Time Standards for the Twentieth Century: Telecommunication, Physics, and the Quartz Clock*

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Scene 1: a full-screen clock, its second hand approaching six o'clock. Dozens of workers rush through the street and into the factory, punch their timecards, and hurry to take their places near the huge machines. Scene 3: the assembly line is set at its maximal speed and the Little Tramp struggles to match the pace of the machine; alas, he fails and is swallowed helplessly between the cogs of the machine.

In these forceful images from *Modern Times*, Charlie Chaplin conveyed the tyranny of the clock in the modern mechanical world. According to this common image, clocks and machines in the hands of the powerful actively imposed time discipline and the breakneck speed of modernity on the reluctant population. Submission to time discipline, however, was a more complex and fascinating process, as it grew out of the interactions of state agencies, corporations, and individuals with an array of changes in modes of transportation and telecommunication. In 1936, when Chaplin made the film, industry had already begun its transition from the mechanical to the electrical and electronic world of smaller machines on the shop floor and smaller appliances and radios in the home. Not that time and speed became less important—on the contrary, their importance only became more pronounced. Scientists, engineers, and technicians invested countless hours in devising new clocks and synchronization devices for the needs of these novel technological systems. The most famous result of their work was the quartz clock. Invented almost a decade before *Modern Times* was released, it was the first chronometer to exceed the accuracy of the mechanical pendulum clock, which had served as the standard since the seventeenth century. With its invisible electromechanical vibration, its often hidden existence in virtu-

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ally any smart electronic gadget, and its almost inescapable presence, the quartz clock disseminated time discipline in a subtler and more comprehensive way than ever before.

As depicted by Chaplin, the mechanization of production required synchronizing the actions of workers in one location, namely, the factory. But the new technological systems such as telephony and radio that characterized the twentieth century required synchronization across vast spaces and political boundaries. Synchronization, in turn, demanded and led to both the widespread availability of accurate time signals and a stronger time consciousness throughout the population. The clock became central to an increasing number of activities, not only in the workplace but also, more significantly, in the home, for such family and leisure activities as listening to or watching broadcasts. Those involved in such activities consequently adopted the concept and discipline of time as marked by the clock. This was not a new development, but it expanded in the twentieth century to encompass a much broader population. Such an expansion could not have taken place without the ubiquity of time signals made available through watches, domestic and public clocks, and time announcements on radio and television, and without the many activities cued by time signals. Historically, it was only the technology of quartz crystal time and frequency measurement, culminating in and symbolized by the quartz clock, that enabled the unprecedented availability of exact time signals and the extensive synchronization and scheduling of daily activities. The result was a time discipline that was on the one hand more subtle, as it was established without explicit compulsion, but on the other hand more powerful, as it had a stronger hold on many more realms of life involving a far greater number of inhabitants of the modern world.

Historians have long recognized that changing concepts of time and of the lives of people vis-à-vis time are central for our understanding of the origins of the modern Western world. Depending on their expertise and understanding of the changing historical roles of the clock, they have concentrated on different epochs, places, and groups, from the origin of the mechanical clock in the European Middle Ages through its evolution in early modern Europe and into the nineteenth century.[1] Both late medieval monasteries and emerging towns have been cited as originating and disseminating the mechanical clock and its usage, leading to a novel conception of time. In an influential article, E. P. Thompson identified the emergence of a stricter and more comprehensive time discipline around the first half of the nineteenth century, which he attributed to British in-

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[1] David S. Landes, *Revolution in Time: Clocks and the Making of the Modern World* (Cambridge, MA, 1983), and Gerhard Dohrn-van Rossum, *History of the Hour: Clocks and Modern Temporal Orders* (Chicago, 1996), suggest general histories of time measurement and clocks in society. References for studies of shorter time spans are given below.

dustrial capitalism and its "puritan ethos."[2] Other historians have pointed out the roles played by astronomers, the bourgeoisie, commerce and technology, and, in particular, transportation and communication in fostering a growing time awareness and a need for coordinated clocks at different locations.[3] The next step in strengthening the power of the clock in daily life during the twentieth century, however, has not received similarly detailed attention.[4]

This article examines the origins and development of highly accurate quartz-clock technologies and the social, technological, and scientific forces that shaped them.[5] To a considerable degree, the pursuit of accurate time determination and

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[2] E. P. Thompson, "Time, Work-Discipline, and Industrial Capitalism," *Past & Present* 38 (1967): 56–97.

[3] Historians have also shown that the increase of time awareness was far from linear and that it varied considerably among different users and social groups. See, for example, Landes, *Revolution in Time*, 53–78; Carlo M. Cipolla, *Clocks and Culture 1300–1700* (New York, 1977); Jacques Le Goff, *Time, Work, and Culture in the Middle Ages* (Chicago, 1980), 29–52; Paul Glennie and Nigel Thrift, "The Spaces of Clock Times," in *The Social in Question: New Bearings in History and the Social Sciences*, ed. Patrick Joyce (London, 2002), 151–74; Glennie and Thrift, *Shaping the Day: A History of Timekeeping in England and Wales 1300–1800* (Oxford, 2009); Michael J. Sauter, "Clockwatchers and Stargazers: Time Discipline in Early Modern Berlin," *American Historical Review* 112 (2007): 685–709; Ian R. Bartky, *Selling the True Time: Nineteenth-Century Timekeeping in America* (Stanford, CA, 2000), 32–44; Carlene Stephens, "'The Most Reliable Time': William Bond, the New England Railroads, and Time Awareness in 19th-Century America," *Technology and Culture* 30 (1989): 1–24; Ian R. Bartky and Carlene E. Stephens, "Comment and Response on 'The Most Reliable Time,'" *Technology and Culture* 32, no. 1 (1991): 183–86.

[4] Historians have examined the spread of the Western notion of time and the development of original views in other societies during the twentieth century, for example, Hashimoto Takehiko and Kuriyama Shigehisa, eds., "The Birth of Tardiness: The Formation of Time Consciousness in Modern Japan," Special Issue, *Japan Review* 14 (2002); Vanessa Ogle, "Whose Time Is It? The Pluralization of Time and the Global Condition, 1870s–1940s," *American Historical Review* 118 (2013): 1376–1402. The creation of the time-zone system based on Greenwich time and the employment of "daylight saving time" at the beginning of the twentieth century have also received attention, but inasmuch as they were connected to the spread of time consciousness, they were mostly the culmination of developments in the nineteenth century rather than an outcome of those originating in the new technologies of the twentieth century. Ian Bartky, *One Time Fits All: The Campaigns for Global Uniformity* (Stanford, CA, 2007). Peter Galison has also studied these issues, examining their influence on physical thought in *Einstein's Clocks and Poincaré's Maps: Empires of Time* (New York, 2004).

[5] I examine the technical, scientific, and experimental research involved in the invention of the quartz clock in more detail in Shaul Katzir, "Pursuing Frequency Standards and Control: The Invention of the Quartz Clock," *Annals of Science* 73 (2016): 1–40, and with a focus on AT&T in "Variations and Combinations: Invention and Development of Quartz Clock Technologies at AT&T," *ICON*, forthcoming; see also 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, 2008), 12–23.

dissemination grew out of the characteristic developments of the twentieth century—the emergence of processes, forces, and organizations that either had not existed or had been considerably weaker in the past. In particular, the quartz clock originated in the formative event of the short twentieth century: the First World War. Further, the technology was shaped and advanced by perhaps the two most central organizational structures of the century: the state and large corporations. Its early history shows both their collaboration and their rivalry: with the development of the quartz clock, a commercial company for the first time successfully employed its own monopolistic economic power to undermine the state's monopoly on standards.[6]

The role of these organizations notwithstanding, in practice the clock was based on and developed through scientific and engineering research, an acknowledged but still underestimated force in shaping the modern world. While relativity and quantum physics attracted popular and historical attention, research in more "mundane" fields of physics such as electricity in crystals and gases provided knowledge crucial for developing the quartz clock. At the beginning of the century, states and corporations started to appreciate that scientific and technological research could sustain and even increase their economic and military power, and they established new kinds of research laboratories that combined scientific and technological research aimed at meeting their needs. Anticipating developments in radio technologies and the feasibility of contriving improved measuring techniques, two of these laboratories played a central role in developing the quartz clock.[7]

By allowing the widespread use of accurate measurement and control in telecommunication, the quartz clock enabled the construction of large centralized systems. Such centrally controlled systems enabled large corporations to dominate their technological fields and to advance a hierarchical view of society at large that was "at odds with America's original democracy." Modern engineers, David Noble has claimed, were "agents of corporate capital." Yet this article shows that some researchers outside corporate laboratories tried to weaken the hold of centralized power and sought to allow individuals and small organizations independent access to the new measurement technology, thus strengthening the position of those smaller entities within the emerging state-regulated networks.

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[6] On the ascent of the corporations and the alternative they offered to the state, see, for example, Alan Dawley, *Struggles for Justice: Social Responsibility and the Liberal State* (Cambridge, MA, 1991), 297–333.

[7] Recently historians have shown growing interest in the way expectations shape historical experience. Technological developments—especially major modern ones such as those discussed here—provide excellent examples, as their developers forecast possible uses of their improved methods in changing environments and feasible ways to develop them. See David C. Engerman et al., "Forum: Histories of the Future," *American Historical Review* 117 (2012).

These researchers manifested a democratic tendency to disseminate technological methods to a relatively large number of users, running counter to the centralized authoritative tendencies of the corporations that wished to control usage of the techniques they developed.[8] As this article will show, the intrinsic scientific and technological properties of the systems themselves tilted the balance toward an open, accessible technology, despite the strong economic power of the corporations.

This was not the only case in which the inherent properties of devices and systems and the scientific and technological knowledge about them constrained technological development and shaped the outcome of the historical process. To understand the emergence of particular technologies and their influence on society, we must explore not only the social and economic interests and consequent needs of different users of those technologies but also the material constraints and internal dynamics of the technologies themselves. The present article thus examines the technological developments that led to the quartz clock in a multiplicity of contexts, including their grounding in science, technology, and preexisting practical methods as well as their evolution in response to the economic, social, and military needs of telecommunication users.

The quartz-clock technologies and the demand for a higher level of synchronization had roots in earlier networks whose coordination required agreement in time measurements. Railway networks, scientific interests, telegraphy, and radio led to high accuracy and standardization in time measurements, which provided the conceptual, technical, and legal framework within which later quartz technologies would develop (Sec. II). New electronic methods for measuring frequency and time originated in research on wireless communication for World War I military uses. These methods were further developed by the British National Physical Laboratory (NPL) and the American Telephone and Telegraph Company (AT&T)[9] in establishing standards for frequency measurement.[10] The NPL needed frequency standards in order to regulate the national and imperial radio network, as did AT&T to integrate its telecommunication system (Sec. III). An expansion of the range of frequencies used for telecommunication, a need to

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[8] Robert H. Wiebe, *Self-Rule: A Cultural History of American Democracy* (Chicago, 1995), 138–61 (quote on 155), emphasizes the role of corporations in the hierarchical order of US society in general; David F. Noble, *America by Design: Science, Technology, and the Rise of Corporate Capitalism* (Oxford, 1979), xxiii, argues that corporations controlled technological development. The development of the quartz clock as presented below suggests a more complex dynamic.

[9] For simplicity's sake I will hereafter use the acronym AT&T, although it was not commonly used at the time.

[10] The standards discussed here are devices and methods for accurately measuring frequency and time. I elaborated on the particular characteristics of these frequency standards in Katzir, "Pursuing Frequency Standards."

limit transmissions to particular values, and the aim of allowing multiple telephone calls on the same wire led AT&T to develop novel methods of crystal frequency control for their standard of frequency and time, resulting in the first quartz clock. A scientific ethos of exactitude stimulated further refinements in the clock's accuracy (Sec. IV). National laboratories developed similar crystal control methods for their own frequency standards and for international comparison and collaboration, as did independent researchers seeking to provide small users flexible control over the frequency of radio transmitters. Both research projects resulted in alternative techniques for constructing quartz clocks (Sec. V). These developments allowed the spread of quartz time technologies, which, as I will argue in Section I, strengthened the grip of objective time and of the clock on modern life. Understanding the origins of these technologies will therefore help us understand the forces that strengthened the role of time and of synchronization in the twentieth century.

I. The Quartz Clock and Stronger Time Discipline

The early twentieth-century Western population showed an increasing awareness of precise time and the need for agreement among different clocks. Uniform clock time became more important as a result of the expanding role of the clock in transportation and the workplace, enabled by the development of timekeeping technologies that allowed for synchronized clock systems and cheaper domestic clocks.[11] Still, the newer technologies of quartz time and frequency measurement constituted a further step in the spread and adoption of time discipline. In particular, these technologies enabled the penetration of time awareness into private and leisure activities, hitherto quite resistant to the rule of the clock. The new technologies strengthened the role of time in society in two ways. First, they led to a dramatic increase in the number and the accuracy of clocks, watches, and other time announcements available to the general population. Second, they allowed an expansion of the number and kinds of actions scheduled by external "mechanical" timekeepers.

Although by 1920 the best pendulum clocks erred by less than 0.01 seconds a day—a level of accuracy far greater than that required for daily needs—the time shown to the public was often surprisingly inaccurate. In 1921 a New York journalist observed that "to obtain accurate time is far from easy in great cities. Naval Observatory service from Washington [providing highly precise time] is

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[11] Ulla Merle, "Tempo! Tempo!—Die Industrialisierung der Zeit im 19. Jahrhundert," in *Uhrzeiten: Die Geschichte der Uhr und ihres Gebrauches*, ed. Igor A. Jenzen and Reinhard Glasemann (Frankfurt, 1989); Hannah Gay, "Clock Synchrony, Time Distribution and Electrical Timekeeping in Britain 1880–1925," *Past & Present* 181 (2003): 107–40. Gay emphasizes that the interest of larger parts of the British population in precision and synchronization was a novel phenomenon.

distributed to a very small part of the population. The public sets its watches by tower clocks, jewelers' chronometers, factory whistles and fire bells, which may vary as much as five minutes." This was still better than "the time as it [was] known to the average New Yorker." "Selecting a typical street [an "electrical man"] walked up one side [of] several blocks and down the other, noting the time displayed on outside clocks maintained by merchants for pedestrians' convenience, inside clocks visible from the street, and jewelers' clocks and chronometers in windows—all of which were running merrily and being taken as a standard by somebody, although they were as much as forty minutes apart!"[12] The situation was probably better in a few large metropolises in western Europe, such as Berlin and London, where some public clocks were synchronized by special systems constructed for that purpose. Still, most Western urban populations (not to mention the rural ones) had no daily access to clocks more accurate than those of New York. Within a few years, however, the emergence of broadcasting would dramatically change the situation. The radio informed listeners about the exact hour many times a day—by frequently announcing the time, by introducing "pips" signals before specific hours, and by scheduling programs at a known regular hour.[13] This allowed individuals to adjust their clocks and watches frequently so that they could keep them accurate enough for their needs. Unlike earlier time-distribution systems, radio did not require advance registration, payment, or special equipment and skills.[14] Hence it spread time announcement to a much broader population than earlier technologies had done. Among other factors, the expansion of broadcasting depended on the quartz-clock technologies of frequency and time measurement. Indeed, as we will see, the quartz clock was invented for and served the needs of electric telecommunication, thereby allowing the distribution of time through electromagnetic waves.

With miniaturization, quartz clocks and watches became inexpensive and thus widely accessible, providing virtually ubiquitous, highly accurate timekeepers for domestic and personal use. By 1913, watches had already become a mass commodity with a world annual output of about 30 million units—a large number for the time, but still very limited in comparison to the more than 1 billion watches exported from China alone in 2012,[15] and even more limited in comparison to the

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[12] James H. Collins, "Electric 'Time Ball': South American System of Adjusting Watches Suggested for This Country," *New York Times*, July 3, 1921, 73; see also Alexis McCrossen, *Marking Modern Times: A History of Clocks, Watches, and Other Timekeepers in American Life* (Chicago, 2013), 174–77.

[13] See Gay, "Clock Synchrony," 128–29, on introducing radio time signals, and Lesley Johnson, "Radio and Everyday Life: The Early Years of Broadcasting in Australia, 1922–1945," *Media, Culture & Society* 3 (1981): 169–71, on time announcements.

[14] On earlier systems, see Gay, "Clock Synchrony," 121–24.

[15] Relative to the population, this is an expansion by about one order of magnitude from one watch to sixty people to one watch to six people (allowing a conservative estimate of the number of Chinese watches produced for domestic use).

total production of quartz timekeepers, only a small portion of which are watches. Quartz clock technology is used not only in domestic, office, and public clocks and watches but also in many electronic gadgets, including every computer and each of the 1.7 billion mobile phones sold in 2012, reaching almost every room and every desk in the world. These ubiquitous timekeepers offer accuracy previously limited to special scientific uses. Common quartz watches were about one hundred times more accurate than their mechanical predecessors. Inexpensive mechanical watches that erred by one to two minutes a day sold in the millions at the middle of the twentieth century, while considerably cheaper quartz watches kept time within one second a day and spared the need for daily maintenance.[16] Quartz clock technologies thus allowed the spread of exact timekeepers to virtually every corner of the world, raising awareness of the exact time and strengthening its role in everyday life.

Quartz-clock technologies not only enabled widespread knowledge of the time but also created a need to act according to the exact objective time. They did so especially through radio and television broadcasting, scheduled according to a central quartz clock and transmitted with the help of quartz-clock technology. Catching trains, which departed at fixed times, raised time consciousness in the nineteenth century—yet a train trip was still a rare event for most people, and even daily commuters did not need to worry about the exact time after they returned home. This situation was changed by radio. Unlike taking a train trip, listening to the radio was a daily activity common to a large urban and rural population. Turning on the radio in time to listen to one's favorite program required knowledge and awareness of the time. This was true when the same show was always scheduled at the same hour and also when sequels were broadcast at different hours and days of the week. In the first case, people often adopted a routine organized by the central clock; in the second, they needed to be alert to the exact time of the transmission at different hours of the day. Listeners' "home lives were placed on strict timetables to fit in with their favourite shows . . . their family life, particularly in the evenings, was organized according to these requirements."[17]

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[16] Figures for the worldwide export of clocks (not including domestic sales) are from: Federation of the Swiss Watch Industry, "The Swiss and World Watchmaking Industry in 2012," http://www.fhs.ch/file/59/Watchmaking_2012.pdf; figures for telephones are from http://www.gartner.com/newsroom/id/2335616; estimation of watch production in 1913 is based on Landes, *Revolution in Time*, 326; on the accuracy of cheap watches, see ibid., 339–40; and Michael Lombardi, "The Accuracy and Stability of Quartz Watches," *Horological Journal* 40 (2008) 57–59. For comparison, highly accurate pocket watches were allowed to err by up to ten seconds a day in 1931. Unlike their quartz successors, their performance deteriorated because of many sources of error and aging. [R. E. Gould], "Testing of Timepieces," *Circular of the Bureau of Standards*, no. 392 (Washington, DC, 1931).

[17] Johnson, "Radio and Everyday Life," 170; on the "domestication" of standard time, see also Shaun Moores, *Interpreting Audiences: The Ethnography of Media Consump-*

Moreover, from the late eighteenth century and into the nineteenth, awareness of the exact time became important for commerce, transportation, and labor. Stricter requirements for working according to the clock in the factory and at schools contributed to the spread of a time discipline that also aroused antagonism.[18] Listening to the radio, in contrast, was usually a leisure-time activity carried out within the family's private sphere at hours when they had not previously cared much about the exact time. In the past, the rule of the clock at home had usually been connected to external obligations. From Kafka to Ken Loach, the alarm clock became a popular symbol for the way social organizations such as the workplace imposed their discipline on the population. No similar compulsion was felt regarding radio. Listeners chose to arrive home or to turn on their radios at a certain time to listen to a particular program. With the voluntary embrace of radio within the domestic sphere, acceptance and adoption of the time discipline suggested by a broadcasting schedule became widespread.[19]

II. Unification and Standardization of Time before World War I

At the beginning of the nineteenth century, time was a local matter, defined by the position of the stars as observed at a specific place. In 1830, for example, when trains connected Manchester to Liverpool, time in the port city lagged that of its eastern neighbor by about three minutes. Noon was defined by the transition of the sun at its highest point in sky, but due to the daily rotation of the spherical earth, the sun reaches that position first in Manchester and three minutes later in Liverpool. By the end of the century, a national synchronization network ensured that clocks in the two cities would show the same legal time, which was valid in the whole of Great Britain. Moreover, this legally binding standard, known as Greenwich time, was also a reference for an international system of time reckoning. The extension of railway networks was the central force behind the transformation of time designations from local to regional and later national and international values.

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tion (London, 1993), 85–88; on the penetration of radio into the domestic realm, see, for example, Paddy Scannell and David Cardiff, *A Social History of British Broadcasting*, vol. 1, *1922–1939, Serving the Nation* (Oxford, 1991), 356–80. The BBC preferred to avoid a fixed scheme for its programs. American stations usually did use a fixed timetable, a policy adopted in many countries and eventually also in Britain (ibid.).

[18] Merle, "Tempo!"

[19] The voluntary embrace of a time regime in domestic leisure time is reflected in sentences reported by interviewers in the 1930s, such as: "Well, I want to be home by nine. There's a good programme on," Scannell and Cardiff, *History of British Broadcasting*, 364. See there also for radio as a leisure activity. For a short discussion of the effect of broadcasting on time discipline, see also McCrossen, *Marking Modern Times*, 244 n. 15.

A railway network required that train traffic be coordinated to enable its flow and to prevent collisions. Knowledge of the time in the various cities in the network and in the trains that departed from those cities was necessary for this end. Different cities could keep different times, but the system required that all these different clocks be synchronized, in the sense that they had to run at the same pace and thus keep constant known differences. The interdependence of train companies, stations, and users made uniform time—that is, one time shared within a large zone—a preferable way of coordinating the railway system.[20] In retrospect, the process stimulated by the trains can be seen as one major stage in tightening time coordination across space, a process that advanced another step following the stronger interdependence of electrical communication from the 1910s.

Notwithstanding the role of transportation, scientific interests and the technological characteristics of the clock also contributed to the standardization and unification of time. The time used by train companies and hence by their users was not the one directly observed by a sundial but a "mechanical time" defined and monitored by astronomers. For their observations, astronomers needed an accuracy and regularity greater than that required by civil life. As the motion of the earth around the sun was known to be nonuniform, astronomers devised a theoretical scheme to calculate the exact time from sidereal observations, producing equal hours, minutes, and seconds along the year. These uniform seconds were manifested in accurate pendulum clocks monitored by astronomical observations. The same kind of uniform time, if not one of similar accuracy, characterized mechanical clocks in general and was adopted by a large segment of society, especially among the bourgeoisie.[21]

Systems of precise time coordination emerged from a combination of national, scientific, and commercial needs and were enabled by technologies of timekeeping and electric communication. The telegraph network provided a means to distribute time signals from astronomical clocks and to synchronize wide areas. In the early 1850s, George Airy, the British royal astronomer, initiated a system of transmitting the time from the Greenwich observatory "directly to the main centres of government and commerce as well as through the country generally." By connecting Greenwich time to the centers of government, Airy and the British officials who sanctioned his move made it the state time (even if not by legislation). Since the observatory itself was a state institute, as most major observatories were, time determination and its distribution became a concern of the state. The state thus became the authority on time and assumed the responsibility of providing exact knowledge of that time to its citizens. Joseph Conrad captured the role of

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[20] Dohrn-van Rossum, *History of the Hour*, 335–50; Bartky, *Selling the True Time*, 19–31, 93–96; Stephens, "The Most Reliable Time."

[21] Sauter, "Clockwatchers and Stargazers."

the observatory in his 1907 novel *The Secret Agent*, in which the Greenwich observatory became a target for an anarchistic bombing directed at a symbol of science and the centralized power of the state. Counterpart observatories in Europe played similar roles in their states. The case was somewhat different in the United States, where university and private observatories provided exact time signals; nonetheless, the most authoritative time signal originated in the astronomical clock of the US Naval Observatory.[22]

In addition to their needs for scrutinizing the sky, observatories needed to know time differences between distant locations in order to determine longitudes—the exact east to west angular distance between places. Exact clocks in both locations and telegraph transmissions assisted in this mission. In 1908 the French suggested addressing the same problem by using the new radio technology to send time signals, accurate to within 1/100 of a second, from the central state observatories. Once broadcast, the new state-approved time signals were received and used by many patrons. Still, until 1922, when time began to be announced in regular broadcasts, these signals were received and interpreted only by special users with an interest in highly precise time measurement and were inaccessible to the general public.[23]

The use of radio waves to send time signals across political borders marked a shift from national to international authority and responsibility for time determination. A discrepancy between the clocks at French and German observatories was one reason for summoning an international conference on time measurement in 1912. The conference decided on the creation of an independent international bureau for the task, similar to the one for weights and measures. This plan did not materialize, but a Union internationale de radiotélégraphie scientifique (URSI) that depended on the various national organizations was eventually established after the First World War. At its second meeting in 1927, two researchers from AT&T, J. W. Horton and Warren Marrison, announced the construction of the first quartz clock.

This connection between radio and time standard was neither accidental nor totally new. Robert Goldschmidt, a Belgian scientist and radio entrepreneur, had initiated the establishment of the URSI during the 1912 conference on time measurements. After the war this private initiative was incorporated as a suborgani-

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[22] Iwan Rhys Morus, "'The Nervous System of Britain': Space, Time and the Electric Telegraph in the Victorian Age," *British Journal for the History of Science* 33 (2000): 466; Bartky, *Selling the True Time*; David Rooney and James Nye, "'Greenwich Observatory Time for the Public Benefit': Standard Time and Victorian Networks of Regulation," *British Journal for the History of Science* 42 (2009): 5–30; Stephen Kern, *The Culture of Time and Space 1880–1918* (London, 1983), 16. On the role of the state centralized bureaucracy, see also Helga Nowotny, *Time: The Modern and Postmodern Experience*, trans. Neville Plaice (Cambridge, 1994), 22–24.

[23] Bartky, *One Time Fits All*, 141–45; Galison, *Einstein's Clocks*, 84–107.

zation of the novel international research council. It was a nongovernmental association that was still organized by national committees. Many of the URSI members worked within state organizations; others worked for telecommunication companies such as AT&T.[24] After the war, both commercial companies and state agencies showed a strong interest in precisely determining radio frequencies—that is, the number of oscillations per second of the radio (electromagnetic) wave. As a measure of cycles per second, frequency is closely linked to time. Its accurate measurement thus required a precise time determination. Since the growing demands of radio, or wireless, communication required high precision in frequency measurement and coordination, it also demanded accurate time measurement. Arguably, radio was the most rapidly expanding and exciting technology of the 1910s and 1920s, attracting numerous researchers and significant investments.[25] One of the fields studied, frequency measurement, resulted in new technologies based on quartz crystals and tuning forks to measure both frequency and time. Electric communication required much higher accuracy than that needed for the railway network, and it presented new challenges to researchers.

III. Tuning-Fork Standards

Horton and Marrison's quartz clock originated in First World War research on accurate means to measure frequencies, carried out mostly by civilian scientists who joined the effort to improve wireless communication following their mobilization for war research. In their work for French military radio telegraphy, the physicists Henri Abraham and Eugène Bloch devised a new method for measuring high radio frequencies (tens of thousands of cycles per second, or Hertz) with the help of the tuning fork, a device long used by acousticians to determine sound frequencies. Exact knowledge of frequencies was necessary for Abraham and Bloch's project of improving the novel amplifier that had come into use: the triode, an electronic vacuum tube with three electrodes (fig. 1) that was the central device beyond contemporary 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

[24] Bartky, *One Time Fits All*, 146–48; B. Guinot, "History of the Bureau International de l'Heure," in *Polar Motion: Historical and Scientific Problems—IAU Colloq 178* (2000), 175–84; Jean Van Bladel, "The Early History of URSI," in *SNRV 75 år*, ed. Gerhard Kristensson (Lund, 2009), 1–12; Sylvie Lausberg, "Robert Goldschmidt (II)," *Le soir* 23, no. 7 (1998); Bruno Brasseur, "Robert Goldschmidt," *Hallo, hallo, hier radio Laken . . .*, 78–87, http://bruno.arnebrasseur.net/wordpress/wp-content/uploads/2011/10/07-Robert-Goldschmidt3.pdf.

[25] Hugh G. J. Aitken, *The Continuous Wave: Technology and American Radio, 1900–1932* (Princeton, NJ, 1985); Susan J. Douglas, *Inventing American Broadcasting, 1899–1922* (Baltimore, 1987).

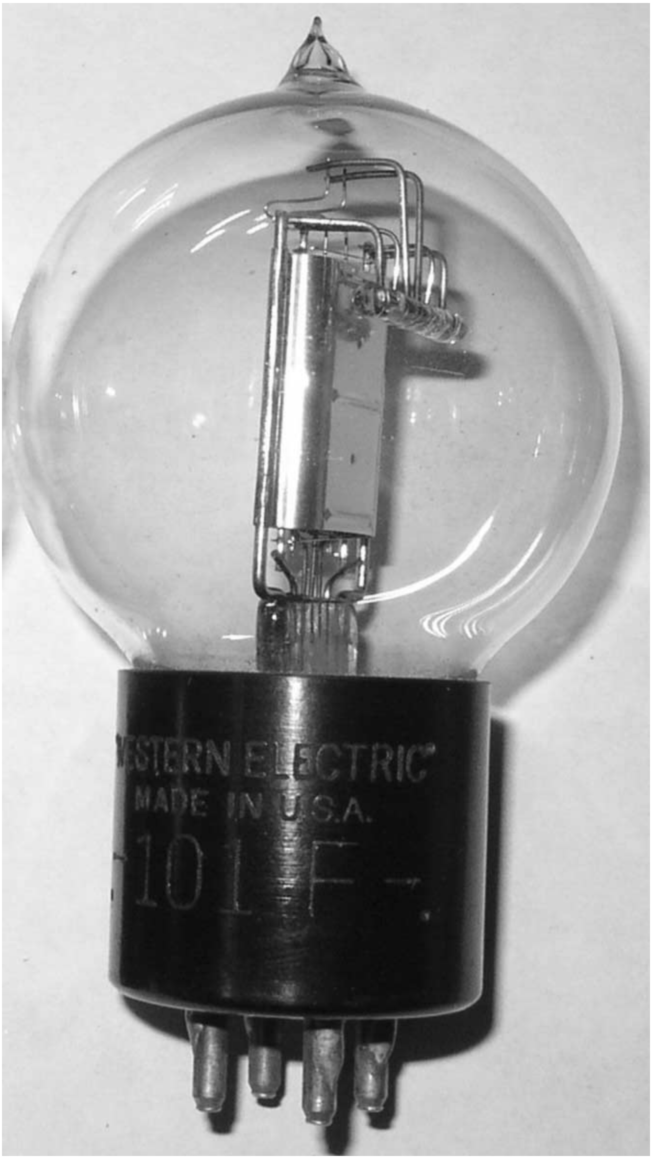

FIG. 1.—A triode (an electronic vacuum tube with three electrodes), Western Electric (the manufacturing arm of AT&T) 101F, about 11 cm high. Picture from stonevintageradio.com.

space of low-density air ("vacuum") and two or more electrodes (three in the case of a triode), allowing an electric current ("discharge") under specific conditions. Abraham and Bloch utilized the triode in a new device, which they termed a "multivibrator," to multiply the frequency of the tuning fork to reach radio frequencies. Their method enabled comparing the radio oscillations with the vibrations of the tuning fork and then to the period of an astronomical clock that served as a highly accurate time standard. Abraham and Bloch devised this method for the immediate needs of their research on improving the triode for war radio communication, but its high accuracy stemmed from their own scientific attitude as well as from a nineteenth-century scientific tradition of exactitude in using the tuning fork.[26]

Abraham and Bloch further devised a triode circuit that could oscillate at the steady frequency of a tuning fork incorporated in that circuit. Although accuracy was one of their broad concerns, their initial aim in designing this apparatus was to amplify currents at low known frequencies for use in the military wireless. A similar goal of measuring amplification power had motivated William Eccles, an engineering professor and radio expert, in his war research in England. Unlike his French colleagues, however, Eccles had already considered the combination of tuning forks and triodes for radio before the war for commercial reasons. He had tried, albeit unsuccessfully, to circumvent a patent of the German company Telefunken.[27]

Indeed, even before the war, telecommunication had already entered a period of massive changes because of the development of the new vacuum tubes. Since John Fleming's 1904 invention of the electronic valve, many inventors had improved and modified the device for multiple uses in radio: as a current rectifier, an amplifier, a sender, and a receiver. Invented by the independent scientist Lee de Forest, the triode and methods for its use were extensively developed by the research laboratory at AT&T for application in telephony. Physicists at the laboratory exploited findings and methods from electron physics, which had emerged

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[26] Henri Abraham and Eugène Bloch, "Mesure en valeur absolue des périodes des oscillations électriques de haute fréquence," *Journal de physique théorique et appliquée* 9 (1919): 211–22; David Pantalony, *Altered Sensations: Rudolph Koenig's Acoustical Workshop in Nineteenth-Century Paris* (Dordrecht, 2009). The history of tuning-fork measuring standards is discussed in more detail in Shaul Katzir, "Frequency and Time Standards from Acoustic to Radio: The First Electronic Clock," in *Standardization in Measurement: Philosophical, Historical and Sociological Issues*, ed. Laura Huber and Oliver Schlaudt (London, 2015), 111–24.

[27] Henri Abraham and Eugène Bloch, "Entretien des oscillations d'un pendule ou d'un diapason avec un amplificateur à lampes," *Journal de physique théorique et appliquée* 9 (1919): 225–33; W. H. Eccles, "The Use of the Triode Valve in Maintaining the Vibration of a Tuning Fork," *Proceedings of the Physical Society of London* 31 (1919): 269; J. A. Ratcliffe, "William Henry Eccles: 1875–1966," *Biographical Memoirs of Fellows of the Royal Society* 17 (1971): 198.

in the late nineteenth century, and they continued to explore new questions relevant for understanding the behavior of the vacuum tube. In particular, the new device allowed for amplification of the diminishing signals of long-distance telephone calls, considered a strategic aim by the heads of the company, enabling the first (and highly publicized) transcontinental conversation in 1915. Even though the big corporation had developed the triode for telephony, other organizations and researchers, notably those developing military communications, refined and applied the improved tube for radio, where it opened new possibilities, many of which were realized only after the war.[28]

The rapid technological development of radio techniques during the war boosted the expansion of wireless communication in the war's aftermath. While commercial companies and the armed forces expected such growth in using electromagnetic waves to transmit messages between a limited number of stations (e.g., from a shore station to ships) to replace and extend telegraphy and telephony, they did not expect the emergence of public broadcasting—that is, one broadcaster sending signals to a large number of listeners. Yet, broadcasting was a second major factor driving the expansion of radio communication in the early 1920s—an expansion that suggested new applications for the tuning-fork technology developed during the war. The British NPL developed frequency-measuring methods based on the tuning fork for the government to regulate and improve communication, two functions that required similar technological solutions but achieved two different governmental aims.

One aim was to improve military communication, and especially naval communication, which required electromagnetic waves of increasing frequencies for communicating over long distances. David Dye at the NPL provided accurate standards based on a tuning fork for measuring these hitherto unused frequencies. Here the state, through the military, played the role of a user of the technology much like other users, such as commercial companies, which in the late 1920s helped to fund the endeavor. The state also took on the role of an impartial regulator of civil radio. As a regulator it needed, among other things, to provide a standard for measuring frequencies in order to require each transmitter to keep within its own allocated band. To prevent interference between transmissions, the regulator had to ensure that each transmitter was transmitting waves only at the frequencies allocated to it.[29] To allow a high number of transmitters to operate simultaneously, the useful radio spectrum had to be divided into small units. This required some officially approved means to measure precisely the actual frequency

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[28] Leonard S. Reich, *The Making of American Industrial Research: Science and Business at GE and Bell, 1876–1926* (Cambridge, 1985), chap. 7; Gerald F. G. Tyne, *Saga of the Vacuum Tube* (Indianapolis, 1977).

[29] An electromagnetic wave is defined either by its frequency or its wavelength; each determines the other.

in use. Given the social and economic interest in providing greater access to radio communication, accuracy became an imperative.[30]

Primarily with the intention of regulating telecommunication, the NPL constructed a standard of radio frequencies to serve as a basis for any such measurement in the United Kingdom. Dye and his colleagues connected the circuit controlled by the stable period of the tuning fork to Abraham and Bloch's multivibrator for reaching high frequencies. To confirm the stability of their frequency standard, they further drove a chronometer by the tuning-fork circuit and compared it to a standard pendulum clock. This chronometer was not a full tuning-fork clock, but it ran for up to a week, reaching an impressive agreement of three parts in 10 million (10^7) with the standard pendulum clock. As it coupled frequency with time measurement, it can be seen as a precursor of the quartz clock. The laboratory was able to inform interested users of the frequency of this primary standard by transmitting wireless waves of known wavelength and by portable circuits used as secondary standards.[31] In this way the NPL played a role equivalent to that of the Greenwich observatory in determining the value of a standard and distributing it to the interested public. The state kept its role as the arbiter of magnitudes and measurements as part of its capacity of supervising commerce, industry, transportation, and communication.

Founded in 1900 on the model of the German Physikalisch-Technische Reichsanstalt (PTR), the National Physical Laboratory was nonetheless a new kind of research institute of the modern state that differed from the long-established observatory. Unlike the observatory, its main aim was not to assist state organs such as the navy (although it also did that) but to foster national industrial growth. Just as important were the means through which the laboratory was expected to foster such growth by combining research in physics with research in technology. Such research laboratories aimed at a stronger and more effective combination of science and technology than was common in either industry or the university. It originated from the view, quite common but still contested, that scientific research about phenomena pertinent to technological processes was crucial for the successful growth of key modern "science-based" industries. In the commercial sector, research laboratories first appeared in the German chemical industry in the late 1870s. At the beginning of the twentieth century, research laboratories spread into the electrical and telecommunication industries, which hired qualified physicists

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[30] Douglas, *Inventing American Broadcasting*, 292–314; David Dye, "The Valve-Maintained Tuning-Fork as a Precision Time-Standard," *Proceedings of the Royal Society of London*, ser. A, 103 (1923): 240–60; Annual Reports of the National Physical Laboratory (Teddington) for the years 1920 (p. 63), 1923 (p. 84), 1924 (p. 77), 1926 (p. 11), 1928 (p. 13).

[31] Dye, "Valve-Maintained Tuning-Fork"; D. W. Dye and L. Essen, "The Valve Maintained Tuning Fork as a Primary Standard of Frequency," *Proceedings of the Royal Society of London*, ser. A, 143 (1934): 285–306.

to carry out research on a regular basis. By the end of World War I, General Electric and AT&T, the largest corporations in those two fields, maintained strong, vibrant, and well-funded research laboratories. Unlike research carried out in the state laboratories, the research in these industrial institutes was directed at answering the specific interests of their corporations. The means to reach those ends, however, were similar to those employed by the state laboratories, namely, original research that combined scientific and technological approaches to matters of industrial interest.[32]

In the case of frequency determination, however, the state and the commercial interests overlapped. While the state coordinated wireless communication in its territory to prevent clashes, AT&T sought not only to coordinate but also to integrate its own telecommunication system, known as the "Bell system." The corporation regarded its "interdependent, intercommunicating, universal system" as a strategic advantage over smaller competitors, which could not offer a similar service, and a justification for its monopoly. Its slogan "One System, One Policy, Universal Service" reflected its business strategy, namely, to construct an integrated system that would allow each user to connect to any other subscriber to the system.[33] Such a system required coordinating the various wired and wireless techniques used by the world's largest and most complex communication network. Earlier, AT&T had hardly exploited frequencies beyond those used in speech (up to a few thousand hertz). Yet, the rapid development of electronic-based radio during the 1910s changed that. The corporation adopted new radio techniques that allowed transmission of the human voice over a distance to complement its extensive wired network and the array of services it provided. It also developed new methods, known as multiplex telephony, to multiply the number of conversations that could be transmitted over its wired network. These methods utilized oscillations at a wide spectrum of frequencies from hundreds to millions of hertz. A common standard for measuring these oscillations was a prerequisite for coordinating the expanding number of methods in use, since it was necessary for comparing the signals transmitted

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[32] Russell Moseley, "The Origins and Early Years of the National Physical Laboratory: A Chapter in the Pre-History of British Science Policy," *Minerva* 16 (1978): 222–50; David Cahan, *An Institute for an Empire: The Physikalisch-Technische Reichsanstalt, 1871–1918* (Cambridge, 1989); Reich, *American Industrial Research*; Ernst Homburg, "The Emergence of Research Laboratories in the Dyestuffs Industry, 1870–1900," *British Journal for the History of Science* 25 (1992): 91–111.

[33] For example, Reich, *American Industrial Research*; Robert MacDougall, "Long Lines: AT&T's Long-Distance Network as an Organizational and Political Strategy," *Business History Review* 80 (2006): 297–327; the quotation is from AT&T president Theodore Vail in 1910, on 303. Milton Mueller, *Universal Service: Competition, Interconnection, and Monopoly in the Making of the American Telephone System* (Cambridge, MA, 1997), 92–103.

in them, and was thus essential for the corporation. Its construction was a task given to a group of researchers with backgrounds in physics and engineering headed by J. W. Horton, a physics graduate, at the corporation's research department.

Like David Dye's group at the NPL, Horton's group employed the triode-tuning-fork techniques developed during the war to construct a frequency standard that could be used to "cover the entire range between a few cycles per second and several million," and whose "absolute value . . . is known to be one part in 100,000." Put into practice in 1923, this standard surpassed the system of the NPL in two respects. First, it operated continuously, providing a reference that could be always consulted; and, second, it drove its own clock, controlled by the vibration of the tuning-fork circuit—the first electronic clock. Through this clock the researchers monitored the precision of their frequency standard by continuously comparing its rate to that of a pendulum clock and to the time signals received from the Naval Observatory's astronomical clock, ensuring its high accuracy.

Using the wired and the wireless network of the corporation, this new standard allowed the dissemination of unprecedentedly exact frequencies to the remote parts of the Bell system. Already in 1921 the group employed a preliminary standard, located in New York, to calibrate equipment in Havana.[34] As a large corporation, AT&T preferred to develop its own system of standards rather than to depend on the standards given by the US National Bureau of Standards (known today as the National Institute of Standards and Technology). From AT&T's perspective the issue was too important to be left to outsiders. The company was large enough to warrant a full system for its own use, making the expenses (amounting to a few years of work and some equipment) inconsequential in comparison to the financial benefits of the system. Still, the big corporation did not completely dispense with the help of the state. It continued to monitor its frequency standard against the navy's astronomical clock.

IV. AT&T's Quartz Clock

Novel electronic devices and further research on the behavior of electromagnetic waves led to a continuous increase in the range of the frequencies useful for communication in the 1920s. Beyond the previously used radio waves (still used today for AM broadcasting), the so-called short waves were found to be useful for long-distance communication. Radio experts continued to explore waves shorter than "short waves" (i.e., waves of higher frequency) and exam-

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[34] 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): 730–41, 730; Katzir, "Pursuing Frequency Standards," 5–10.

ined their application for different uses. Some of these uses, such as radiotelephony and television, were high-stake fields for AT&T. Consequently, by 1928 the corporation required a frequency standard that would reach frequencies of several hundred million hertz, a hundred times higher than five years earlier. In light of these concrete technological demands, Horton's group had to extend its accurate standard to higher frequencies. Further multiplying the oscillation of their tuning-fork circuit was possible, but it required a delicate, and thus problematic, procedure.[35]

Moreover, while the tuning fork could be used to measure the frequency of a radio transmitter, it did not offer a practical method of setting its frequency to a particular value. In 1923–24, however, such a method of frequency control became almost imperative as the corporation developed a system of national broadcasting. To prevent mutual interference, two nearby transmitters either had to use totally different frequencies or had to keep their frequencies at the same value within 50 hertz (i.e., to a difference of less than one in ten thousand). Since the corporation wanted to cover large areas with the same programs, and it used quite a few transmitters, it opted to keep the frequencies at the same value, which required coordination between all the transmitters.[36] As with the early trains, which employed clocks for this end, coordination was gained by providing instruments that oscillated at an identical pace—not properly clocks but devices for frequency control. In both cases, as well as with earlier overseas navigation, the extension of the territorial units led to a tighter form of synchronization (of time, or of frequency). Radio waves, moreover, traversed economic and political boundaries more quickly and easily than trains. Therefore, their use in one place often influenced reception in distant locations. To prevent mutual interference, regulating agencies required users to keep strictly within their allocated radio frequencies. The problem of interference between distant transmitters intensified in the shortwave region where transmissions reached the far ends of the earth, indicating a need for a global coordination. Radio technology thus challenged compartmen-

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[35] 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): 1101–23; Russel W. Burns, "The Contributions of the Bell Telephone Laboratories to the Early Development of Television," *History of Technology* 13 (1991): 181–213; Burns, *Television: An International History of the Formative Years* (London, 1998), 220–41; Joseph W. Horton and W. A. Marrison, "Precision Determination of Frequency," *Proceedings of the IRE* 16 (1928): 142.

[36] Chen-Pang Yeang, "Characterizing Radio Channels: The Science and Technology of Propagation and Interference, 1900–1935" (PhD diss., Massachusetts Institute of Technology, 2004), 327–56; Hugh Richard Slotten, *Radio and Television Regulation: Broadcast Technology in the United States, 1920–1960* (Baltimore, 2000), 24–26; Warren Marrison to William O. Baker, 12.7.1977 (AT&T Archives loc: 86 08 03 02).

talization by political and economic territories, even when its users did not attempt to challenge boundaries.[37]

The new method of crystal frequency control provided AT&T with an answer for the two technological problems mentioned above: establishing a standard for high frequencies and controlling radio frequencies. Like the tuning-fork frequency standard, crystal frequency control originated in war research, albeit not from attempts to improve communication but rather from an effort to locate submarines. The strategic threat posed by German U-boats led to concentrated research on submarine detection in France and Britain. In early 1917, following an idea of the Russian émigré inventor Constantin Chilowsky, the French physicist Paul Langevin designed a practical method for locating submarine objects by reflecting ultrasonic waves off of them, a method known today as sonar. To produce the ultrasonic waves and to detect their faint echoes in ocean waters, Langevin employed the piezoelectric effect in quartz. The piezoelectric effect is the phenomenon by which a change of pressure on certain crystals generates opposite charges at its ends and the converse effect where electric voltage induces mechanical pressure in the crystal. Since its discovery in 1880, scientists had examined piezoelectricity and its relations to broader issues in physics and crystallography as "pure science" unrelated to any possible application—but the utilization of piezoelectricity for sonar changed that. Suddenly, Langevin's vibrating piezoelectric crystal became the object of intense practical research by the Allied scientists and engineers.[38]

With the end of hostilities, one of these researchers, Walter Cady, an American physics professor, turned his attention to an open-ended, and in this sense scientific, study of vibrating piezoelectric crystals unrelated to their use for submarine detection. He soon discovered that when quartz crystals vibrated at their "resonance frequency" (the frequency at which they provide the lowest resistance to vibration) their electrical properties changed sharply. Moreover, he observed that the crystals kept a highly stable resonance frequency. These natural properties of the crystals suggested to Cady that quartz crystals embedded in electronic circuits could be used as frequency standards for the radio range. Furthermore, in early 1921 he devised a method of harnessing the vibrating crystals to control the frequency of electronic circuits, forcing the circuits to oscillate at

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[37] The interwar period is portrayed as an era in which territoriality became a strong organizing principle in human affairs; yet frequency allocation and synchronization in telecommunication suggest that contrary globalizing forces were already active during that time, even if the principle of territoriality was not shaken until the 1970s. Charles S. Maier, "Consigning the Twentieth Century to History: Alternative Narratives for the Modern Era," *American Historical Review* 105 (2000): 807–31.

[38] Shaul Katzir, "Who Knew Piezoelectricity? Rutherford and Langevin on Submarine Detection and the Invention of Sonar," *Notes and Records of the Royal Society* 66 (2012): 141–57.

the known stable resonance frequency of the quartz. Like his colleagues at AT&T, Cady realized that techniques for controlling frequencies could find many important applications in telecommunication.[39]

Researchers at AT&T were not the only ones who adopted crystal frequency control for their needs. They were, however, unique in employing it for the two distinct, though connected, aims of establishing standards and controlling the frequencies of their senders. Other commercial companies, such as General Electric, the Radio Corporation of America (RCA), and Westinghouse, also studied, developed, and employed crystal frequency control for radio transmitters. Yet they did not have a clear interest in measurements and standards. AT&T was the only corporation that devoted a great deal of research to absolute measurement, due to its interest in integrating its complex system.[40] National research institutes that developed standards, such as the Bureau of Standards, the NPL, and the PTR, on the other hand, did not develop methods for controlling transmitters' frequencies. The combination of the two aims within the same group at the AT&T research laboratory led to concentrated research on piezoelectric techniques. Even when the applicability of the quartz crystal to the corporation's primary frequency standard seemed questionable, research continued, since the method was still deemed useful for controlling frequencies in its broadcasting system. A basic standard for the Bell system should have reached not only the high frequencies exploited by new radio techniques at the high end of the spectrum but also the low frequencies at the lower acoustic end of the spectrum. Moreover, only oscillations at low frequencies could drive a clock mechanism and thus enable a comparison between the rate of the corporation's basic standard and the astronomical standard of time. This comparison was necessary in order to establish a standard that could replace the tuning fork. To reach these relatively low frequencies, it was necessary to devise a method that would produce oscillations at an exact known fraction of the high frequency of the quartz resonator. AT&T needed such a method for use in multiplex telephony as well. The financial benefits were obvious, as these novel methods would obviate the need to multiply expensive copper wires. Yet multiplex telephony exploited fre-

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[39] 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): 469–87; Katzir, "War and Peacetime Research on the Road to Crystal Frequency Control," *Technology and Culture* 51 (2010): 99–125.

[40] Christopher Shawn McGahey, "Harnessing Nature's Timekeeper: A History of the Piezoelectric Quartz Crystal Technological Community (1880–1959)" (PhD diss., Georgia Institute of Technology, 2009), 111–12, and passim. In 1928, Bell Labs was mentioned along with the Navy Department and the Bureau of Standards as the only US organizations making absolute measurements of piezo-resonators. I have found no hint of interest in the task from a commercial company outside the United States. J. H. Dellinger, "The Status of Frequency Standardization," *Proceedings of the Institute of Radio Engineers* 16 (1928): 582.

quencies lower than those produced by the quartz crystals.[41] To employ crystals for that end, the corporation needed a way to reduce their high frequency. A few specific technological aims thus converged at the telecommunication giant because of its size and its comprehensive character—that is, its interest in controlling, or at least using, the various practical means of voice and picture telecommunication.

Within Horton's group, the design of a reliable method for reaching an exact known fraction of a high-input frequency was assigned to a subgroup headed by Warren Marrison in 1924. Marrison, who had an academic education in physics and practical experience in radio, had suggested and experimented with quite a few methods, most of them based on electronic manipulations. In January 1927 he designed a rather complex circuit that he and his colleagues found powerful and stable enough to incorporate into a new frequency and time standard based on a quartz crystal. By summer, the group had constructed the first quartz clock as part of the corporation's frequency standard. Like the tuning-fork system, which it replaced, the new standard enabled the corporation to reach a wide range of frequencies. Furthermore, the new quartz standard improved on the accuracy of its predecessor and could disseminate a highly exact frequency value and thereby an exact time standard for the whole Bell system, and thus for almost any corner of the United States. Each electromagnetic wave of an exact frequency carried with it the rate of the standard and the clock located at the company's laboratory in New York.[42]

The quartz clock driven by the crystal resonator reached an accuracy of one hundredth of a second a day, equal to that of the best contemporary pendulum clock, the culmination of 250 years of horology. The accuracy of the new standard exceeded the immediate needs of the Bell system (although similar high needs were forecast). Still Marrison kept refining the system to improve its accuracy. From a purely practical perspective, one can observe here an excess of precision, suggesting the influence of forces not directly connected to business aims, even in the research inside the commercial company. One of these forces was the power of inner technological dynamics, which calls for further refinements of an existing system—especially when, as in this case, the system in question was a new one open to substantial improvements. Another such force originated in an ethos of exactitude in science and especially in metrology, where accuracy was regarded as an end in itself. This ethos and related practices

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[41] E. H. Colpitts and O. B. Blackwell, "Carrier Current Telephony and Telegraphy," *Transactions of the American Institute of Electrical Engineers* 40 (1921): 205–300.

[42] Marrison notebooks 1444 and 2161 from 1924–1927, in AT&T Archives; Katzir, "Pursuing Frequency Standards," 12–17; Horton and Marrison, "Precision Determination of Frequency"; Warren A. Marrison, "A High Precision Standard of Frequency," *Proceedings of the Institute of Radio Engineers* 17 (1929): 1101–22.

had roots both in the exact sciences and in the traditions of high-end artisans, including clockmakers and makers of scientific instruments.[43] Although Marrison's quartz clock was developed for the specific needs of electronic communication, scientific research led to the new frequency-control method and the scientific ethos of exactitude contributed to the high level of precision that it attained.

V. A Few Roads to a Quartz Clock

One could, it seems, end the story at this point, viewing the invention of the quartz clock as a result of the following factors: the developing field of electronic telecommunication, the mobilization of scientists and engineers for World War I research, the monopolistic interests of AT&T, and the scientific research that enabled the technological innovations. This, however, would be only a partial picture of the developments that led to the quartz clock and the conditions that spread the technology. While AT&T constructed the quartz clock to ensure its monopoly, other organizations developed technologies for dividing the high frequency of the crystal resonator that enabled the construction of a quartz clock for a few different and even contradictory aims (table 1). As mentioned above, AT&T was concerned with integrating its system; similarly, national laboratories had an interest in coordinating and regulating telecommunication within their own spheres of authority. Measurement units, however, were viewed as universal quantities, which should have an accepted global value. The fact that radio transcended political borders further highlighted the need for international agreement. Consequently, national laboratories conducted an international comparison of standards, disseminating quartz measurement techniques that would lead to an additional method for constructing a clock. Technologies for reaching a known fraction of an input frequency could be used not only for central control of radio communication (as had been done by Bell and the national agencies) but also for self-control and decentralization. Other agents thus developed related technologies that would allow accurate, inexpensive, and relatively simple manipulation of radio frequencies, enabling smaller users to cope with the increasing level of precision in the field. This impetus toward decentralization originated in the competition inside the private sector and, more significantly, in academic research that aimed at assisting independent users. This impetus and the research in the national laboratories resulted in a dissemination of accurate quartz techniques to a large group of users. Moreover, it led to a variety of meth-

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[43] J. L. Heilbron, *Weighing Imponderables and Other Quantitative Science around 1800* (Berkeley, CA, 1993); Klaus Hentschel, "Gauss, Meyerstein and Hanoverian Metrology," *Annals of Science* 64 (2007): 41–75; M. Norton Wise, ed., *The Values of Precision* (Princeton, NJ, 1995).

Table 1
Methods Enabling the Construction of Quartz Clocks

Date	Inventor	Organization	Immediate Aim	General Goal
Jan. 1927	Marrison	AT&T	precise wide-range frequency standard	integrating the Bell system
Feb. 1927	Clapp	Shortwave lab, MIT	obtaining many frequencies from one quartz standard	developing inexpensive radio methods
June 1927	van der Pol & van der Mark	Philips	unclear whether there was a specific aim	improving radio electronics
Aug. 1927	Vecchiacchi	Italian naval laboratory	measuring quartz frequency; high frequency standard	frequency standards for radio
Late 1927?	Dye	NPL	precise frequency standards for radio range	regulating electromagnetic communication

ods for constructing a quartz clock, which prevented AT&T from monopolizing the device and enabled its spread.

Like his counterparts at AT&T, Dye at the British NPL looked for a substitute for its laboratory tuning-fork standard that would cover the increasingly high frequencies used in radio communication by the armed forces, by amateurs, and by commercial companies. By early 1928, he had constructed a complete frequency standard based on quartz. As a complete system, it included a quartz clock driven by the same resonator that determined the frequencies for comparing its pace to that of an astronomical clock. By the time the details of a more elaborate system were published six years later, the laboratory had built one of the most exact clocks to date. The lengthy research on the frequency and time standard reflects the high priority given to accuracy in the laboratory—an accuracy important for maintaining the state's role as the arbiter on standards. Indeed, the NPL was widely recognized for its expertise in setting high standards of measurement.[44]

With all his interest in accuracy, Dye had not begun research on the employment of quartz before Cady arrived at the NPL with his piezoelectric resonator in 1923 to compare the British standard with other national frequency standards. The initiative for this international comparison was Cady's own, although he had no official role either in government or in a corporation with an interest in the re-

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[44] Dye and Essen, "Tuning Fork as Primary Standard"; Dellinger, "Frequency Standardization," 582; Katzir, "Pursuing Frequency Standards," 23–24.

sults. He suggested using his new quartz frequency standard as a universal yardstick for the American Bureau of Standards, which supported the initiative. Cady also enjoyed the collaboration of the French, Italian, and British civilian and military laboratories responsible for determining frequencies in their countries. The internationalist spirit that characterized the exchange of knowledge in science and technology seemed to influence Cady and his partners at the various laboratories. Still, internationalism did not always prevail over national political considerations: in the aftermath of World War I, the comparison by Cady's group left out Germany despite its important scientific establishment. Yet the waning of the boycott on German science helped lead to the inclusion of the German PTR in the international comparisons that were organized by the Bureau of Standards between 1925 and 1928 and facilitated the spread of piezoelectric frequency techniques to Germany.

Beyond the interest of these institutes in accuracy, which required that all laboratories agree in their measurement of frequency, other practical considerations also prompted global coordination. Since radio waves traversed territorial boundaries, commonly accepted standards for measuring their frequencies were required. Agreement about precision in time measurement, as manifested through frequency determination, was needed not only for exact geodesic measurement at the beginning of the century but also for the daily coordination of radio communication. After regular broadcasting had made radio transmission international in the relatively narrow territorial scope of the European states, shortwave technology made it global. The different laboratories modified and refined their frequency-measuring methods to agree both with one another and with absolute time measurement by astronomical clocks. These governmental agencies thus advanced the globalization of frequency standards. While private corporations were seen as a major force of globalization in the late twentieth century, they contributed little to this process, probably because their international character was not strong at the time. Scientists and engineers, in contrast, took an active role in the international distribution of knowledge and methods for constructing and coordinating standards. They published their findings, read one another's contributions, and implemented new ideas in their own systems.[45]

This global exchange led to the invention of another method that enabled the construction of a quartz clock by Giancarlo Vallauri and his assistant Francesco

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[45] The exchange of information between these laboratories can be seen in the similarities between methods used in different places and the references to foreign methods and publications; some of these are mentioned in Dellinger, and in W. G. Cady, "An International Comparison of Radio Wavelength Standards by Means of Piezo-Electric Resonators," *Proceedings of the Institute of Radio Engineers* 12 (1924): 805–16; Dellinger, "Frequency Standardization"; Brigitte Schroeder-Gudehus, "Challenge to Transnational Loyalties: International Scientific Organizations after the First World War," *Science Studies* 3 (1973): 93–118.

Vecchiacchi at the Italian Navy's Istituto Elettrotecnico e Radiotelegrafico. It was only the international comparison effort that prompted the Italian institute to study piezoelectric resonators. In preparing for the second comparison organized by the Bureau of Standards in summer 1927, the Italian team modified a method that had been used previously by researchers at the Bureau of Standards. Comparing the frequency of their own tuning-fork standard to that of a crystal oscillator, they found unexpectedly that the crystal control circuit could "lock" the frequency of a connected circuit. In view of the task associated with their participation in the international comparison, Vecchiacchi suggested a way to use this effect for dividing the frequency of the crystal to allow direct comparison of its high frequency to a clock. The product of this method was equivalent to those of Marrison and Dye. The Italians did not construct a clock mechanism, however; they were satisfied with comparing their frequency standard to an external clock for merely 135 seconds. Vallauri and Vecchiacchi's concern for high accuracy did not match that of Dye or Marrison, and they did not construct a permanent standard based on their method.[46]

A similar aim of using crystal frequency control in radio led James Clapp to devise his own method for reducing the high frequencies of the quartz resonator. Based on the known multivibrator, which hitherto had been used only to multiply frequencies, his method could be used to drive a quartz clock. Clapp worked at the shortwave research laboratory of MIT, which had been established by its department of electrical engineering with funds from the radio enthusiast Colonel Edward Green. Although it was an academic institute, the MIT laboratory shared the interest of the national laboratories in employing scientific methods for the advancement of technology, in this case especially for the benefit of independent radio operators (small broadcasters and amateurs). The development of sophisticated measuring instruments allowed regulating agencies to require higher stability in the frequencies employed by such users, who often could not afford to buy the expensive instruments that were needed to comply with the regulations. In February 1927, Clapp had these users in mind when he established a relatively cheap and uncomplicated method for accurately reaching many frequencies from one affordable quartz crystal oscillator.[47] His work grew out of a democratic, egalitarian impetus to use technology as an opportunity to empower individuals, including the poor (without aiming at economic equality). In this case, Clapp aimed to decentralize the power to determine exactitude, so that

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[46] G. Vallauri, "Confronti fra misure di frequenza per mezzo di piezorisuonatori," *L'Elettrotecnica* 14 (1927): 445–52; Vallauri, "Confronti fra misure di frequenza per mezzo di piezorisuonatori," *L'Elettrotecnica* 14 (1927): 682–84; Francesco Vecchiacchi, "Applicazione all'oscillografo catodico della demoltiplicazione statica di frequenza," *L'Elettrotecnica* 15 (1928): 807.

[47] James K. Clapp, "'Universal' Frequency Standardization from a Single Frequency Standard," *Journal of the Optical Society of America* 15 (1927): 25–47.

a large number of radio experts and amateurs would have that ability without being dependent on big corporations and state agencies. This effort ran counter to that of AT&T, which invested in exactitude in order to preserve its monopolistic power.[48] Still, Clapp did not suggest any radical change; his system was based on authorizing standards, as the certified factory value of the piezoelectric oscillator was the basis of the procedure. His contribution was to suggest a way in which individuals might conform to the shared standard rather than having to establish their own independent ones. As with the diffusion of clocks, the spread of this exact measurement method enabled amateurs to attain stable and precise frequencies, and in the process to adopt the discipline of the frequency standard.

The same tendency toward decentralization of power can be seen in Clapp's construction of a quartz clock for the General Radio Company (GR), a modest-sized company that specialized in producing measurement instruments for small laboratories and radio amateurs. In 1928 he worked with the physicist Lewis Hull on a system for calibrating secondary crystal frequency standards, which the company marketed for radio stations. The system relied on one stable "primary" quartz oscillator, which also drove a clock mechanism using the method that Clapp had developed at the shortwave laboratory. Clapp and Hull used the clock to monitor the frequency of the crystal by comparing it to the time signals from the navy astronomical clock. Their system attained a precision that had previously been achieved only by large organizations such as national laboratories or AT&T. Moreover, while national and large commercial laboratories—such as the NPL, Bell Labs, and, following them, the PTR—constructed quartz clocks only for their own use, GR soon designed and constructed its own quartz clock and put it on the market. This clock was still a rather large laboratory device, but it nonetheless contributed to the process of decentralization. Moreover, it was a forerunner of the domestic and personal clocks and watches that followed the miniaturization of electronics in the 1950s.[49]

While AT&T had filed a few patents related to the quartz clock, it could not employ them to control the field since other organizations used alternative

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[48] On the view that the new electric technology offered a route toward a more egalitarian and decentralized society, see Thomas P. Hughes, *American Genesis: A Century of Invention and Technological Enthusiasm, 1870–1970* (New York, 1989), 232, 284–85, 303–5.

[49] In 1930, AT&T declined to sell a quartz clock to scientists from California. Instead it directed them to General Radio (AT&T Archives loc. 80 002 02 08). Later the company as well as national laboratories did construct a few clocks for special uses. Lewis M. Hull and James K. Clapp, "A Convenient Method for Referring Secondary Frequency Standards to a Standard Time Interval," *Proceedings of the Institute of Radio Engineers* 17 (1929): 252–71; McGahey, "Harnessing Nature's Timekeeper," 212–18; Carlene Stephens and Maggie Dennis, "Engineering Time: Inventing the Electronic Wristwatch," *British Journal for the History of Science* 33 (2000): 477–97; Michael Schuldes, "Erste tragbare, batteriebetriebene Quarzuhr der Firma Patek Philippe," in Graf, *Die Quarzrevolution*, 52–61.

methods for dividing the high frequency of the quartz resonator. The limited power of patents in this case was first suggested by the work of Balthasar van der Pol. In February 1927, van der Pol pointed out the general properties of a family of electronic circuits that can oscillate at a stable fraction of an incoming high frequency. This showed that one was not restricted to any specific method to reach the kind of low frequency needed for a quartz clock. With an assistant, Jan van der Mark, he implemented the idea and suggested an original method for frequency "demultiplication." This method could be used to drive a clock mechanism by a quartz resonator, although the two Dutch researchers did not apply it to that end.[50]

By pointing out that the ability to attain stable fractions of high frequencies is shared by a family of circuits, van der Pol contributed to the democratization of frequency and time determination. Yet this was an unintended consequence of his research. A respectable young physicist, van der Pol worked at the research laboratory of the large Dutch electric company Philips pursuing a long-term study of the triode, central to the new markets to which the company was expanding. This research led him to a new equation for the device and for electronic circuits more generally, and to new mathematical solutions.[51] Philips did not share the shortwave laboratory's mission of assisting independent radio operators. Van der Pol's insight about this family of oscillators shows, rather, that sometimes technical-scientific systems have intrinsic properties that determine the conclusions drawn from studying them. In this case, his conclusion favored decentralization by showing that AT&T could not hold a monopoly on the production of quartz clocks. Denying AT&T's monopoly on the technology strengthened the power of the quartz clock itself by facilitating its distribution. Technological systems thus should not be seen as passive material that can be shaped toward any ends that socioeconomic powers might desire; rather, they should be recognized as having an active influence over the way humans develop and use them. Still, while the multiplicity of methods for reducing frequency strengthened decentralization, the use of crystal frequency control to determine highly accurate frequencies allowed a high degree of coordination that was useful for the centralized needs of big corporations and for the regulative power of the state.

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[50] Balthasar van der Pol, "Über 'Relaxationsschwingungen' II," *Jahrbuch der drahtlosen Telegraphie* 29 (1927): 118; Balthasar van der Pol and J. van der Mark, "Frequency Demultiplication," *Nature* 120, no. 3019 (September 1927): 363–64.

[51] Marc J. de Vries, *80 Years of Research at the Philips Natuurkundig Laboratorium (1914—1994): The Role of the Nat. Lab. at Philips* (Amsterdam, 2005) (with contributions by Kees Boersma), 33–63; Katzir, "Pursuing Frequency Standards," 30–35.

VI. Conclusion

Researchers developed the quartz clock in response to the emerging need for greater precision in frequency measurements and control in electronic communications. During the First World War, scientists working on radio invented new electronic methods for determining wireless frequency for military communication. In the aftermath of the war, exact frequency standards became imperative for the monopolistic business strategy of AT&T, which aimed at providing unified telecommunication and broadcasting services. State agencies also required precise frequency measurement standards, in their case to regulate the fast-expanding radio communication network. Consequently, groups at AT&T and the NPL developed tuning fork–based electronic standards and connected them to a clock mechanism. Yet, due to an expansion of the radio spectrum and to commercial and military interest in controlling frequencies, these and other laboratories turned to the new crystal frequency-control technology. The new method also allowed a still higher level of accuracy in measuring frequency and time. This striving for perfection originated not only in the unprecedented need for precision in electronic communication but also from a scientific ethos of exactitude. While researchers at the big corporate and government laboratories developed the technology in order to regulate and control radio traffic, other researchers saw in frequency control a way of empowering independent actors in the field. New electronic methods allowed independent users to stay competitive while accommodating the higher level of precision imposed by technological needs and the states. Moreover, although researchers at AT&T and national laboratories could construct and maintain more precise quartz clocks than those at smaller organizations, they could not monopolize the new timekeeping technology due to the diverse interest in the electronic technology and its intrinsic properties.

Answering a number of related but distinct aims, a few researchers developed methods that allowed the construction of quartz clocks. Time as such and its distribution were far from their initial interest. For most, time remained at best a marginal concern. Yet, their work had a greater influence on the general population's attitude toward time than did the space-time concept of relativity theory, notwithstanding the revolutionary character of the latter and its elaboration by contemporary philosophers.[52] The increased power of clock time was an unplanned and indirect result of the dynamics of telecommunication technology, with its growing demand for high accuracy in frequency measurements and control, which induced researchers to construct methods for accurate time measurement. Techniques for sending oscillations at exact frequencies also allowed the spread of time values. For Marrison and Dye, the high accuracy attained by their

[52] For example, Kern, *Culture of Time and Space*, 16–35.

instruments made time determination a considerable concern in its own right. More importantly, electronics made knowledge of exact frequency and time relevant for more than just the few experts in their measurement. Frequency, and therefore time, became important for the engineers who developed telecommunication techniques, as well as for the operators of the vast wired and wireless communication networks, if not for the end users. People speaking over the telephone could be oblivious to the need to keep clocks vibrating at the same pace in Chicago and New York so that their voices would be recognizable; yet they were conscious of the clock when they turned on their radio receivers to hear the news or their preferred entertainment programs. For that purpose they lived by the sender's clock, which depended on the use of quartz technology.

In 1939, AT&T installed a modern public clock at its headquarters in downtown Manhattan, presenting its command of time as part of its technical mastery of modern telecommunication. Governed by the corporation's quartz frequency and time standard, and advertised as "the world's most accurate public clock," the device publicly displayed the connection between telecommunication and exact time synchronization and the leading role played by AT&T in its technology. A modern design based on a new principle of timekeeping helped to convey a notion of progress (fig. 2). Public clocks were commonplace at the time, and it was common for private businesses to present the time to the public. Yet, the accuracy of such clocks relied, directly or indirectly, on governmental time standards. AT&T, however, claimed to be more accurate than governmental public clocks and independent of the time service of the state.[53] While American corporate capitalism took over the governmental roles of conducting foreign policy and caring for their workers' welfare,[54] AT&T challenged the symbolic monopolistic power of the state to regulate life under its domain by substituting for the state in producing standards.

Just as with earlier public clocks, people used to set their own watches to the exact time shown by the hands of the new AT&T quartz clock. In late eighteenth-century Berlin, such a practice was essential for the spread of the astronomical time. Watching the observatory's exact clock was still important for clock makers who wanted to calibrate their own clocks in nineteenth-century Paris. At the middle of the twentieth century, however, the practice did not carry a similar significance; the pace of the clock, and the discipline it could convey, found additional routes reaching many more people, not least through communication net-

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[53] Warren A. Marrison, "The Evolution of the Quartz Crystal Clock," *Bell System Technical Journal* 27 (1948): 561; Landmarks Preservation Commission, July 25, 2006, Designation List 379 LP-2194, *American Telephone & Telegraph Company Building*, http://www.nyc.gov/html/lpc/downloads/pdf/reports/ATT_Ext.pdf. In its advertisements AT&T emphasized both accuracy and interdependence; see, for example, *Popular Mechanics* (March 1952), 2.

[54] Dawley, *Struggles for Justice*, 297, 322–23.

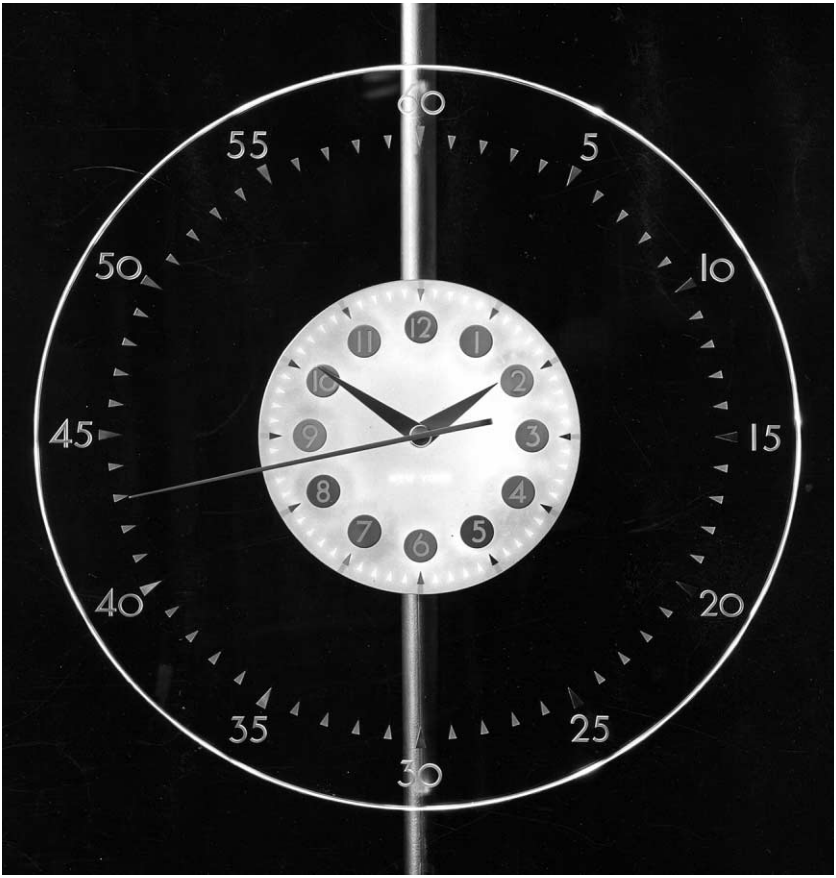

FIG. 2.—AT&T public clock at 195 Broadway in 1940. The clock was displayed behind a glass window and was itself made of glass and metal. Its long second hand and clearly marked seconds assisted passers-by in viewing the exact time. Courtesy of AT&T Archives and History Center.

works like the one of AT&T. Its public clock served mainly as a visual manifestation of the accurate methods that the corporation had already applied to regulate frequency and time throughout its system, also reaching laypeople through regular radio programs, time announcements, and designated time services.[55]

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[55] Passersby setting their watches can be seen in AT&T's advertisements and also in a short film probably from ca. 1950 at https://www.wpafilmlibrary.com/videos/102297. On setting watches by earlier public clocks, see Sauter, "Clockwatchers and Stargazers"; Alexis McCrossen, "'Conventions of Simultaneity': Time Standards, Public Clocks, and Nationalism in American Cities and Towns, 1871–1905," *Journal of Urban History* 33 (2007): 234.

Modern telecommunication did not just disseminate the notion of time and its knowledge; it was also the driving force behind the development of the new primary timekeepers—electronic tuning forks and quartz clocks—and systems for distributing their values. Marrison and Horton at AT&T, like Abraham and Bloch, Eccles, Dye, Clapp, and others elsewhere, developed methods for the precise measurement and determination of time for specific needs of radio and telephony. Electronics was central not only in specifying technical needs but also in providing resources for answering those needs. Scientific research, partly performed independently from any application, provided complementary resources that were necessary for the development of the quartz clock, as well as an ethos of pursuing high exactitude. Beyond the specific needs of short waves or multiplex telephony that were required for developing the particular technologies lay the requirement for coordinating and therefore synchronizing the telecommunication system. Even more than rapid transportation methods in the nineteenth century, electronic telecommunication in the twentieth century allowed spatial distances to be overcome and encompassed in integrated networks. Telecommunication thereby contributed to the enlargement and expansion of modern technical and social systems and the interdependence between those systems and their parts. That increased interdependence, however, required higher levels of spatial coordination, itself acquired through the higher level of synchronization presented by the quartz clock. That in turn allowed a greater degree of integration across spatial distances, also beyond that field. AT&T's public clock, for example, was connected to a subsystem that had already provided the time reference for New York electric light and power services. Systems for synchronizing clocks across various networks, like the announcement of precise time in broadcasting, introduced information not only about the exact time and its pace but also about the ethos of exactitude and time discipline to expanding circles of the population.

The crucial role of technological and scientific dynamics in creating such a quotidian instrument as the quartz clock, with its vast influence on the cultural notion of time, shows the significance of the history of technology and science for understanding the twentieth century. This significance goes beyond a few large, famous projects—often, like the atomic bomb, connected to warfare—to encompass more common methods and gadgets that shaped modern life. It also goes beyond conceptually revolutionary fields such as relativity and quantum physics to mundane fields of science that stimulated consequential technological developments. A historical account of the emergence of the modern world requires an understanding of such scientific and technological developments and their interaction with the physical and social world. In other words, "general historians" should place science and technology within the scope of general histories.