horton suggested a way to produce 'any required harmonic frequency wave, or a series of such waves from a given sine wave of fundamental frequency'. His scheme enabled the combination of circuits of different frequencies that are integer multiples of a basic frequency to reach any integer multiplication of the original. This work provided him resources for developing Western Electric's frequency standard, and probably contributed to his appointment as head of its development.[14]

During 1921–1923, Horton's group developed a compound system that would serve as a frequency standard for any radio wavelength used by AT&T. The system followed earlier systems for measuring radio frequencies like that of Abraham and Bloch with a few significant changes and additions. It included an electronic-tube-maintained tuning-fork that provided a fundamental exact frequency, a 'harmonic generator' for multiplying this frequency and modulators to reach intermediate frequencies between the values produced by the harmonic generators. Since AT&T required a means to measure frequencies to within one hundred hertz, the group chose a tuning-fork with that natural resonance instead of the tuning-forks used by other groups, which resonated at approximately one thousand hertz. It also decided to design a new more complex harmonic generator to multiply the basic tuning-fork frequency, in place of Abraham and Bloch's multivibrator. This harmonic generator (also called a 'harmonic producer') multiplied the basic standard frequency to its tenth harmonic, which went into a second generator and into a third reaching one hundred thousand hertz. Electronic circuits oscillated at each of these frequencies (in the later working system its exact frequency could be tuned by a variable circuit). 'Balance modulators' produced oscillations whose frequencies were the additions and subtractions of the incoming frequencies. The scheme was similar to the one suggested by Horton in 1920 for multiplex telephony, showing the similarity between the projects on multiplexing and frequency standards. Individual balance modulators had already been used for telephony in the Bell system. The modulators allowed the system to generate any intermediate frequency that is an integer multiple of the fundamental 100Hz.[15] The resulting oscillation could be compared to and thus could measure the frequencies of other oscillations. The system also included an ingredient of quality-control – a method of comparing the basic frequency standard to a more reliable and known standard, i.e. a pendulum clock.

Horton's group developed the individual components of its system of frequency standards mostly in parallel to each other. Apparently, the electronically driven tuning-fork was the earliest piece of the circuit to work;

the group had used it already before June 1921. A few of the group's members continued to improve it until the spring of 1922. In its design they relied directly on the suggestion of William Eccles in England and its improvement by E. Eckhardt et al. at the American Bureau of Standards. To prevent variations in its frequency, the Bell group kept the tuning-fork under constant temperature and pressure. The sensitivity of the tuning-fork's frequency to temperature change followed from elastic theory and had been established experimentally in the nineteenth century.[16] The group at Bell thus used extant scientific knowledge and did not need to carry out its own research on the effect of temperature to recognize the need to prevent temperature variations. As Horton later remarked, his group did not engage in discovering new knowledge.[17] It did examine the performance of its own tuning-forks and suggested improvements in their design. For example, it modified their shape and the location of the electromagnets that induce their vibration.[18]

Abraham and Bloch's use of the multivibrator to reach multiples of the tuning-fork frequency clearly inspired Horton's group to design an electronic method for generating harmonics. Horton probably knew also that David Dye at the British National Physical Laboratory (NPL) controlled the multivibrator's frequency by a tuning-fork circuit (which Abraham and Bloch had not done), even though the latter had not published the details of his method at the time.[19] Still, the group chose a somewhat different approach to the problem of harmonic generation, an approach that shaped also its research on the frequency divider for the quartz clock. The Western Electric group looked for a system vibrating sinusoidally, while the multivibrator did not produce a sine oscillation. Moreover, the group sought a mechanism to ensure that the target circuit vibrated exactly at a harmonic of the tuning-fork. To this end, the members of the group devised a way to enforce the vibrations of the target circuit using a cue from the source: a tuning-fork circuit.

In July 1921, Ricker put forward the basic principles of the harmonic producer that the group adopted. In Ricker's method, a triode circuit (V_1 in Figure 1) coupled to a circuit that oscillated at the input frequency through an inductive coil, was arranged so as to allow a passage of electric current at only a small fraction of the incoming period (when the voltage in the grid was higher than a particular threshold). Thus it produced brief intervals of electric current at the frequency of the input oscillation. This brief current induced an electric current through the inductive coils (T_2) in a second RLC circuit (L_1C_1).[20] Like a hammer on a piano string, the brief current induced voltage generated a continuous oscillation in the L_1C_1 circuit. This circuit oscillated in one of its own natural frequencies, as determined by its coils, condenser and resistor, in the same way as the natural frequency of a string is determined by its width and length. Unlike a piano hammer, however, the input circuit induced voltage in exact periods, forcing the more flexible

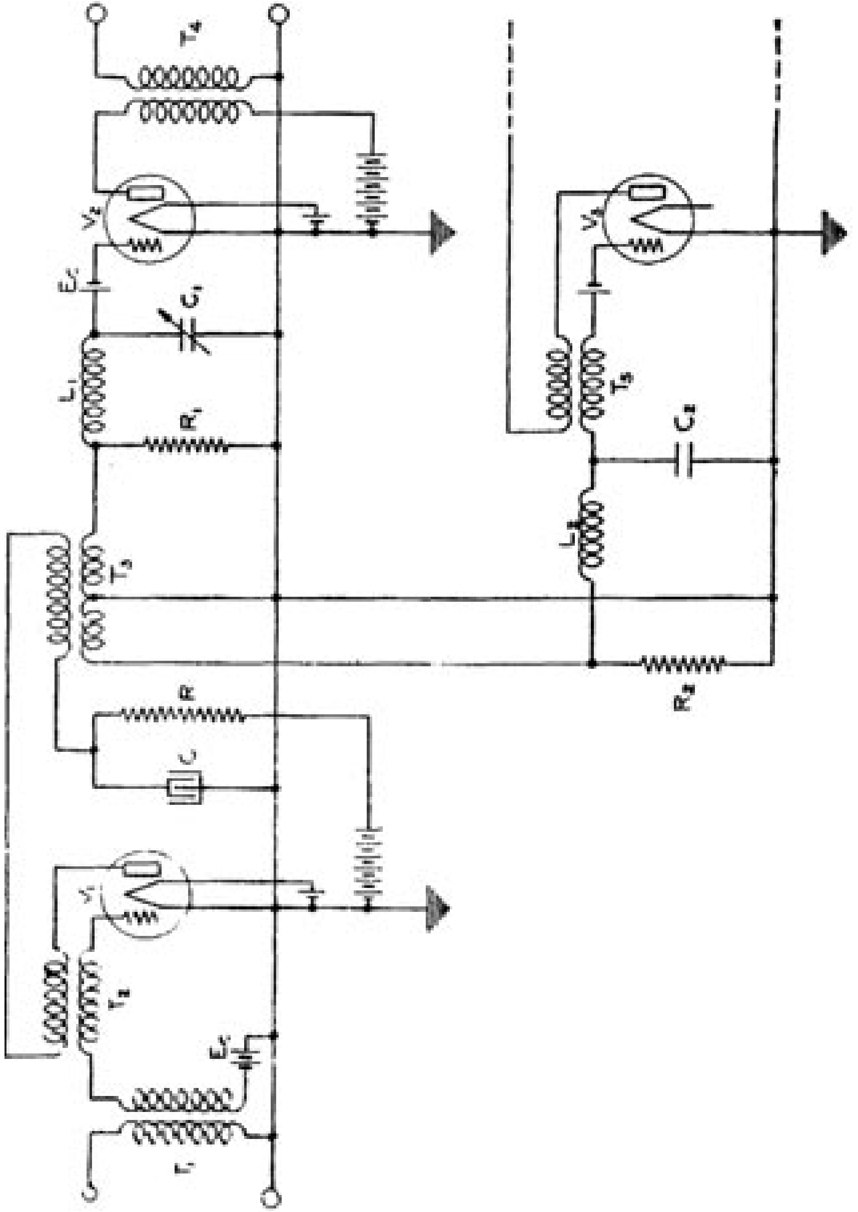

Figure 1. Horton, Marrison and Ricker's 'harmonic producer' for the tuning fork standard of AT&T. $V_{1,2,3}$ are triode tubes showing (from left to right) the grid, cathode and anode. (Source: Horton, Ricker, and Marrison, 'Frequency Measurement in Electrical Communication', 739)

oscillations of the RLC circuits into a harmonic of the input frequency. Slight deviations from this frequency would be opposed by the induced voltage through a coil (T_3), which would restore the output to a harmonic of the income frequency. The multivibrator, the alternative harmonic producer in use, did not posses a similar compensating mechanism. As is shown below, this preference for a compensating mechanism would also characterize Marrison's frequency divider.[21]

The accuracy of the frequency to come out of the circuit hinged on that of the basic standard, i.e. the tuning-fork. Since the vibrations of the tuning-fork were regarded as more stable than those of any other device used as frequency meter, the group needed another way to check the accuracy of the tuning-fork. Following earlier practice, it found such means with a clock, since frequency was defined as the inverse of time. Moreover, time was defined precisely by astronomical clocks, which were, thus, suitable to test frequency meters. Horton therefore suggested comparing the vibrations of the tuning-fork with that of a steady clock, as the new system should have 'the general characteristics of a good clock'.[22] To this end, the group needed to connect the tuning-fork to a mechanism that would count its vibrations, i.e. create a clock. Such a clock mechanism would also make it possible to detect small systematic deviations in the tuning-fork, as they would accumulate and become visible after many cycles. By June 1921, Horton proposed coupling the tuning-fork to a synchronous motor, geared to a clock mechanism, forming a tuning-fork based clock (see Figure 2). His team compared this clock with the reading of a 'phonic wheel' pendulum clock at their

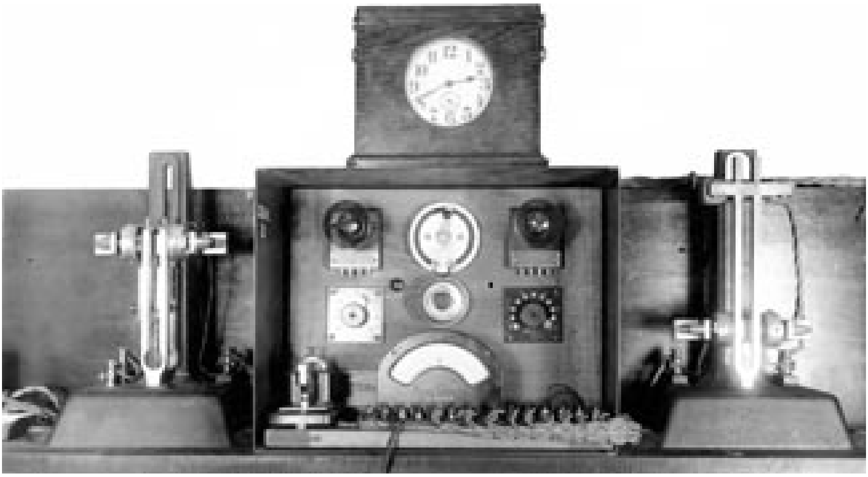

Figure 2. A clock connected to two tuning-forks at Western Electric research department, caption says from 14 November 1921. Notice that the clock is connected (probably alternatively) to two forks of different dimensions. The left one is excited by magnets near its upper part and the right one by magnets near its lower part. (Courtesy of AT&T Archives and History Center)

laboratory and with the exact time signals sent by the Arlington Navy station; the latter signals were determined by a regular pendulum clock regulated by observed stellar transits at the Navy observatory in Washington DC. Like the system as a whole, the clock mechanism was based on well-known methods, but still required research and development to adapt it to the needs of the new, highly accurate system.[23]

Arguably, the connection of the basic frequency standard to a clock was the most novel and important ingredient in the tuning-fork standard system. Like the other ingredients of the system, however, the idea and the means to accomplish it had precedents. These included using a clock to examine the frequency of a mechanically vibrating tuning-fork, a feat first accomplished by Rudolf Koenig in 1879. In Britain, William Eccles and Frank Jordan had already connected an electronically maintained tuning-fork to a phonic wheel for synchronization in 1918. Their colleagues at the NPL, Frank E. Smith and David Dye, utilized the method for measuring very short periods of time. These methods were probably known at AT&T. Still, both the linkage of radio frequency to continuous time measurement and the construction of a clock using an electronically maintained tuning-fork were important original steps made by Horton's group.[24]

The comparison between the tuning-fork clock and exact time signals strengthened Horton and Marrison's confidence in the accuracy of their standard. In early 1923, using a chronograph, they found an average difference between the tuning-fork and the laboratory clock of 'about 6 parts in 1,000,000', well within AT&T's goal of one part in one hundred thousand.[25] By 1927, they found that the daily deviation of the 'fork-controlled clock' was less than 0.0007 per cent and its average deviation from the Navy time standard was of less than 0.0002 per cent (i.e. less than 0.2 second a day). This measure of error was only about one order of magnitude lower than that of the standard clock of the Bureau of Standards. Still, they believed that improvements in the connection of the tuning-fork unit to the clock would increase the accuracy about twenty times. In the same period as Horton's group, David Dye and his assistants at the NPL in Britain also began developing a tuning-fork standard that included a clock mechanism. They continued with the same standard after 1923, when the AT&T group concentrated on other standards, attaining the high accuracy envisaged by the group at AT&T.[26]

Notwithstanding their pioneering work on the electronic tuning-fork clock, frequency standards were the main aim of Horton's group. The clock was only a means to determine the consistency and accuracy of the frequency standard, and as such it was only part of the group's effort. The researchers also improved other parts of the system, such as the tuning-fork itself, its electronic circuit and the thermostat used to keep it at a constant temperature. Although satisfied with the performance of the tuning-fork, Marrison also continued to explore alternative electro-mechanical vibrators as sources of constant frequency: steel bars and rods. Such an examination of alternatives is common in technological research. With its rich resources, AT&T often invested in the search for alternatives to methods that worked. Even if they did not lead to useful methods for the corporation, patenting them could obstruct competing firms.[27] Yet, these attempts were not pursued as vigorously as the further study of the tuning-fork system and the exploration of using the new frequency measurement and control based on piezoelectric resonators.[28] Steadily resonating at frequencies of tens and hundreds of thousands of hertz, piezoelectric quartz oscillators suggested convenient secondary standards for this range – a range which the tuning-fork required a complex system of multiplication to reach.

Moreover, piezoelectric resonators suggested a way to reach frequencies beyond the reliable range of the tuning-fork system. In the five years between 1923 and 1928, AT&T raised the upper limit requirement of its frequency standards by two orders of magnitude to several hundred million Hertz (10^8), following the expansion of the useful range of electromagnetic waves. In fact, AT&T had a special interest in high frequencies for radio-telephone links and television.[29] The original tuning-fork standard no longer covered the whole spectrum used by the corporation.[30]

THE PIEZOELECTRIC RESONATOR

AT&T's methods for measuring and controlling crystal frequency originated in Walter Cady's research on piezoelectricity. During WWI, Cady, a physics professor at Wesleyan university, studied vibrating piezoelectric crystals for their use in ultrasonic detection methods (later known as sonar). After the war ended, he researched other properties of these vibrating crystals. He soon discovered that piezoelectric crystals, in particular quartz, show a particularly sharp and steady electric resonance: near their resonance frequency (i.e. when they oscillate with minimum resistance) the crystals dramatically change their electrical properties with only a small variation in their vibrating frequency. Further, Cady found that the crystals present this behaviour under changing physical conditions, retaining their resonance frequency. Familiar with the scientific and technical importance of frequency measurements, Cady realized that the phenomenon allowed a novel means for creating a frequency standard for the radio-range. By March 1919, he had designed a few circuits that allowed the stable resonance frequency of quartz to be compared with external electric oscillations – providing, in other words, a frequency standard. Physically, Cady's methods relied on the special electrical properties of quartz resonance; electronically, the methods relied on the properties of RLC circuits and the triode valve, both used in contemporary radio.[31]

Cady further sought a way to employ the electric resonance of crystals for controlling, not merely measuring, the frequency of an electronic circuit; in early 1921, he designed and patented a few piezoelectric oscillators. Like the electrically maintained tuning-fork, such circuits offered a way to couple mechanical vibration with electric oscillation at a fixed frequency, and thereby provided more stability to the electronic circuit.[32] In the realm of standards, crystal frequency control offered a more useful method for creating a standard than a comparison to a piezoelectric standard. The piezoelectric oscillators were simpler to manipulate than the piezo-resonators. In particular, they allowed one to combine oscillations at several frequencies, each determined by a piezoelectric resonator to produce circuits that would oscillate at any desired function of the input frequencies. Thus, a circuit built around a piezoelectric crystal could replace the tuning-fork as the primary frequency standard, an idea that had been raised in Horton's group as early as May 1922.[33]

Western Electric's research branch enjoyed personal and professional connections, which included mutual visits, consultation and knowledge exchange with Cady, a former teacher of Harold Arnold, the corporation's director of research. Thanks to this connection, Horton and his colleagues gained earlier and more direct information about the piezo-resonators and their technological applications than researchers in other places. This facilitated the early consideration of their use for the corporation's primary frequency standard. For telecommunication providers and users like AT&T, crystal frequency control offered a way to keep their transmitters at the desired frequencies. This was especially important for AT&T, since both its planned system of a national broadcasting network and its multiplex telephony network required some means to force the electronic oscillations to particular exact frequencies. This would prevent interference between different transmitters of the same station as well as a distortion of voices over the telephone. Horton's group carried out research both towards frequency standards and frequency control.[34]

QUARTZ FREQUENCY STANDARD

The piezoelectric oscillator had clear advantages over the tuning-fork in reaching high frequencies as well as in controlling oscillations. It also offered a stability that seemed at least to equal that of the tuning-fork standard. AT&T, like others in the field, adopted the piezoelectric resonator for secondary portable standards 'inherently' tuned to radio frequencies, and for controlling frequencies in emitters and other devices. At the early stage, however, two main shortcomings hindered its use as a primary frequency standard: there were no means for reaching the lower part of the useful electromagnetic spectrum from its relatively high frequency, nor for directly comparing the resonator's vibration to that of a standard clock, a necessary condition for verifying its accuracy. Both shortcomings stemmed from the contemporary inability to produce a lower stable frequency that was an exact integer division of a higher input frequency. While generating a exact multiplication of an input frequency was a known art, no method had been succesfully developed for the reverse process.

By 1924, accuracy in measuring and controlling frequency had become crucial for the practical needs of AT&T, which included eliminating interference and coordinating high frequency wireless communication. To ensure the required high accuracy, Horton's group, and particularly its sub-group headed by Marrison, sought some means to monitor the frequency of quartz resonators whether used as a secondary or as a primary standard. Following the established tradition of exact absolute measurements and the practice of monitoring the Horton group's tuning fork standard by a clock, Marrison suggested that the resonators be compared to an external clock. While the idea became almost self-evident its realization was not so simple to develop.

In November 1924, Marrison suggested a method based on a feedback mechanism for controlling the pace of a clock by high frequency electric oscillations like those of a piezoelectric oscillator. He proposed an electromechanical method 'for synchronizing a rotary machine with a current at radio frequency' (see Figure 3). A synchronous motor (M) is 'driving a generator G which supplies current at 10 times the motor input frequency f_1 [of about 1000Hz]'. The frequency of the current was multiplied another ten times by a harmonic producer (HP). An electronic modulator ('Moo' – like those used in the general scheme of the corporation's primary standard) then subtracted the resultant frequency ($100f_1$) from the frequency F of an oscillator (O), which could be a piezoelectric resonator. The resulting current was fed back to the synchronous motor forcing its frequency ($F-100f_1$) on the motor. Through his earlier work on the tuning-fork frequency

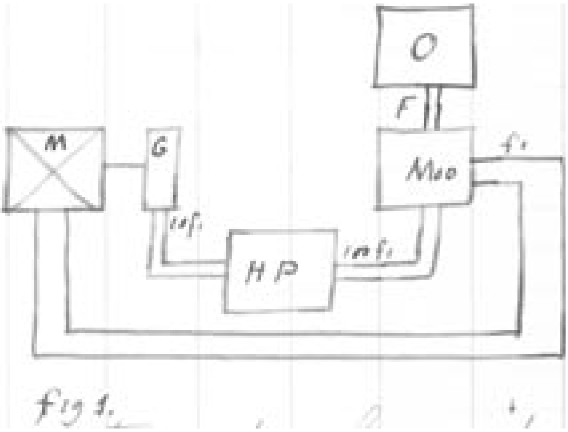

Figure 3. Marrison's suggestion for attaining an oscillation at a frequency 1/101 of the original from 15 November 1924. (Source: NB 1444, 55) (Courtesy of AT&T Archives and History Center)

standard, Marrison had gained knowledge of the main devices involved in the new system: synchronous motors, high frequency generators, and harmonic producers. This background enabled him to modify the structure of the system to reduce (instead of increase) an input frequency. As with the tuning-fork clock, the devices motor 'could be geared to a clock or any suitable recording device to facilitate checking frequencies'. Thus, the new method coupled a timekeeper to the period of a vibrating quartz crystal, so in principle it could be used as a quartz clock. Yet, Marison's device was not meant to mark time but to check the stability of a crystal vibration, an aim important enough to warrant the construction of such an apparatus.[35]

In July 1925, Marrison put on paper a modified 'suggestion', as devices and methods that might have served as a basis for a patent were called at Bell Labs. In his new suggestion, he employed two motors, probably to increase the reliability of the system. Conceived of as a way to validate the accuracy of secondary high frequency standards, the suggestion did not seem to offer an alternative to the corporation's primary standard – it could not reach even a significant range of electromagnetic waves used by AT&T. The apparatus actually provided only two frequencies (the original and its 101st part). Although the lower frequency (f_1) could have been used as a basis for further manipulations, its indirect connection to the oscillator made it less reliable for that role.[36]

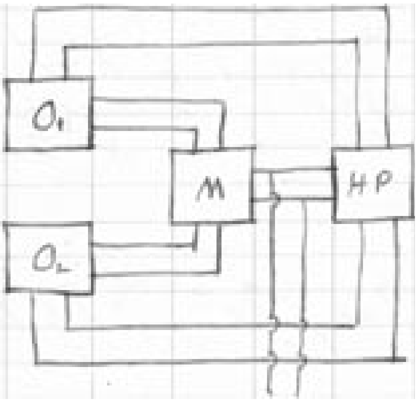

Figure 4. Marrison's two oscillators suggestion from March 1925. In this circuit, Marisson replaced the motor of his earlier device with a second piezoelectric oscillator (O_2) that resonated at a frequency close to that of the first (O_1), and used the modulator (M) to subtract the frequency of one oscillator from that of the other. The resulting frequency, which is the difference between the two original ones and equals about one-tenth of them, was coupled to the piezoelectric oscillators (O_1) through a harmonic producer (HP). That oscillation could be further used for any end, such as measuring, control, and a comparison to a clock. (Source NB 1444, 129) (Courtesy of AT&T Archives and History Center)

While wireless communication exploited ever higher frequencies, exact knowledge of frequencies below the common radio spectrum became important for multiplex telephony. The lower frequencies used for multiplex, those in the range of one-thousand to thirty-thousand Hz, lay below the practical range of quartz resonators.[37] From about 1925, Marrison seems to have been occupied with trying to use quartz crystals to determine frequencies in this range, answering two of AT&T's chief aims: checking the accuracy of the frequency standard (by comparison to a clock) and in making them applicable to additional uses within the Bell system.[38] In March 1925, he devised a way to reach frequencies at that lower range in a variation of the clock synchronizing circuit, which he had suggested four months earlier. In the new version, he replaced the motor with a second piezoelectric oscillator (O_2 in Figure 4), and used the modulator (M) to subtract the frequency of one oscillator from that of the other. The resulting frequency, which is the difference between the two original ones and equals about one-tenth of them, was coupled to the piezoelectric oscillators (O_1) through a harmonic producer (HP). That oscillation could be further used for any end, such as measuring, control, and a comparison to a clock (see Figure 4).[39]

Three months later, in June 1925, Marrison proposed a frequency divider that worked using totally different principles. His new idea was to control the oscillation of a target circuit, so as to ensure that its period would be an integer multiplication of the original in a manner similar to the way that the tuning-fork circuit controlled oscillations at an integer multiple of its own frequency (i.e. the inverse of its period). The tuning-fork circuit also inspired Marrison's idea of using a triode circuit to achieve the goal of reducing frequency. Moreover, just as he had used the harmonic producer to control the frequency of a target circuit through periodic physical influence from the source circuit, Marrison invented a 'subharmonic producer' that could generate exactly known lower frequencies. Marrison was looking for a way for a quartz resonator to force an electric circuit to oscillate at one of its subharmonics. The subharmonic producer was probably the first frequency divider that he actually constructed and experimented with.

In his earlier realization of the idea, a triode circuit (the 'target' circuit) was coupled to a piezoelectric oscillator (the 'source') through coils (see Figure 5).[40] By inducing a voltage on the tube's grid, the source controls the discharge in the tube, and thereby the current in the target circuit. The grid is also connected to opposing sources of voltage in the target circuit. Decoupled from the source, the target circuit would have a periodic oscillation based on its own properties (in this case, on the time of accumulating charge on a capacitor depending on a resistor and the properties of batteries and the tube). The voltage induced by the source guaranteed that discharge in the tube would begin only at the peaks of the source oscillations. The peaks of the high-frequency source voltage play a similar role to that of the lower-frequency voltage peaks in the tuning-fork harmonic producer, in this case forcing them to occur only every fix (integer) number of the source periods. The power of division can be manually adjusted by varying elements in the target circuit.

Marrison's earliest 'subharmonic producer' started to fulfil AT&T's needs but didn't fully meet them. Before describing the proposal in his notebook, Marrison had experienced with the device on the various components that required replacement, modification, and tuning. Through experimentation,

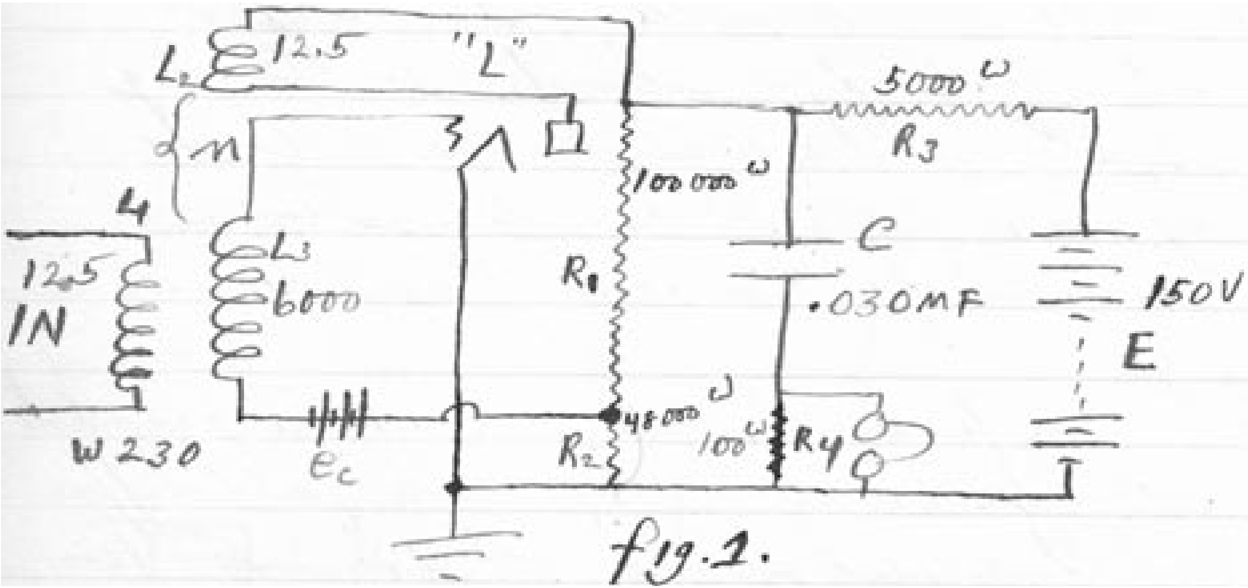

Figure 5. Marrison's electronic suggestion to reach low frequencies from June 1925: An ellipse was added around the triode 'L' to help the modern reader. The zig-zag line on the left side presents the grid, the cut triangle at the centre the cathode and the square on the right the anode. Through an inductive coil (L_3), the source induced oscillating voltage in the circuit branch connects to the triode's grid, which controls the discharge in the triode tube (L), and thereby controlled the current in the target circuit (on the right side). In the initial setting, no current flows through the tube, since the triode's grid is connected to a high negative voltage, which blocks any discharge from the cathode. While there is no current through the triode, however, the battery E charges the condenser C. The condenser then applies (through the resonator R_2, which with R_1 forms a potentiometer) an opposing positive voltage on the grid. At some point the sum of the condenser voltage and the maximum of the alternating voltage induced by the source through L_3 is just sufficient to overcome the negative voltage on the grid and allow a discharge through the tube (since the rate of change of the voltage on L_3 is much higher than that on the capacitor C, the threshold is reached while the source voltage is maximal). Once current flows, it reinforces itself by a feedback mechanism: the coil L_2, which is connected to the anode (and therefore becomes magnetically active when currents flows in the triode), is coupled to the grid through coil L_3, and thus induces additional positive voltage on the grid. Due to this feedback mechanism, with the proper choice of variables, current continues to flow 'until practically the whole of the charge on C has been dissipated'. At this point the system had run a full cycle and returned to its initial setting. The period of the cycle depended on the properties of capacitor and coil in the RLC circuits. The capacitor needed to reach the breakthrough voltage depended on the relation between R_2 and R_1 in the potentiometer. 'By [manually] adjusting the various elements of the circuit the rate of change of C can be adjusted so that it will be discharged once for one, two, three etc. cycles of the high frequency circuit'. (source NB 1444, 168) (Courtesy of AT&T Archives and History Center)

he managed to reach the fourth 'subharmonic'. This satisfied some of AT&T's requirements, such as extending the range of frequencies controlled by piezoelectric crystals. It did not, however, satisfy other criteria, for it lacked, for example, the ability to drive a clock mechanism. In subsequent attempts to improve the mechanism, Marrison failed to reach higher subharmonics. Two years later, when he filed a patent for the device, it was still unstable in high subharmonics, and the inventor suggested 'using several circuits in tandem' in order to reach lower frequencies.[41]

Although he learned a great deal from his first producer, Marrison clearly needed to modify his device. By 1926, he had conceived of a few other subharmonic producers. These more efficient circuits enabled him to compare the period of the piezoelectric oscillator with a clock, as well as control the frequency and measure lower frequencies. By July 1926, Marrison had connected the two goals of standards and control in his circuit, devising a few methods to 'obtain from a high frequency (crystal) oscillator a subharmonic for the purpose of operating a synchronous clock'.[42] The device that he described on 23 July resembled the subharmonic producer that he had suggested in June of 1925. Like its predecessor it included a source circuit that controlled a target circuit by inducing voltage on its grid (see Figure 6). The arrangement here, however, allows flow of current from the triode to the capacitor in each peak of the source voltage, making its period equal to that of the source. A new separated branch of the target circuit oscillated at a subharmonic following discharging of the capacitor. This separation released him from the reliance on the grid's voltage, as in his June 1925 idea, which did not allow high subharmonics. To allow a strong discharge current he incorporated

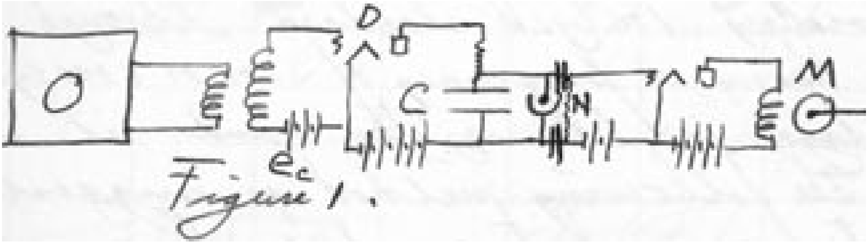

Figure 6. Marrison's 'typical method' for subharmonic producer using a neon tube (N), from 23 July 1925. The input oscillator (O on the left side) controlled the target circuit by coils coupled with the grid branch of a triode (D), which is connected to a negative potential (induced by the battery e_c). In this arrangement, however, a 'peak of the input wave' overcomes the negative voltage, which is otherwise 'large enough to prevent plate current from following [in the triode]'. 'Adjustments are made such that a definite quantity of space current flows [in the triode] for each wave' and consequently charges a capacitor (C). As with the previous method, C is charged until the voltage reaches a particular maximum value. Now, however, Marrison replaced the potentiometer, which set the breakdown voltage with a neon tube. The neon tube generated current in another triode branch (on the right side) thereby dispensing with the coil-feedback arrangement. An advantage of the circuit was, in his words, that the discharge current 'may be amplified sufficiently to run the low frequency motor M'. (Source: NB 2161, 28) (Courtesy of AT&T Archives and History Center)

a neon tube – a well-known if less popular electronic device. It was known that once the insulation of a neon glow lamp breaks down, the current ionizes the gas and continues until it reaches a nearly complete discharge. Since the capacitor in this arrangement is charged over very short intervals in which the source has maximal voltage, Marrison concluded that breakdown voltage would be reached at an integer multiple of the input cycles, which would become the period of a triode circuit that incorporates a neon tube.[43]

Theoretically, the circuit that Marrison made could have driven a synchronous motor, and thus a quartz clock. In practice, however, this and similar circuits were probably neither stable nor reliable enough for the task, and Marrison did not connect them to such a mechanism. Apparently, Marrison found out that the breakdown voltage of the neon tube alone was insufficient to ensure that discharge would always begin at the same number of cycles, and not one cycle earlier or later. By 31 July he had suggested a remedy: connecting the neon tube to a coil and capacitor circuit that was 'tuned to the desired subharmonic' (see Figure 7). The tuning did not need to be highly precise, since the source oscillator forced the period of the neon tube circuit to an integer division of its own. By adding the tuning circuit to the neon tube, Marrison produced a system flexible enough to be tuned to a specifically precise value, but also stable enough not to slip from one subharmonic of the source to another.

Within two days, Marrison realized that he could dispense with a triode and a separate quartz oscillator as a source. In his newest design, Marrison made use of the physical properties of the quartz resonator, namely the sharp change in its capacity near resonance. He connected a quartz resonator in parallel to a neon tube circuit that contained a resistor, capacitor and battery (see Figure 8). Without a crystal, the circuit would oscillate at a frequency depending on the properties of the battery, resonator, capacitor and the

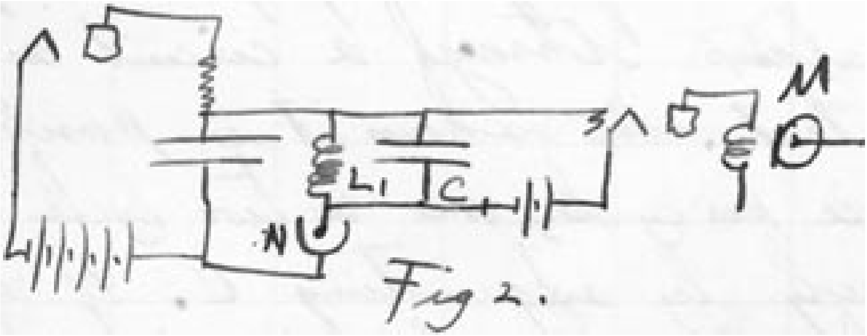

Figure 7. Marrison's second neon tube circuit from 31 July; the figure shows only the right side part of Figure 6, while the left side of the circuit remained the same. Notice that the neon tube is connected here to an additional coil (L_1) and condenser (C). (Source: NB 2161, 28) (Courtesy of AT&T Archives and History Center)

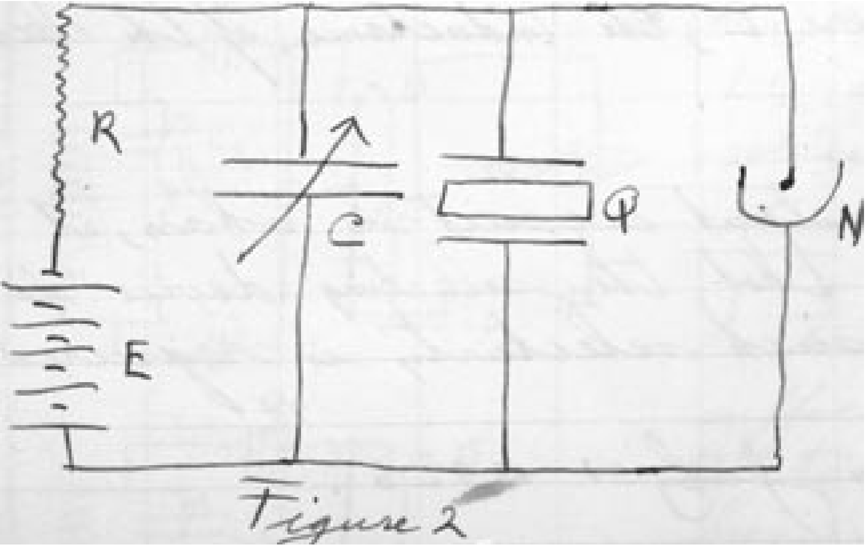

Figure 8. Marrison's neon-tube – crystal subharmonic producer of 2 August 1926, C is a variable capacitor, Q a quartz crystal and N a neon tube. (Source: NB 2161, 32) (Courtesy of AT&T Archives and History Center)

break-down voltage of the neon tube. According to Marrison, due to the sharp changes in the crystal's electric capacity near resonance it would 'control the frequency' of the circuit 'within narrow limits'.[44] Now, similar to the way that the changing voltage on the capacitor determined the period in the neon tube circuit that he had proposed a week earlier (see Figure 6), the changing capacity of the resonator determined the circuit's period. 'The frequency of the neon tube discharge [would] be controlled when it is 1/n of that of the crystal when n is any integer'. An additional virtue, the circuit could 'be regarded as either a harmonic producer, a sub harmonic producer or both. The frequency of the crystal is stepped down while the frequency of the neon tube oscillation is stepped up.' In its use as a subharmonic producer it could drive a clock mechanism. The dual role of the circuit points at the close connection between the research and development of subharmonic and harmonic producers. The circuit functioned well in tests, although its 'degree of control' decreased as the subharmonic frequency decreased.[45]

Three months later, Marrison modified the triode-based circuit with a capacitor and potentiometer that he had first proposed in June 1925. Instead of coupling a quartz oscillator to the grid through coils, as in the original design, he connected a quartz resonator directly to the grid, dispensing with the use of a 'source' oscillator. The similar step that he took with the neon tube circuit probably inspired him to embed the resonator in the grid branch of the circuit also in this earlier circuit. More concretely he was aiming to increase the voltage induced by the quartz resonator, since low voltage made the grid more

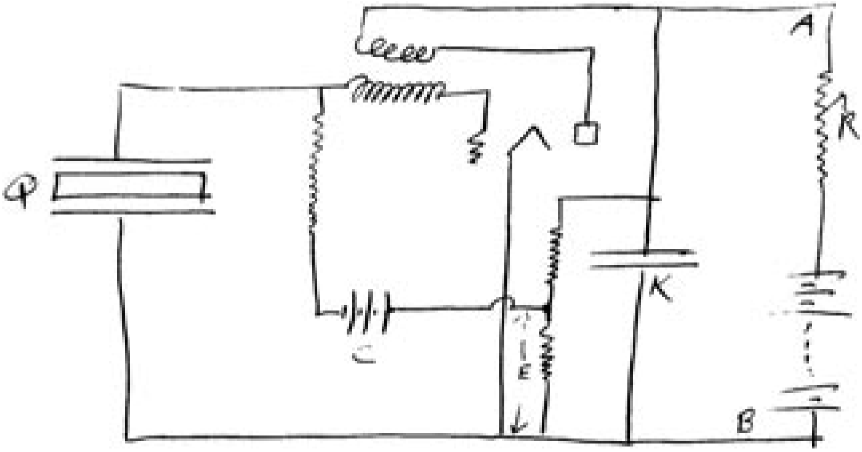

Figure 9. Marrison's subharmonic producer of November 1926. Here K is a capacitor and B a battery, while E represents the EMF available by the potentiometer. The oscillating voltage from the crystal (Q) suffices to overcome the negative voltage on the grid (from a battery) only as the condenser (K) charges up, which happens 'after the 1st, 2nd, 3rd (etc as desired) cycle of the crystal'. Once discharge begins, feedback coils keep sufficiently high voltage on the grid to ensure an abrupt discharge of the condenser, as in the design from June 1925 (Figure 5). (Source: NB 2161, 62. (Courtesy of AT&T Archives and History Center)

sensitive to fluctuations in the voltage due to other components of that branch of the circuit. These fluctuations were a probable source for the discharge that had occurred in the middle of the crystal's cycle before it had reached its maximal voltage. This premature discharge had lead to instability with large subharmonics in the original design and was therefore undesirable. In the modified design, the working principle remained the same (see Figure 9).

Tests made by George Hecht from Marrison's group showed that the method allowed reaching the twenty-fifth subharmonic. Even though 'the stability decrease[d] rapidly as we go to higher orders (lower frequencies)', this was a clear advantage over the original design. As with other methods, one needed to tune the apparatus manually to reach a new subharmonic, but it kept each frequency without further human intervention. To improve stability Marrison suggested driving the quartz crystal with an independent tube circuit. His reasoning: 'By this means the crystal is kept vibrating at larger amplitudes than otherwise would be obtained and it has a greater controlling effect on the low frequency output.'[46] Here, Marrison went back to dividing the circuit into sub-circuits, a general tendency in his design, although in this case he did not return to a separate piezoelectric oscillator until two months later, when he used a new method, which AT&T would adopt for its frequency standard.

The first quartz frequency standard and clock

By 27 January 1927, Marrison invented a new device, which he called 'A Sub

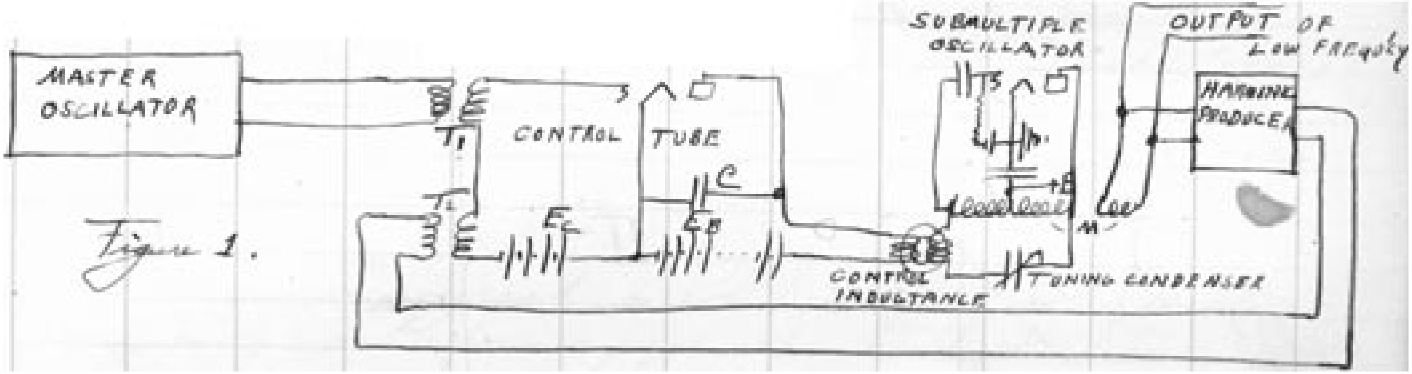

Figure 10. Marrison's 'Sub-Multiple-Frequency Control System' of January 1927. (Source: NB 2161, 73) (Courtesy of AT&T Archives and History Center)

Multiple-Frequency Control System'. The new system was deemed reliable enough for use by AT&T in its frequency standard. Because it furnished means to reach frequencies useful for driving a clock to monitor the accuracy and stability of the resonator's frequency, Marrison's new frequency divider enabled the construction of AT&T's central frequency standard on a quartz resonator. The timekeeper was not only an important part of AT&T's first crystal standard, but was also the first operating quartz clock.

Enjoying insights and experience gained from two years of research, Marrison combined in the new method a few earlier ideas in modified form with one important novelty. As in most of the earlier methods, a separated quartz oscillator controlled the voltage on a grid of a 'control tube' without being integrated in the circuit. The current from the tube controlled a circuit tuned to oscillate by its own capacity and inductance at the desired (sub) frequency (labelled 'Submultiple Oscillator' in Figure 10), an idea that Marrison had first used in his neon tube controlled circuit of 31 July 1926. The important novelty that he incorporated was a self-regulating mechanism that adjusted the frequency of the submultiple oscillator to the desired one by changing the inductance of the circuit through a special coil (labelled 'Control Inductance' in Figure 10). This mechanism relied on feedback from the controlled frequency, which included a harmonic producer that multiplied the oscillation back to the higher input frequency. The role of the harmonic producer was to compare the submultiple oscillation with the input frequency. This resembled the working principle of Marrison's first proposal to synchronize a motor with a high frequency oscillator, from November 1924. The new design, however, was totally electromagnetic (except for the crystal, of course). In order to run a clock, or to use the frequency in any other way, Marrison coupled an output circuit to the submultiple oscillator.[47]

In the feedback mechanism, Marrison coupled the output of the harmonic producer to the grid branch of the control tube through inductive coils (T_2) in series with the voltage induced from the piezoelectric resonator (labelled 'Master Oscillator' in Figure 10). Its design was based on a theoretical understanding of the alternating current produced by harmonic producers and piezoelectric resonators. The combination of their induced voltage determined the existence and strength of current through the tube. While the piezo-oscillator induced a steady voltage wave, changes in the frequency of the submultiple oscillator altered the wave induced by the harmonic producer and thereby changed the phase relations between the two induced waves. Constructive or destructive interference would thereby change the voltage on the grid and, in turn, the discharge through the tube. The control tube and the control inductance were tuned so that when the submultiple frequency was too high the phase difference between the two waves would increase and the positive voltage on the gird would decrease (see Figure 11 for more details).

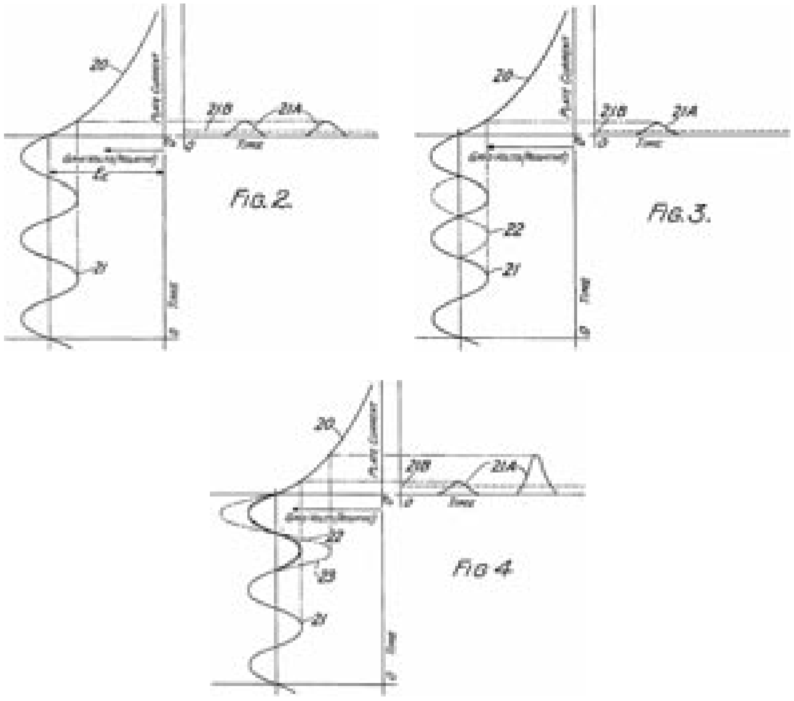

Figure 11. The effect of the harmonic producer on the control tube current – a graphical presentation: The left figure ('FIG 2') shows the grid voltage (left side) and the resulting current on the triode ('plate current' – on the right side) under the influence of the voltage induced by the master (piezoelectric) oscillator alone. In this case the maximal voltage on the grid branch of the control tube would suffice to produce a small stable periodic current in the triode, as shown in the right side of the figure. The two other figures show the effect of connecting the harmonic producer to the circuit when the frequency of the submultiple oscillator is either faster (right figure) or slower than the subharmonic (lower figure). When the frequency of the submultiple oscillator increased, the phase of the electric wave produced by the harmonic producer advanced in relation to that of the master oscillator. As shown for an extreme case in the right figure ('FIG 3'), in that case the two waves have destructive interference, which nullifies the current at the plate. Since the harmonic producer sends a wave only once every few cycles of the piezoelectric oscillator, the current would be zero only at these cycle and would keep its normal value at the other cycles, as in 21A at the figure (corresponding to 21 of the grid voltage on the left side). When the output frequency decreased, it would retard so as to approach the master oscillator phase ('FIG 4' at the bottom). Their constructive interference would lead to a higher voltage on the grid (23) resulting in a stronger current in the control tube, as shown on the right side of the figure. When synchronized the two voltage waves would keep an in-between and constant phase difference that maintained a constant current in the tube. (Source, Marrison, 'Frequency-control system')

Consequently, the average current in the tube and in the control inductance in that branch would also decrease, resulting in an increase in its inductance and in the inductance of the submultiple oscillator which thereby lowered the frequency back to its desired value. A decrease of the output frequency would cause a reverse process: raising the voltage on the grid, resulting in a lower inductance in the submultiple oscillator and an increase in its frequency to the desired value.[48] The two therefore functioned as a feedback mechanism that held the output frequency stable with respect to the grid.

By means of an ingenious mechanism, Marrison ensured the self-regulation of the circuit. The control inductance consisted of a ring of magnetic core having two windings, one connected to the plate (anode) of the control tube, the other forming a part of the controlled oscillator. The material at the core had a highly variable permeability, which meant that the magnetic field strength (**H**) of the magnet was not a linear function of the external magnetic field (**B**), but rose faster with the increase of the external field (e.g. twice the external field induced more than twice the inner field). A change in the magnetic field in one part of the control inductance sufficed to change the permeability and thereby the inductance of the whole. Thus, when the direct current in the control tube winding increased, it would induce a stronger magnetic field (as current always does), which would increase the inductance of the control inductance and, with that, the inductance of the submultiple oscillator, thereby decreasing its frequency. A decrease in the current would lead to a reverse process.

The methods and practices of Bell Labs provided Marrison with many of the resources he needed to devise this self-regulating circuit. A few researchers at that laboratory had already suggested exploiting the strong response of a core of variable permeability on the magnetic and electric behavior of coils and circuits. Although different from its use in Marrison's clock, such uses were suggestive for his search of circuits with a self-regulating mechanism. In addition, in late 1922, Ralph V. L. Hartley, Horton's direct supervisor, suggested a harmonic generator based on coupling two circuits by a common magnetic core with windings in each circuit. The high inner magnetic permeability of the core blocked an electric voltage, except for short intervals when the magnetic flux is changed. Hartley relied on a specific material developed by Western Electric, dubbed 'permalloy', due to its very high permeability relative to that of other ferromagnets. Starting from 1913, Gustaf Elmen from the research branch developed the alloy to provide high permeability for the needs of high load in long telephone wires of the Bell system. Once the alloy was available, researchers at AT&T, such as Hartley, continued searching for uses in other technical contexts. Their regular meetings and other interactions provided knowledge about such resources and methods for their use. The size of AT&T and its comprehensive care for the full system of telecommunication were crucial for developing the alloy for use in one realm (cables understood with the tool of electromagnetic fields) and later for its implementation in others (electronic system). Marrison himself had already employed permalloy coils before he suggested the subharmonic producer. In July 1925, he used such coils as a balance tilted by a current initiated by speech in a 'suppressed carrier system'. Apparently, Marrison's own ideas of using the control inductance in the subharmonic producer inspired at least one additional researcher at Bell Labs, William A. Knoop, who used it to couple a few circuits in a synchronization system, patented in 1928.[49]

Marrison's new subharmonic producer performed very well. By October 1927, Marrison and Horton had 'found that the frequency of a given current can be controlled by a current of higher frequency with much greater stability than by a current of lower frequency'.[50] The inventor had already filed a patent in March.[51] Interestingly, AT&T decided to patent Marrison's earlier suggestions for subharmonic producers only after reaching the newer more stable method. Apparently only after frequency division had seemed practical, did AT&T try to defend it against potential competition (although unsuccessfully).[52] With their application in the patent office, the Marrison group continued to examine the different components of the crystal based frequency standard system and made further improvements. They found that the new subharmonic producer allowed them to produce frequencies in a ratio of fifty to one, twice as much as attained earlier and probably with steadier results. Although by using two dividers in series it would have been feasible to reach a frequency of one hundred hertz to drive a synchronous motor, the group preferred dividing the frequency in two steps: one electronic and one mechanical. Their work therefore relied on proved devices from the tuning-fork clock even as these devices complicated the system.[53]

Improving the precision of the clock

In the summer of 1927, Marrison's group installed at AT&T the first frequency and time standard based on a quartz resonator. A quartz clock was an integral part of this system, ensuring its accuracy. The group could have stopped its development, since the system had attained the accuracy needed for AT&T's telecommunication techniques, yet the success of the standard encouraged the researchers at Bell Labs to carry out elaborate research aimed at the clock's further improvement. One reason for their continued work was their expectation that the continuous increase in the useful radio range would lead to a demand for higher accuracy in frequency measurement and control. Still, it seems that the quest for higher precision gained its own momentum, and this pushed the group to pursue higher accuracy.

Marrison and other researchers at Bell Lab examined, reconsidered and suggested improvement of the different ingredients of their frequency and time standard: the crystals and their cuts, the mounting and gaps of the crystal oscillator and its circuit, as well as the subharmonic producer, the synchronous motor, the means of producing a wide range of frequencies from the resonator, and the method for comparing the quartz oscillator to an astronomical clock. Although not a direct interest of AT&T, metrology and methods of keeping time in particular occupied an increasing place in

Marrison's attention. The field was not new for him; he had participated in time measurements for their own sake at least since he had taken part in the measurements of the 1925 solar eclipse.[54] By April 1929, the quartz clock had reached an error rate 'in the order of 0.01 second a day [about 1 in 10^7]'. This was twice as accurate as the pendulum clock at the Bureau of Standards. The most accurate contemporary clock based on the new Shortt free pendulum mechanism, the culmination of two hundred and fifty years of pendulum horology, had an error between one-hundredth and one-thousandth a second a day.[55] Although the quartz clock could not yet replace the best pendulum clock, in 1930 Marrison suggested using it to display sidereal and mean solar time for astronomical needs from the same time-keeping element, which one could not do with a pendulum clock.[56]

To reach and exceed the accuracy of the best pendulum clocks, Marrison had to improve the individual components of his quartz system. He deemed the crystal itself to be '[b]y far the most important element in a crystal-controlled oscillator' and dedicated much effort to improving its stability. Identifying the effects of changing temperature as the greatest single source of error in the quartz system, he worked in two directions. First, he tried to improve the thermal regulators in the system (an endeavour continued from tuning-fork standards). Second, he worked on reducing the sensitivity of the quartz resonator to temperature variations. In May 1927, Marrison made a breakthrough in the latter effort with an innovative cut of the quartz crystal. He reasoned that since 'plates of quartz cut in the plane of the optic and electric axes usually have positive temperature coefficients and . . . plates cut in the plane of the optic axis but perpendicular to an electric axis have negative coefficients' a cut between these directions, or a vibration that involve both, would have practically a zero coefficient. In order to get the effect he wanted, Marrison applied knowledge of physics concerning the elasticity of quartz and its dependence on temperature. The implementation of his idea, however, required further experimental research on the elasticity of quartz (the value of the temperature coefficient at angles to known cuts is not simply a function of the values in those cuts) and also a practical search for appropriate angles and shapes of the crystal cuts carved at the laboratory. Only experimentation showed that rings 'have a temperature coefficient lower than disks of the same diameter and thickness' (see Figure 12). With these rings the researchers attained at room temperature a coefficient of 'less than one part in a million per degree C'. As a by-product, 'the ring shape permit[ted] of an improved method of mounting in which there is very little friction to the holder'.[57]

Marrison's ability to use the results of previous and contemporary researchers points to the professionalization and specialization of science and technology in the twentieth century. His method of applying compensating effects, for example, resembles Wilhelm E. Weber's development a century

Figure 12. Georges Hecht, Marrison's assistant, finishing the first set of 'zero-temperature-coefficient' quartz rings. (Courtesy of AT&T Archives and History Center)

earlier of reed pipes that keep constant pitch under changing airflow. Weber had also studied two opposite effects, in his case the effect of the airflow on the metal reed and on the air column within the pipe, and found that they can neutralize each other. Whereas Marrison built on the work of other researchers, Weber had had to study much of the corresponding information about the acoustics of reeds and air columns himself.[58]

Bell Labs offered rich resources for designing and constructing the new cut of the quartz crystal that Marrison needed. Its facilities allowed cutting and polishing the crystals in house, its manpower long research hours for extending the empirical knowledge on which his idea lay, and for examining its practical application. Moreover, he could use the results of another group within Bell Labs. Following Raymond Heising's observation of a discontinuous change of frequencies with the dimensions of crystal cuts, his assistant Frederick R. Lack examined the effect of specific directions of cuts and temperature on the frequencies of crystal resonators. Heising suggested a special cut, different from Marrison's, that exploited the observer phenomenon to reduce the crystal's thermal coefficient to practically nil. Already in July 1927, Heising had filed a patent suggesting the use of two crystal cuts, one with a positive and one with a negative thermal coefficient 'to reduce undesired variations in the frequency of the controlled oscillator due to temperature changes'. Marrison began by examining the effect of two perpendicular pairs of electrodes in the same quartz plate, and only later found a direction that combines coefficients of opposite signs in one crystal cut. Heising, however, had been working, not on a better standard, but on components for radio transmitters. Thermally stable crystal cuts were valuable both for such circuits, which lacked thermal control, and also valuable to attain the high accuracy required in AT&T's frequency and time standard. Working at the same company, Marrison and Heising easily exchanged knowledge and experience about the resonators, which advanced the research of both groups.[59]

Although the rich resources and specific needs of AT&T made Marrison's development more likely, other researchers devised resonator rings too. A few months earlier Erich Giebe and Adolf Scheibe at the German Physikalisch-Technische Reichanstalt (PTR) also devised a resonator ring. The German researchers, however, were not looking for higher thermal stability. Instead, they wanted to obtain a wide range of frequencies from piezo-resonators, including relatively low ones (they reached 800Hz). They also sought to observe their resonance in special electric discharge containers illuminated by the strong vibration that they developed. In 1927, the German pair used torsional modes of vibrations, hitherto unexplored, and utilized quartz rings cut in the plane of their electric axes, which vividly showed their modes of vibration. While they utilized ring cuts similar in form and in some properties to Marrison's, they did not look for better thermal stability and their cut did not share the characteristics of Marrison's cut in this aspect.[60] Unlike Giebe and Scheibe, another foreign researcher, David Dye of the British National Physical Laboratory, did seek more stable piezoelectric resonators (although he was probably more concerned about the resonators' mechanical stability since he designed a mechanism for compensating for variation of frequency with temperature). Like Marrison, Dye found a solution in a quartz crystal ring. In the mid-1920s, Dye too developed a frequency standard based on quartz to replace the tuning fork standard. It is not clear, however, when he begin using a quartz ring for his standard. Moreover, Dye cut his crystal perpendicular to its electric axes, i.e. in perpendicular to Marrison's cut.[61]

Ironically, following his scrutiny of the frequency standard system, Marrison replaced the component of his system that had initially enabled the construction of an operating quartz clock: the subharmonic producer based on controlled inductance. Initially content with the performance of the subharmonic producer, by April 1928, he judged that it has 'not been as good as desired' and suggested improvements in the control circuit, without altering its basic principles. Although Marrison expressed satisfaction with the improved design, sometime during the following year he replaced it too with a circuit that worked on different principles. Originally, Marrison's main strategy was to construct a circuit with a stable but adjustable internal frequency, and to limit its oscillations to a subharmonic of a controlling circuit, similar to the harmonic producer controlled by the tuning-fork circuit. In his new design he dispensed with the idea of a stable submultiple circuit and settled for an inherently unstable tube circuit oscillator, i.e. a circuit able to vibrate at a large range of frequencies. Such a circuit would oscillate at a frequency 'which is a small multiple or submultiple of' the control frequency.[62]

In replacing the subharmonic generator in his system, Marrison adopted an approach that originated outside of Bell Labs. Researchers at MIT, Philips, the Italian Navy, the National Physical Laboratory and the Tokyo electro-technical institute all developed alternative frequency dividers. One of them, Balthasar van der Pol, provided a theoretical account for the tendency of inherently unstable oscillators to vibrate at a harmonic or subharmonic of a source voltage.[63] These developments by other researchers helped Marrison replace his rather complex, if ingenious, submultiple circuit with a simpler circuit. Despite the replacement of a key ingredient in his frequency and time standard with a component that originated outside of AT&T, Bell Labs maintained its lead in quartz time standards for a few years.[64] With the exception of the quartz resonator itself, the system as a whole was more important than the specific details of its single components. Thus, the quartz clock required more than the invention of one component (like the subharmonic generator). More than that, it required the development of the way they were assembled. Notwithstanding Marrison's prime role, this system originated from a network of physicists, engineers and inventors, both inside and outside the Bell system.

CONCLUSION

Inventing the quartz clock system, Marrison followed a twisted road. Table 1 summarizes the devices that he suggested for a time and frequency standard, their sources and the relationships among them. Quite a few of the devices that he suggested for dividing the frequency of piezoelectric resonators did not evolve from their immediate predecessor. Instead, he adopted ideas from the tuning-fork standard, in use by AT&T at the time, and from other systems. Others of his devices clearly were evolved from previous ones. Yet sometimes the processes of modification and elaboration led to completely new designs. For example, the circuits that Marrison devised during July and August of 1926 began with the utilization of a separate piezo-oscillator and ended with embedding a piezo-resonator within a main neon tube circuit. At other times, Marrison returned to an older design in a modified form. For example, in November 1926, he considered a different way of connecting the piezo-resonator to the triode, in a circuit otherwise equivalent to the one he had suggested in June 1925. Marrison's methods for reducing frequencies can be grouped into two approaches: mechanical and electronic. He began with the former and turned to the latter in March 1925. Still, a month later he returned to a mechanical method. Although not ultimately used, his earlier methods provided ideas that he incorporated in later circuits. For example, the 'inductance control' method, which he used in the 1927 quartz clock, shared a logical structure with his first suggestion from November 1924. In both cases Marrison remultiplied the lower output frequency and compared it with that of the piezoelectric oscillator. Similarly, although Marrison's quartz clock was not used by others, his ideas are worth recording in detail because they reveal how industrial inventors worked, using the resources of the laboratories they work in a proceeding along many different tracks in pursuit of a given goal.

Oftentimes novelty emerges from implementing known ideas in a new

Table 1. Marrison's suggestions for reaching a known lower frequency from that of a quartz resonator, November 1924 – January 1927

Date	*Kind*	*Operating principles*	*No. of frequencies obtained*[1]	*Highest division of frequency*	*Possible uses*	*Predecessor method*	*Background knowledge*[2]
Nov. 24	Synchronous motor	Mechanical + modulator	1	101	Clock[3]		Clock mechanism, harmonic producer & modulator of tuning fork standard
Mar. 25	Two piezo-oscillators	Modulator	1	About 10	Clock	Nov. 24	
June 25	Subharmonic producer	Controlled tube-capacitor circuit	3	4	Attaining lower frequencies		Harmonic producer (as in the tuning fork standard)
July 25	Two synchronous motors	Mechanical + modulator	1	About 20	Clock	Nov. 24	
23 July 26	Subharmonic producer	Controlled tube-capacitor circuit with neon tube	Unknown	Unknown	Clock & lower frequencies	June 25	General use of neon tube in electronics
31 July 26	Subharmonic producer	Controlled tube-capacitor with neon tube and its own LC circuit	Unknown	Unknown	Clock & lower frequencies	23 July 26	
2 Aug 26	Subharmonic producer	Piezo-resonator – neon tube	Unknown	Unknown	Clock & lower frequencies	31 July 26	Experience with piezo-electric resonators
Nov. 26	Subharmonic producer	Piezo-resonator connected to controlled tube	24	25	Clock & lower frequencies	June 25	
Jan. 27	Submultiple oscillator	Magnetic control inductance, feedback	49	50	Clock & lower frequencies	Jun. 25; Nov. 24; 31 Jul 26	Use of variable inductance at Bell system

Notes

[1] Above the input frequency/ies

[2] Beyond the knowledge that was used in the predecessor methods.

[3] That is, the method allowed driving a clock mechanism.

context. Many of Marrison's innovations followed from variations on previous techniques and adaptations of methods and procedures from one realm (e.g. tuning-forks) to another (e.g. quartz resonators), or from one device (e.g. piezo-resonator connected to a neon tube in August 1926) to another (e.g. piezo-resonator connected to a triode in November). Replacing the tuning-fork with the quartz resonator required considerable changes to AT&T's frequency standard, but Marrison's group continued to use parts from the preceding standard system (e.g. the clock mechanism), and to combine ideas and techniques from other parts of that system. For example, in November 1924, Marrison employed the technique of driving a synchronous motor by electric oscillations, a technique previously used with the tuning-fork standard. Replacing this mechanical method with an electronic one, a few months later he devised a subharmonic producer in analogue to the harmonic producer used with the older standard. As he had done in its predecessor, he controlled the frequency of a target circuit, tuned to oscillate at the desired frequency, by a periodic physical influence from the source circuit. In these and other cases, novelty resulted from combining known and usually common components and modifying their specific properties. Though known, the components that he used were state-of-the-art devices available at the corporate laboratory, from the common triodes, through the less ordinary neon tubes, to the relatively new piezoelectric resonators and oscillators and the uncommon coil with a high permeability core. Their combinations resulted in novel devices.

The new way to cut a quartz crystal that he developed, the high point (but not the end) of the research on stabilizing the crystal resonator, exemplifies Marrison's debt to theoretical knowledge. Although he contributed to the knowledge of elasticity by empirically finding the exact direction of a zero thermal coefficient in a quartz crystal, fostering science was only an atypical by-product of his group's research. The members of Horton's group at Bell had little freedom to pursue more general, in this sense scientific, questions that did not relate directly to their immediate technological aims. They were, however, well-versed in the current scientific and engineering literature. In addition, they learnt about new developments and approaches, sometimes before they were published, through direct exchange with researchers, outside of Bell Labs, like Cady. While outside developments were discussed within Bell Labs, more important was the circulation of ideas in use at AT&T, like those of combining crystal cuts in different manners to reduce the variations of their frequency with temperature, and the use of permalloy in coils to control electric circuits. The laboratory's own large staff allowed its researchers to experimentally explore a sizeable number of their ideas. Like his colleagues, Marrison also had rich material resources at his disposal. These included, among other things, state of the art electronic tubes,[65] the means to cut and polish crystals at the laboratory, and the permalloy for his coils. The general strategy of combining and varying extent techniques and components was well-known and used by inventors. Yet the facilities of the modern corporation made it particularly potent. The rich intellectual and material resources allowed the modern corporate inventor to employ varied devices and methods, to modify them to specific needs, combine them and examine the performances both of the individual components and of the composite devices. While Marrison, Horton and other researchers at Bell Labs showed ingenuity, these resources were crucial for their inventions and their success in constructing the first quartz clock.

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NOTES

1 Thomas P. Hughes, *American Genesis: A Century of Invention and Technological Enthusiasm, 1870–1970* (New York: Viking, 1989), 138–9.

2 Hughes, *American Genesis,* 66–71 (independents' choice of problems).

3 E.g., Hugh G.J. Aitken, *The Continuous Wave: Technology and American Radio, 1900–1932* (Princeton, N.J.: Princeton University Press, 1985), 188–189, 228; Ian Wills, 'Instrumentalizing Failure: Edison's Invention of the Carbon Microphone', *Annals of Science*, 64 (2007): 383–409.

4 On the history of tuning-fork standards, see, Shaul Katzir, 'Frequency and Time Standards from Acoustic to Radio: The First Electronic Clock', Lara Huber and Oliver Schlaudt (eds) *Standardization in Measurement: Philosophical, Historical and Sociological Issues* (London: Pickering and Chatto, 2015), 111–124.

5 For a comprehensive discussion of the technological and societal aims and problems that led to the development of quartz clock technologies by the various groups that worked towards them in the academy, industry and state laboratories, and of the research carried by those groups, see Shaul Katzir, 'Pursuing frequency standards and control: the invention of quartz clock technologies', *Annals of Science*, 73 (2016): 1–39. Here I refer only briefly to the reasons that directed AT&T's researchers to the specific technological problems that they examined. Other histories of the developments in AT&T do not suggest the close analysis of the invention and development process offered here. See Carlene E. Stephens, 'Reinventing Accuracy: The First Quartz Clock of 1927', in *Die Quarzrevolution: 75 Jahre Quarzuhr in Deutschland 1932–2007*, ed. Johannes Graf (Furtwangen: Dt. Uhrenmuseum, 2008), 12–23 and the fair reconstruction by the chief protagonist: Warren A. Marrison, 'The Evolution of the Quartz Crystal Clock', *The Bell System Technical Journal*, 27 (1948): 510–588.

6 For an elaborated discussion of the consequences of the quartz clock technologies see Shaul Katzir, 'Time Standards for the Twentieth Century: Telecommunication, Physics and the Quartz Clock', *The Journal of Modern History*, 89 (2017): 119–150.

7 Joseph W. Horton, Norman H. Ricker, and Warren A. Marrison, 'Frequency Measurement in

Electrical Communication', *Transactions of the American Institute of Electrical Engineers* 42 (1923): 730.

8 Aitken, *The Continuous Wave: Technology and American Radio, 1900–1932*; Sungook Hong, *Wireless: From Marconi's Black Box to the Audion* (Cambridge, MA: MIT Press, 2001), 155–189.

9 Horton, Ricker, and Marrison, 'Frequency Measurement in Electrical Communication', quote on p. 730; Marrison NB 1112-2, p. 38 (29 May 1922), which mentions also earlier work, Riker NB 1097-2 (June 1921–December 1922). (Unless otherwise indicated, unpublished material is taken from AT&T Archives and History Center, Warren, NJ. The abbreviation NB throughout these notes stands for Notebook.)

10 The unit was also called the Research Department.

11 Joseph Warren Horton, *Excursions in the domain of physics*, a typed manuscript, 1965 at the American Institute of Physics library, quotations on 3, 5; Obituary in *IEEE Spectrum*, 4 (1967): 38–39; Brittain, James E., 'Joseph Warren Horton', *Proceedings of the IEEE*, 82.4 (1994) (http://ieee.cincinnati.fuse.net/reiman/11_2006.html accessed 25 February 13). For more details see Katzir, 'Pursuing Frequency Standards', 7.

12 Norman Ricker *Autobiography*, typed manuscript at 'Norman Hurd Ricker Papers', in Woodson Research Center, Foundren Library, Rice University (23/206), 36–40; 'Chart of Western Electric Company Research Department, Dec. 1922', (14/142); W. R. Topham, 'Warren Marrison – Pioneer of the Quartz Revolution', *NAWCC* [*The National Association of Watch and Clock Collectors Bulletin*], April 1989, 126–134. Marrison's first dated notebook entry in AT&T is from June 1920; Marrison's 'record card' at Harvard University Archives. I thank its staff for informing me about the content of this file.

13 NB 111-2, began by Davidsson (October 1921–March 1922) continued by Marrison from 29 May 1922. Leonard S. Reich, *The Making of American Industrial Research: Science and Business at GE and Bell, 1876–1926* (Cambridge: Cambridge University Press, 1985), 202–04. Horton, Ricker, and Marrison, 'Frequency Measurement in Electrical Communication'.

14 Joseph W. Horton, 'Harmonic generator system' US patent 1519619, filed 23 December 1920, patented 1924, quotations on 1; E.H. Colpitts and O.B. Blackwell, 'Carrier Current Telephony and Telegraphy', *Transactions of the American Institute of Electrical Engineers*, 40 (January 1921): 205–300.

15 Marrison NB 1112-2, 38–39 (29.5.22), Horton, Ricker, and Marrison, 'Frequency Measurement in Electrical Communication'. One could attain a specific frequency also directly by multiplying the original oscillation by the desired number. This was the strategy of David Dye at the British National Physical Laboratory, using one or two multivibrators. Horton's group divided the process into two separate steps first generating known high harmonics and then combining them to reach any specific frequency. Horton, Ricker and Marrison claimed that this division leads to higher accuracy and fewer mistakes with higher frequencies since direct multiplication of high order is prone to lead to a non-intended harmonics (ibid., p. 741). David Dye, 'The Valve-Maintained Tuning-Fork as a Precision Time-Standard', *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character*, 103 (1923): 240–260.

16 E.g. David Pantalony, *Altered Sensations: Rudolph Koenig's Acoustical Workshop in Nineteenth-Century Paris* (Dordrecht: Springer, 2009), 102–104.

17 However, the group did examine the effect of temperature on the frequency of its own tuning-fork, finding a coefficient of 0.0109 per cent per degree C. Joseph W. Horton and W.A. Marrison, 'Precision Determination of Frequency', *Proceedings of the IRE*, 16.2 (1928): 137–154, 139–140.

18 Horton, Ricker, and Marrison, 'Frequency Measurement in Electrical Communication'.

19 The connection of the tuning-fork to the multivibrator was mention in the *Annual Report of the National Physical Laboratory* for the Year 1919 (Teddington: National Physical Laboratory, 1920), 51, and *Annual Report of the National Physical Laboratory* (Teddington: National Physical Laboratory, 1922), 71.

20 To understand the working principles of the method we can ignore the third circuit in the figure (of L_2 and C_2).

21 Horton, Ricker, and Marrison, 'Frequency Measurement in Electrical Communication', 739–741; Ricker NB 1097-2, especially 41–42 (22 July 1922); Joseph W. Horton, 'Source of Waves of Constant Frequency', patent, US1560056, filled 1 May 1923 (issued November 1925).

22 Horton, Ricker and Marrison, 'Frequency Measurement in Electrical Communication', 731.

23 Marrison NB 1112-2, 38–41; Horton, Ricker and Marrison, 'Frequency Measurement in Electrical Communication', 734–736; a report of R.V.L. Hartley to Harold Arnold 28 November 1922 (loc 79 10 01 14, in Arnold's papers), Warren A. Marrison, 'The Evolution of the Quartz Crystal Clock', *The Bell System Technical Journal*, 27 (1948): 510–588, 528; Marrison (NB 1444, 42, 149–153).

The synchronous motor was based on the phonic wheel, a well-known instrument at the time, consisting of a cogwheel whose centre is an electromagnet and its circumference is made from soft iron. When the iron-circumference moves near a tuning-fork, itself made from a magnetized metal, it becomes magnetic. Consequently, magnetic forces on the teeth, from the electromagnet and the tuning-fork the teeth adjust the wheel to rotate in phase with the tuning-fork. Due to a few technical problems with the motor the group devised a few models eventually settled on a 100-cycle motor geared directly to the clock mechanism.

24 On these methods and the relations between AT&T's clock and earlier tuning-fork based frequency standards and clocks see Katzir, 'Time Standards from Acoustic to Radio', 116–120.

25 Horton, Ricker, and Marrison, 'Frequency Measurement in Electrical Communication', 736.

26 Horton and Marrison, 'Precision Determination of Frequency', first quote 141. Marrison, 'The Evolution of the Quartz Crystal Clock', 528–530; United States National Bureau of Standards, *Standards Yearbook* (U.S. Govt. Print. Off., 1927), 44. D.W.Dye and L. Essen, 'The Valve Maintained Tuning-fork as a Primary Standard of Frequency', *Proceedings of the Royal Society of London. Series A*, 143 (1934): 306.

27 The high number of 'suggestions' recorded in the laboratory's notebooks and the diversity of their subjects, even within the same notebook, testify to the practice of examining alternative means also to methods in use. See, for example, notebooks of Ricker and Marrison.

28 Davidson and Marrison, NB 1112-1, especially 38 (Marrison, 29 May 1922 – a report about earlier work), Ricker NB 1097-2, especially 21 (26 July – rod) 23, 30 (26 August, 2 December 1921 – bar), Marrison, NB 1444, *passim* 55 (12 November 1924 – bar), 73–78 (8 December 1924 – torsional oscillations). On quartz see also the list of suggestions in NB 2161 and NB 2162. AT&T archive has not kept Horton's notebook, so the discussion here relies more on Marrison's research. His notebooks, however, mention also work of the group in general without assigning a particular author.

29 Warren A. Marrison, 'Some Facts about Frequency Measurement', *Bell Laboratories Record*, 6 (1928): 385. Lloyd Espenschied, 'The Origin and Development of Radiotelephony', *Proceedings of the Institute of Radio Engineers*, 25, (1937): 1101–1123.

30 To reach the new frequency range, by 1928 Horton group added a cathode ray oscillograph, which allowed higher multiplications of the input frequency. Still, piezoelectric resonators suggested a simpler method to attain very high frequencies. Horton and Marrison, 'Precision Determination of Frequency', 142.

31 Shaul Katzir, 'From Ultrasonic to Frequency Standards: Walter Cady's Discovery of the Sharp Resonance of Crystals', *Archive for History of Exact Sciences*, 62 (2008): 469–487; idem, 'War and Peacetime Research on the Road to Crystal Frequency Control', *Technology and Culture*, 51 (2010): 99–125.

32 Ibid., 117–120.

33 Marrison, NB 1112-1, 38 (29 May 1922).

34 Katzir, 'Pursuing Frequency Standards', especially 13–14.

35 Marrison NB 1444, 55 (15 November 1924).

36 NB 1444, 177 (20 July 1925). In his history of the quartz clock Marrison implies that his November 1924 suggestion was a first attempt 'for a combined time and frequency standard', which did not became a basis for a clock only because a simpler method was proposed. Marrison, 'The Evolution of the Quartz Crystal Clock', 537–539. The contemporary evidence, however, points to the use of the clock as 'a convenient method of checking the frequency over long intervals' (NB 1444, 177), rather than an attempt to establish a time standard.

37 On the use of this range for multiplex at the Bell system see E.H. Colpitts and O.B. Blackwell, 'Carrier Current Telephony and Telegraphy', *Transactions of The American Institute of Electrical Engineers*, 40 (1921): 205–300; T.E. Shea and C.E. Lane, 'Telephone Transmission Networks Types and Problems of Design', *Transactions of The American Institute of Electrical Engineers,* 48 (1929): 1031–1044.

38 See Marrison's notebooks for efforts to extend the range of quartz frequencies, and for attempts to use the same oscillator for a few frequencies. For an explicit mention of control at these frequencies see Hecht in Marrison NB 2162, 169 (15 November 1926).

39 NB 1444, 129 (19 March 1925).

40 With a thought to future patent claims Marrison referred to the source in a general way. Yet from the context it is clear that the radio frequency source in his mind (and the one actually used in its tests) was a piezo-oscillator.

41 Marrison NB 1444, 168–169 (25 June 1925), Marrison, 'Subharmonic frequency producer', US patent 1733614, filed 20.8.27. Unlike the source frequency the resulted alternating current is not sinusoidal (i.e. symmetric in time and in positive and negative current). Yet this was not an obstacle for using the output oscillation as an input for further manipulations.

42 Marrison NB 2161, 28 (23 July 1926). Marrison wrote that '[s]everal methods are possible for' operating a synchronous motor and presented a 'typical method' for that end. Unfortunately, the AT&T archives do not possess records of the team's crystal research from October 1925 to April 1926.

43 NB 2161, 28 (23 to 31 July 1926).

44 NB 2161, 28 (signed 31 July 1926) and 32 (2 August 1926).

45 NB 2161, 34 (5 August 1926). Since the resonator possesses significance capacity, in checking the device Marrison dispensed with the independent capacitor. To allow reaching different values from the same circuit he used a variable resistor.

46 NB 2161, 62 (10 November 1926), 63 (17 November 1926), NB 2162, 169–171 (15 November 1926).

47 NB 2161, 73–74 (27 January 1927).

48 In the initial suggestion the voltage from the piezo-oscillator alone was insufficient to overcome the negative potential of the battery E_c, as was the case in Marrison's earlier suggestions. In the operating version, which the group developed in the coming weeks, the circuit was tuned to allow current at the peeks of the oscillator's positive voltage, and the voltage from the harmonic oscillator was used only to vary the value of the average current through the tube; Warren A. Marrison, 'Frequency Control System', US patent 1,788,533, filed 28.3.1927.

49 R.V.L. Hartley, NB 1060-1101-3 (30 December 1922); quotation from Marrison NB 1444, 175 (10 July 1925); S Millman, ed., *A History of Engineering and Science in the Bell System: Physical Sciences (1925–1980)* (New York: Bell Telephone Laboratories, 1983), 801–808; William A. Knoop, 'Synchronizing system', US1747248, filed 10 February 1928, patented 18 February 1930. Apparently uses of variations of magnetic permeability were rare outside AT&T, for an exception see Quincy A. Brackert, 'Receiving system', US1567566, filed 12 April 1921. Brackert worked at Westinghouse.

50 They imply that this conclusion had been reached before the invention of the circuits described in their paper, i.e. before March 1927, but I haven't found an earlier indication for such a strong claim; Horton and Marrison, 'Precision Determination of Frequency', 143.

51 Marrison, 'Frequency Control System'. US patent 1,788,533. The patent included a few improvements on the suggestion from January.

52 On the development of alternative frequency dividers, see Katzir 'Pursuing Frequency Standards'.

53 Horton and Marrison, 'Precision Determination of Frequency', 148–149, NB 2162, 188, 189, (31.3.1927, 8.4.1927, entries by J.L. Whittaker, a researcher at Marrison's group).

54 Marrison, 'The Evolution of the Quartz Crystal Clock', 528–530; Marrison NB 1444, 97–105, (24 January 1925).

55 Steven J. Dick, *Sky and Ocean Joined: The U.S. Naval Observatory 1830–2000* (Cambridge University Press, 2002) Chapter 11, especially 461–462.

56 Marrison, 'A High Precision Standard of Frequency', 1112; Warren A. Marrison, 'The Crystal Clock', *Proceedings of the National Academy of Sciences of the United States of America*, 16 (1930): 496–507.

57 To increase accuracy, the crystal resonator was still put in a temperature control chamber. Marrison, 'A High Precision Standard of Frequency', quotations on 1103, 1104, 1106; Fredrick R. Lack, 'Observations on Modes of Vibration and Temperature Coefficients of Quartz Crystal Plates', *Proceedings of the Institute of Radio Engineers*, 17 (1929): 1123–1141. Marrison NB 2161, for example 92–93 (10 May 1927): 'Temperature Coefficient of Quartz Control' (first appearance of the oblique cut idea), 99, 126, 129, 130, 147 (24 May, 25 August, 3 October, 4 October, 16 December 1927), also in Marrison's next 'Suggestion Book', NB 2658, which he opened on 14 June 1928.

58 Myles W. Jackson, *Harmonious triads: Physicists, musicians, and instrument makers in nineteenth-century Germany* (Cambridge, Mass.; London: MIT, 2008), 114–118. Weber's technological endeavour was part of more general research on the phenomenon under question − acoustics. Marrison, on the other hand, concentrated on the use of piezoelectricity (and earlier elasticity of forks) for precision measurements.

59 Marrison recalled his collaboration with Heising concerning 'Crystals and Quartz Clock', Marrison to Baker 12 July 1977. In 1929, he and Lack referred to the papers of each other, which appeared in the same issue (above fn. 54). Raymond A. Heising, 'Crystal-controlled Oscillator', US patent 1840580, filed 25 July 1927. According to their collaborator on quartz crystals, Warren P. Mason, Marrison preceded Heising in suggesting a special cut from the same crystal ('Low Temperature Coefficient Quartz Crystals', *Bell System Technical Journal*, 19 (1940): 74–93, on 75). 'Raymond A. Heising − Member Board of Direction, 1929', *Proceedings of the Institute of Radio Engineers*, 17 (1929): 6; 'Raymond A. Heising: Board of Directors-1947', *ibid.* (1947), 1179; Lloyd Espenschied, 'R. A. Heising, former President of IRE, dies at 76', *Spectrum, IEEE*, 2 (1965): 222.

60 By early 1927 Giebe and Scheibe concluded that 'the influence of temperature is utmost small [äußerst gering]', ('Die Tätigkeit der Physikalisch-Technischen Reichsanstalt im Jahre 1926', *Zeitschrift für Instrumentakunde*, 47 (1927): 269–294, 275; E. Giebe, 'Leuchtende piezoelektrische Resonatoren als Hochfrequenznormale', *Zeitschrift für technische Physik*, 7 (1926): 235. E. Giebe und A. Scheibe, 'Piezoelektrische Kristalle als Frequenznormale', *Elektrische Nachrichten-Technik,* 5 (1928): 65–82 (received in November 1927).

61 L. Essen, 'The Dye Quartz Ring Oscillator as a Standard of Frequency and Time', *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 155 (1936): 498–519; Walter G. Cady, *Piezoelectricity: An Introduction to the Theory and Applications of Electromechanical Phenomena in Crystals* (New York: McGraw-Hill, 1946), 77; Ray Essen, 'Greenwich Time: From Pendulum to Quartz 1', *Horological Journal*, 154 (2012): 198–201.

62 Quotations from NB 2161, 184 (23 April 1928) Marrison, 'A High Precision Standard of Frequency', 1112.

63 On these frequency dividers and van der Pol's work see Katzir, 'Pursuing Frequency Standards, 18–35', Balthasar van der Pol, 'On "relaxation-Oscillations"', *Philosophical Magazine*, 2 (1926): 978–992.

64 Marrison, 'The Crystal Clock'. Still, in the early 1930s the national laboratories of Britain and Germany, which had a stronger interest in accuracy, exceeded the precision of AT&T's clock.

65 Cady, for example had to borrow tubes from Western Electric, e.g. H. D. Arnold to B. W. Kendall, 13 Febuary 1918, Arnold to Cady 5 June 1919, AT&T Archive (Loc. 79 10 01 03).