HAROLD ALDEN WHEELER

Figure1. Harold Alden Wheeler, born 10 May 1903, is a recipient of the IEEE Medal of Honor and a current resident of Ventura, California.

CHAPTER 5

From Automatic Volume Control to the Stationmaster Antenna

Harold Alden Wheeler and Applied Electronics

For the United States the year 1930 may be regarded as the beginning of the golden age of radio.[1] By that time some 600 stations were broadcasting, many of them around the clock, and 46 percent of all households had receivers. In that year Lowell Thomas established the lasting institution of the nightly news, delivered electronically. That was when Rudy Vallee started the first of the radio "variety shows" that soon became immensely popular. Serial drama and comedy were rapidly gaining listeners; "Amos 'n' Andy" first went on the air in 1928, "The Rise of the Goldbergs" in 1929, and "Death Valley Days" in the following year. And classical music, supplemented by instruction in music appreciation, was being broadcast regularly; 1930 saw live opera broadcasts, including one from Dresden, Germany, and the beginning of the regular transmission of Sunday concerts of the New York Philharmonic Orchestra.

It was, no doubt, the aficionados of classical music who were then particularly eager to purchase the most advanced Philco radio, the Screen Grid Plus, which had appeared on the market in the fall of 1929. This radio, known as the Model 95 (see Figure 2), boasted an unusually even response across the audio frequencies (giving "balanced" reception) and a new feature, diode AVC (automatic volume control).

Automatic volume control, which had earlier been available only in a more expensive and less effective form, was a remedy to two problems: the tendency of distant stations to fade and swell, and "blasting," which happened whenever one encountered a local station in tuning the radio. The Model 95 was a phenomenal success, and it helped make Philco the leading radio manufacturer in 1930 and throughout the decade.[2]

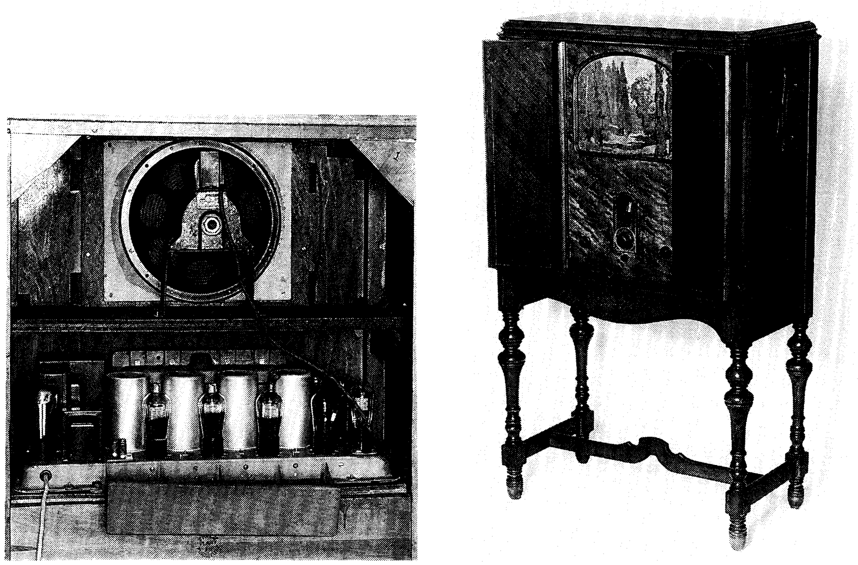


Figure 2. The chassis of the Philco Model 95, also known as the Screen Grid Plus, is shown on the left. It was sold in cabinets of varying style and quality; one of them is shown on the right.[3]

Just three years earlier Philco, the Philadelphia Storage Battery Company, appeared doomed: Its two principal products—batteries for radios and rectifiers to allow radios to be powered by house current—were suddenly rendered obsolete by the availability of AC tubes.[4] It was at that point that the company decided to manufacture radios and turned to a radio-engineering firm, Hazeltine Corporation, for expertise in a field new to Philco. The design of the Model 95, like the design of Philco's first radio, the Model 76, was largely the work of a young engineer at Hazeltine, who incorporated into the design his own invention of diode AVC. That young engineer was Harold Alden Wheeler.

Growing up in South Dakota and Washington, D.C.

Wheeler belongs to the generation of electronics engineers who grew up on crystal radios.[5] He was born in 1903, when Guglielmo Marconi, R. A. Fessenden, John Stone Stone, and many others were working to improve and find a market for the infant technology of wireless transmission. Wheeler's father, William Archie Wheeler, taught agronomy at the South Dakota State College in Brookings until 1907, when he moved to Mitchell, South Dakota, to manage the Dakota Improved Seed Company, which he had helped found. In 1916 he accepted a position with the US Department of Agriculture in Washington, D.C. Wheeler's mother, née Harriet Maria Alden, was thought to be a descendent of John and Priscilla Alden, made famous by Longfellow.

As a boy, Wheeler was fascinated by two technologies just emerging in the first decade of the century: aviation and wireless communication. He remembers the awe evoked by wireless, as when an itinerant lecturer came to Mitchell to demonstrate radio signaling or when an older boy in town used a spark transmitter to steer a model boat. By the time the family moved to Washington in 1916, Wheeler, who had just then completed seventh grade, had decided on radio engineering as a career.

In a workshop in the garage (later the basement) of the family home, Wheeler built simple electrical devices, including an electric motor and galvanometers for measuring weak currents. He attached a crystal detector and headphones to bedsprings and a radiator pipe to listen in on Navy radio signals during the period of US involvement in World War I. After the war he continued his experiments, building several receivers and a transmitter. To qualify for an operator's license he attended evening classes at the National Radio Institute, and in April 1920 he received a license for an amateur station (see Figure 3). In November of that year, the station KDKA in Pittsburgh began regular broadcasting, and this greatly increased the attraction of radio as a hobby. In late 1921 Wheeler built an audio amplifier and a loudspeaker and thereafter often invited large groups of people to the house to listen to KDKA and other stations.[6]

His son's hobby alerted Archie Wheeler to the possibilities of using the new technology for the benefit of farmers. In 1920 he established, as a service of the Department of Agriculture, the Radio Market News Service, which brought the latest market reports to farmers.[7] (Figure 3 is actually a picture of Wheeler receiving the first broadcast of the Radio Market News Service on 15 December 1920.) The father's involvement with radio proved subsequently to be of great value to the son.

College Years

In 1921 Wheeler graduated from Central High School and, having won a scholarship by competitive examination, enrolled at George Washington University. This allowed him to live at home while attending college, which was a great advantage because, as he put it, "at home I had my basement laboratory where I spent more time than I did studying, and that was the beginning of my later career."[8] With his father's assistance, Wheeler obtained summer employment in 1921 and 1922 at the Radio Laboratory of the National Bureau of Standards (NBS), which was directed by John Howard Dellinger.[9] Here he gained experience with some of the most advanced techniques and devices in radio engineering and also became acquainted with many leaders of the new field, such as Frederick Kolster and John M. Miller.

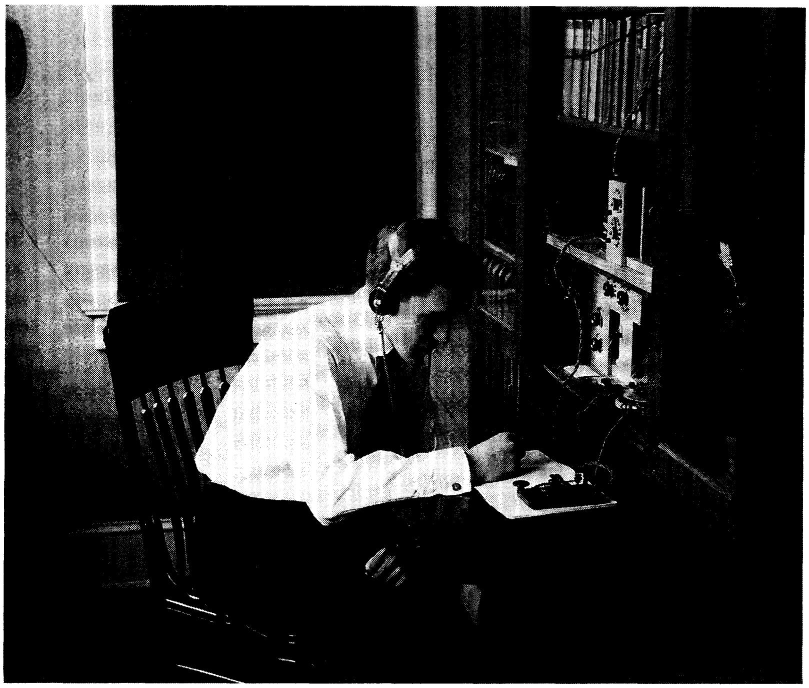


Figure 3. Wheeler and the apparatus for amateur station 3QK.

At that time one way people sought to improve radio reception was by placing a tuned radio-frequency (TRF) amplifier ahead of the detector. The major difficulty was that internal feedback often caused oscillations (heard as whistles or squeals) in the triode vacuum tube used as amplifier. In July 1922 Wheeler devised a circuit to neutralize the internal feedback, and a few days later he built and tested the circuit in his home laboratory.

This invention and a chance meeting the following month set the direction of Wheeler's career. He was accompanying his father on a business trip that in-cluded a visit to a seed company in Hoboken. At a restaurant there, they encountered Alan Hazeltine, professor at nearby Stevens Institute of Technology, who knew Archie Wheeler because both were members of the National Radio Conference, which was organized in 1921 by Secretary of Commerce Herbert Hoover to bring order to the chaos of radio broadcasting. Hazeltine invited the two of them to stop by his office at Stevens that afternoon.

At Hazeltine's office, Wheeler described his neutralized TRF amplifier. Hazeltine, greatly surprised, said that he had made the same invention about three years earlier—he showed Wheeler a pending patent application—but had not implemented it in practice. Two months later, at Hazeltine's suggestion, they discussed an arrangement for cooperation. Wheeler agreed to give Hazeltine rights to some related inventions in exchange for 10 percent of any royalties for the neutralization patent.[10] It was agreed further that Wheeler would work for Hazeltine the following summer. The connection between Hazeltine and Wheeler proved to be a lasting one.

Hazeltine joined the electrical engineering department of Stevens Institute of Technology in 1907 and became department head in 1917. (See Figure 4.)[11] Like Dellinger of the NBS Radio Lab, Hazeltine worked to make a science of radio engineering, as in his 1918 paper, "Oscillating audion circuits," which was the first mathematical treatment of oscillating vacuum-tube circuits.[12] During the war Hazeltine designed for the Navy the radio receiver SE-1420, which went into wide use. In 1922 a group of radio manufacturers asked Hazeltine to design a radio receiver that incorporated his invention of neutralization. These manufacturers were seeking a radio design that would not infringe Edwin Armstrong's patent on the regenerative tube detector, the rights to which were held by RCA. Hazeltine's receiver, called the "Neutrodyne," sold so well that the fourteen companies licensed to produce it could not keep up with orders.[13] It dominated the market until 1928, when the availability of screen-grid tubes for amplification made it obsolete.

In early 1924 Hazeltine established Hazeltine Corporation to manage the neutralization and other patents and to provide engineering services (mainly advice on product designs) to licensees. Wheeler, who had worked for Hazeltine the previous summer, was employed, as he puts it, "for all the time I could make available while continuing my college work."[14] Hazeltine became Wheeler's mentor, teaching him to take a theoretical and experimental approach to design problems. Hazeltine's style is expressed in his statement, "My inventions . . . have all been the result of theoretical studies, verified and modified by subsequent experimental work."[15] Wheeler acknowledges a great debt to Hazeltine, saying, "From the time of our accidental meeting in 1922, he indoctrinated me in his imaginative and creative approach to any problem."[16]

In 1925 Wheeler completed a B.S. in physics and, as further preparation for a career in engineering, continued his study of physics at Johns Hopkins University. (Wheeler took his father's advice to study physics rather than electrical engineering on the grounds that EE education at the time was superficial in its treatment of the relevant science.) In these years, beginning with summer employment in 1923, he was giving more and more of his time to his work for Hazeltine Corporation, and in 1928 he left Hopkins, without quite completing the requirements for a Ph.D., to work full-time for Hazeltine.

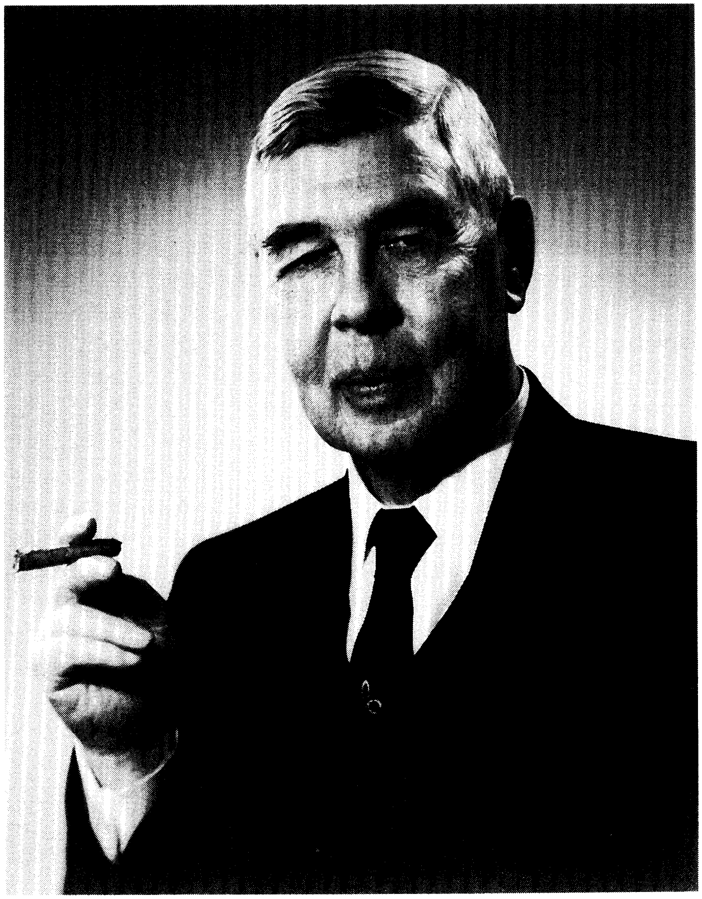


Figure 4. Louis Alan Hazeltine (1886–1964), radio pioneer, professor at Stevens Institute of Technology, and founder of Hazeltine Corporation. He was elected Fellow of the IRE in 1921, Fellow of the AIEE in 1935, and President of the IRE for 1936.

In the three years at Johns Hopkins, Wheeler did important work on several projects not connected with Hazeltine Corporation. He assisted

Gregory Breit and Merle Tuve in 1925 in designing a "pulse transformer" that Breit and Tuve used in their famous measurement of the height of the ionosphere (by reflecting radio pulses off of it).[17] Wheeler made a theoretical study of wave filters composed of repeating sections.[18] He also worked with E. Cowles Andrus, a researcher at Johns Hopkins Hospital, to design and build a device for studying the refractory period of the heart (the period after the initiation of contraction during which the heart is not responsive to electrical stimulation).

Life at Hopkins was a very leisurely experience. They had a small dormitory for graduate students where I had two rooms that I shared with one of my friends. Meals were served inexpensively. So I was in direct contact with the graduate students, mostly in physics and chemistry. The quality of education, however, was not that great. They had qualified professors—some were famous—but the science of education hadn't permeated colleges yet. So the method of education was not terribly good. Nevertheless by attending Johns Hopkins I did gain a broader perspective on physics, at a leisurely pace.

. . . I was commuting to New York at least once a month and [working there] during summers. I was able easily to keep up with the pace and continue these outside activities.

Interestingly, one of these outside activities was the building of a pulse transformer. Among my colleagues and friends as graduate students were Breit and Tuve, who became famous in later years for their work with the ionosphere. [With] Tuve I had a particularly close affiliation because he also came from Minnesota. One evening after dinner they cornered me, and they said, "We've got a problem. We're making a transmitter for high-powered pulses to send up to the ionosphere and reflect back again. And we need a transformer, and we don't know how to make a pulse transformer." Well, during the summers I had worked with Hazeltine, one of the projects he was working on involved what was then unknown—a pulse transformer—and I was familiar with its workings. I translated that knowledge to Breit and Tuve's requirement, and I designed the first radar pulse transformer. It worked in their experiment.[19]

Automatic Volume Control

It was in the summer of 1925 that Wheeler made perhaps his most important invention, that of automatic volume control, also known as automatic gain control. As stated above, this circuit, incorporated in the Philco Model 95, alleviated the problems of "blasting" and fading. Wheeler described the invention in a 1928 article in the *Proceedings of the IRE* [20] (see Figure 5), and in the 1930s it became a standard feature of AM radios. It is still standard. The fiftieth anniversary edition of *Electronics* magazine, which appeared in 1980, contained a section entitled "Classic circuits," which presented twelve circuits that "have been basic to the commercialization of radio, TV, and computers and other data-handling systems." Wheeler's automatic volume control was one of the twelve.[21]

Diode AVC, though invented in 1925, was not immediately used in radio circuits because it was difficult to get much radio-frequency (RF) amplification ahead of the detector, and diode AVC functioned by using the level of the signal in the detector to control the gain in the RF amplifier. When the screen-grid tube, which was very effective as an RF amplifier, became available in 1928, this difficulty was removed. Thus it was that the Philco Model 95, which came out in 1929, was the first commercial radio to incorporate diode AVC.

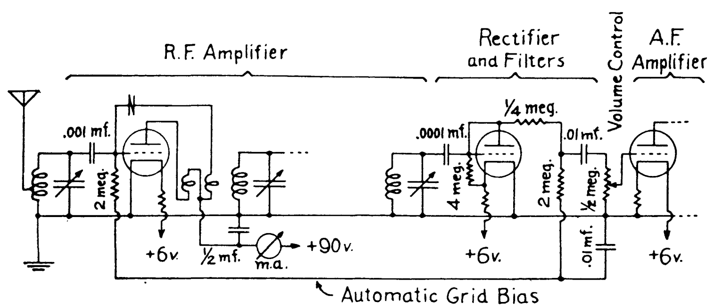


Figure 5. Diode AVC, the circuit Wheeler designed in 1925 for achieving automatic volume control in radio receivers.

The availability of the screen-grid tube had another effect: It rendered obsolete the neutralization that was at the heart of the Neutrodyne receiver. The only source of income for Hazeltine Corporation was the royalties it received from those licensed to use its patents; companies received a blanket license for all Hazeltine patents together with engineering services of Hazeltine engineers. Since the key patent in the Hazeltine portfolio had been the neutralization patent, it was fortunate for the company that just at that time the diode AVC patent became very important, helping to retain current licensees and attracting new ones.

In the summer of 1925, just after graduating from George Washington University in Washington D.C., I went to work a third summer in the Hazeltine Corporation laboratory. It was located in a few rooms in the attic of the Electrical Engineering building of Stevens Institute of Technology in Hoboken, New Jersey, across the Hudson River from New York City.

I was impressed with the amount of RF amplification in the latest designs of tunable receivers for radio broadcasting. Connected with an outdoor wire antenna, the sound level on local stations was so great that a "volume control" was needed to reduce the *sound to a level suitable for listening. There were two tuning dials for antenna circuit and RF amplifier so a "third hand" was needed for the volume control. I perceived that an automatic control was needed to set the sound volume at a desired level for all stations. Then the volume control knob could be set once for all stations within range. I soon decided that the automatic control should be applied to the RF amplifier ahead of the detector and AF amplifier. I aimed to do that by developing from the detector a bias voltage sufficient to control the gain in the RF amplifier if applied to the control grid of one or more of the RF amplifier tubes.*

It was customary to operate the detector with a rather small signal voltage because it was difficult to design a large amplification ahead of the detector in the TRF amplifier. I investigated various circuits for amplifying the small rectified voltage in the detector, but these circuits were complicated and required critical adjustments.

In the fall of 1925, I entered the graduate school in Johns Hopkins University in Baltimore, near my home in Washington. I planned to make a receiver with automatic volume control during the Christmas holidays in my basement laboratory at my home. I decided on a superheterodyne circuit to obtain sufficient RF amplification ahead of the detector. It was my first because that type of receiver was not in common use outside RCA (they refused to license its use by other companies). My design was an advance over others because I used a neutralized intermediate-frequency (IF) amplifier at a frequency only slightly below the broadcast band (550–1600 MHz). This was a preview of later practice when the superheterodyne went into universal use a few years later, in 1930.

I built this receiver on a work table. It was later preserved for exhibit in litigation so a photograph is available. It is now preserved in a showcase at the Hazeltine Corporation headquarters in Greenlawn on Long Island, New York. It incorporated a modular design on eight small wooden bases. I had accumulated the necessary parts before the holidays. There were tunable circuits for the antenna, local oscillator, and four IF circuits. The construction of the receiver took only a few days and its operation was spectacular.

Then I approached the problem of obtaining from the detector a bias voltage for automatically controlling the amplification in the first one or two of the IF stages. I had entered in my notebook some rather complicated circuits using the usual triode detector. One problem I recall was the unavailability of resistors of values intermediate between wire-wound (up to 1000 ohms) and graphite "grid leaks" (around 1 megaohm). I needed some around 10 to 100 kiloohms. Also, those circuits required a floating "B battery" in addition to the common grounded B battery for all amplifier stages. For a few days, I was making little progress.

Then it occurred to me that I had enough amplification to use a diode rectifier as the detector, operating at 10 volts of IF signal. The diode would be made of the available triode with grid and plate connected together. This was heresy, to sacrifice the gain of one triode, costing about $5 apiece (about $100 in today's currency). However, the greater RF (IF) gain made up for the customary gain in a triode detector, so I still needed only two audio (AF) stages to drive the loud speaker. I quickly connected the diode with resistors and capacitors to provide separately the audio (AF) signal voltage and the bias (DC) voltage for control of the first one or two IF stages.

I got around to entering the theory of these connections in my notebook a few days later (January 2, 1926). This was the date we established later for "reduction to practice."[22]

Full-time at Hazeltine Corporation

When Wheeler began full-time employment for Hazeltine in 1928, his first assignment was to develop a standard signal generator for use in testing radio receivers. The device that he and a coworker built was far in advance of anything being used at the time. This was typical of Hazeltine Corporation, which then and in the 1930s led the industry in the development of test equipment. Indeed, the ability of Hazeltine engineers to measure the performance of circuits and components played a large role in the company's success. Wheeler has said, "I can't overemphasize the theme of testing equipment as being a real limitation on the rate of progress."[23]

This was an area to Wheeler's liking, partly, as he put it, "because you didn't have to worry about the market price as you did in receiver design."[24] His most important invention in this area was what he called the "piston attenuator." It was customary, in testing a radio receiver by means of a standard signal generator, to reduce the signal in steps using a ladder network of resistors. Wheeler succeeded in constructing a device that permitted continuous variation of the signal strength. Its name came from its cylindrical form and the fact that one electrode was moved along the axis of the cylinder.[25] This was a forerunner of propagation waveguides, which assumed great importance in the development of radar; indeed, the piston attenuator was reinvented during World War II at MIT's Radiation Laboratory, where it was called a "waveguide beyond cutoff."

Test equipment remained one of Wheeler's principal interests, as a list of his publications suggests. A device to make a photographic record of the frequency variation of the sound from a loudspeaker and a device to measure very small inductances are examples of his work in the 1930s.[26] In 1962 he was invited to write for the fiftieth anniversary volume of *Proceedings of the IRE* a review paper entitled "Microwave measurements."[27]

From the start of his full-time employment at Hazeltine in 1928 until World War II, Wheeler continued work on radio circuits. In the 1930s a principal aim of radio engineers was to lower the price of receivers; Hazeltine engineers, by designing inexpensive superheterodyne receivers, led the industry in this area. Hazeltine excelled also in evaluating loudspeakers—as part of the 1930s movement toward "high fidelity"—and in designing so-called "all-wave receivers" (which could also receive short-wave transmissions from Europe) and, at the end of the decade, FM receivers. In addition, Wheeler says, "we developed some extremely sophisticated broadcast receivers with automatic controls, most of which never reached the commercial market."[28] For use with diode AVC, Wheeler invented a tuning meter, which showed the change of amplification effected by the AVC and which is named for its usefulness as an aid in tuning; various forms of it soon appeared in radio receivers, one being the RCA "Magic Eye."[29]

Wheeler attributes his success in radio design to his taking a scientific approach to problems, which came from his training in physics and the indoctrination in this approach he got from Hazeltine. By the time of US entry into World War II, Wheeler had received more than a hundred US patents. In addition, he published a number of important papers on radio receivers; next in importance to his 1928 paper on diode AVC was probably the lengthy "Theory and operation of tuned radio-frequency coupling systems" coauthored by William A. MacDonald, chief engineer of Hazeltine.[30] Several quite theoretical papers he wrote on FM reception were influential.[31]

Patent Litigation

The story of the development of radio can hardly be told without considerable discussion of patent litigation. Lee De Forest, Edwin Armstrong, and David Sarnoff—three of the most prominent radio pioneers—were all involved in lengthy court battles. The uncertainty of patent rights in the United States no doubt stimulated both infringement and litigation and probably slowed technical progress.[32] In the 1920s, Hazeltine Corporation defended one of its licensees (Garod Corporation) against a suit brought by RCA, charging that the Neutrodyne receiver infringed two patents owned by RCA, and Hazeltine Corporation brought suit against a number of companies for infringing its neutralization patent. Wheeler often served as an expert witness in these cases.

In the 1930s there were a number of cases that concerned Wheeler's patent on diode AVC.[33] Many radio manufacturers were licensees of Hazeltine, so had unquestioned right to use the invention. A number of companies, including RCA and Detrola, used it without taking a license. First, Hazeltine Corporation sued RCA for infringement. After a full trial, but before a decision was given, RCA agreed to take a license. Hazeltine then sued Detrola for infringement. A Federal district court ruled the patent valid and infringed, and this decision was unanimously upheld by the circuit court of appeals. Detrola then appealed to the Supreme Court. In a unanimous decision in 1941, the Supreme Court reversed the verdict of the lower courts, saying, "We conclude that Wheeler accomplished an old result by a combination of means which, singly or in similar combination, were disclosed by the prior art and that . . . he was not in fact the first inventor, since his advance over the prior art, if any, required only the exercise of the skill of the art."[34]

Wheeler explains the adverse decision as resulting largely from the failure of the Supreme Court to make a careful study of this case (suggested by the unanimity of the decision) and its long-term bias against enforcing patent rights. In the first half of this century, partly because patents were seen as monopolistic devices, it became more and more difficult to obtain a court ruling that a patent was valid and had been infringed. Of all patent cases brought before courts of appeal and the Supreme Court in the period 1941 to 1945, 89 percent were declared invalid,[35] and in 1949 Supreme Court Justice Robert H. Jackson said, only partly in jest, "the only patent that is valid is one which this Court has not been able to get its hands on."[36] That most engineers did not agree with the Court is shown by the fact that many companies, including GE and RCA, had agreed to pay royalties for the use of the invention, and by the recognition that professionals have accorded Wheeler as the inventor of automatic volume control.[37]

Because the diode AVC patent was the most important in the Hazeltine portfolio of patents and because the only source of income for Hazeltine Corporation was royalties, the Supreme Court's decision was a devastating blow to the company. As it happened, however, the coming of World War II allowed the company to turn in a new direction—defense contracting. After the war, the adverse climate for patent rights and the demand for military electronics caused Hazeltine to change its mode of operation: Instead of earning money only through patent licensing (including engineering support), the company expanded by seeking and winning defense contracts.

Wheeler was involved in another patent dispute that reached the Supreme Court. It occurred much later in his career and concerned television rather than radio, but it resembled the first case in that the Supreme Court reversed the decision of a circuit court and in that Hazeltine Corporation suffered a crippling blow. Zenith Corporation, sued by Hazeltine for patent infringement, made an antitrust counterclaim, contending that Hazeltine's foreign licensing practices denied Zenith certain export markets. A judgment in the US District Court in Chicago that Hazeltine pay Zenith damages was reversed by a circuit court but reaffirmed by the Supreme Court. As in the earlier case, the fact that the decision by the Supreme Court was unanimous suggests to Wheeler that the judges did not give the case careful consideration.[38]

Television Engineering

It was largely in the 1930s that the technology of television was developed. In the United States, RCA, with its star engineer Vladimir Zworykin, was the acknowledged leader, and in early 1933 RCA built and operated an entirely electronic television system.[39] A year earlier Hazeltine Corporation began work on television receivers, and in the years 1936 to 1940

Hazeltine engineers built a series of television receivers of increasing sophistication.

Wheeler gave particular attention to two problems: circuits for scanning the picture tube, and circuits for amplifying the wideband signals that television required. He carried out a largely theoretical study of the reproduction of an image by the scanning process. A product of this work was a paper he coauthored with Arthur Loughren, "The fine structure of television images," which became a basic reference on the subject.[40] Wheeler's study of distortion in a wideband amplifier led to the introduction of the concept of "paired echoes" and the publication of the article, "The interpretation of amplitude and phase distortion in terms of paired echoes," which is probably Wheeler's most famous paper.[41]

Television, in contrast to radio, operates with signal pulses rather than a continuous carrier. In order for an amplifier in a television receiver to reproduce pulses accurately it must both respond to the wide range of frequencies making up a pulse and maintain the phase relations of the components. The latter requirement necessitates the inclusion in amplifying circuits of phase correction. The phase distortion could be described in terms of an "echo" pulse before and after the main pulse. Wheeler introduced the term "paired echoes" and showed that any phase distortion can be analyzed as made up of a symmetrical pair of echoes and an asymmetrical pair.

Wheeler went on to make a general study of wideband amplification and introduced a number of other concepts—such as "dead-end filter," "feedback filter," and "speed of amplification"—useful in the analysis of wideband amplification. Some of this work is reported in a very influential paper published in 1939, "Wide-band amplifiers for television."[42] This and other papers brought him in 1940 the Morris N. Liebmann Award of the IRE, "For his contribution to the analysis of wideband high-frequency circuits particularly suitable for television."

World War II

World War II caused Hazeltine Corporation to set aside television development, but the experience gained with pulse techniques—pulses of current produce the spots of which the television image is composed—proved valuable in work on radar. After the war Wheeler did not return to television circuits, but Hazeltine Corporation became a leader in the development of color television.

In June 1940, as US involvement in the European war was appearing increasingly likely, President Roosevelt approved a plan advanced by Vannevar Bush to coordinate civilian research for military ends. The coordinating agency, the National Defense Research Committee, arranged for the participation of civilian scientists and engineers in military research and development. Hazeltine Corporation, which became involved in several military projects, was given sole responsibility to develop, for the Army Corps of Engineers, a device to detect buried antitank mines.

Wheeler, who directed this project, started with an existing device, a so-called "treasure finder." In Wheeler's words, "The treasure-finder was some coils on a long pole, and the coupling between the coils had to be critically balanced out in order to detect the reaction of a buried metal object. Their principal defect was that the balancing was so critical that even exposure to daylight would cause expansion and upset the balance."[43] Wheeler replaced the double coil with three coplanar concentric coils, the opposing inner and outer coils being the transmitter and the intermediate coil the receiver. As his calculations had predicted, the balance between the coils became insensitive to temperature change. This innovation, together with an inspired mechanical design that was largely the work of Hazeltine engineer Leslie Curtis, yielded an effective mine detector, the SCR-625 (see Figure 6), which was rushed into service for the North African campaign of 1942.[44] The SCR-625 went into quantity production (by another company) and saw wide use in World War II and in the Korean War.

Among the other projects in which Hazeltine was involved was an exploration of the possibility of a television-guided bomb. Though the feasibility of the idea was demonstrated, the project with Hazeltine was discontinued. It soon happened, however, that work on the development of radar, first for the Signal Corps and then for the Navy, required all of Hazeltine's resources, so no other projects were undertaken.

A technology in the early stages of development before the war, radar was of such obvious military value that the major combatants soon developed it to the point of being able to detect airplanes and ships at great distances and through clouds and fog. But the blip on the radar screen did not reveal whether or not the airplane or ship was hostile. IFF, Identification Friend or Foe, was a system designed to answer this question. Friendly aircraft and sea vessels were equipped with a transponder or radar beacon, which, when triggered by a surveillance radar (or by a separate transmitter called an interrogator), sent out a coded reply. The absence of a reply was taken to mean that the airplane or sea vessel was hostile. The British tested an IFF system, the Mark I, in 1939; Mark II and Mark III were improved British systems.[45]

Hazeltine obtained the contract to design all the Navy's IFF equipment and arrange for its manufacture. Starting with an experimental model of the Mark III, Hazeltine engineers designed an improved system. Because IFF used a frequency band higher than Hazeltine had dealt with before, Wheeler undertook studies of the antennas and transmission-line circuits appropriate to this frequency range.

Earlier, Wheeler had done work in antenna design. In the 1930s, as receivers were designed for radio waves of higher and higher frequency (6 to 18 MHz), it became possible to make great improvements in antennas. Thus, says Wheeler, "antenna design became a new field of expertise which I embraced immediately."[46] Because the IFF system used an even higher frequency range (157 to 187 MHz), new antennas were required. Wheeler set up within Hazeltine an antenna group, and over the next several years this group of three or four engineers, under his direction, designed a series of IFF antennas—for aircraft, surface vessels, submarines, and ground

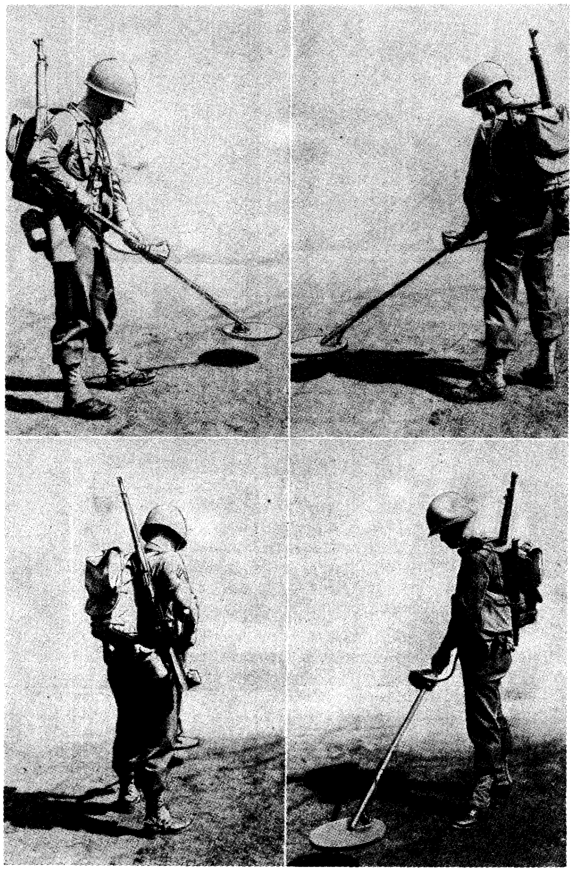
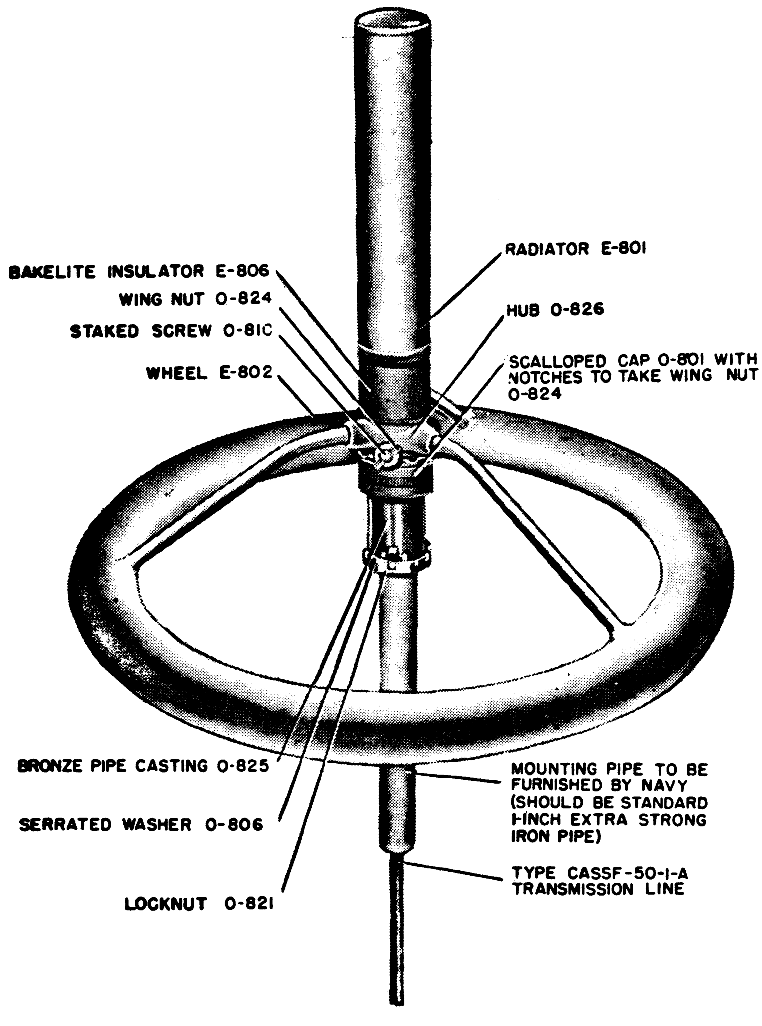


Figure 6. The mine detector SCR-625, widely used in World War II and the Korean War, designed by Wheeler and other engineers of Hazeltine Corporation.

stations. Most famous was the so-called "lifesaver antenna," which contained three radial spokes in a wheel beneath a vertical monopole antenna (see Figure 7); by the end of the war, this antenna had been placed on all of the Allied ships. Other antennas he designed were a vertical antenna with folding legs (for the paratrooper beacon PPN-1 used to guide airborne landings behind enemy lines in Italy and France) and a horizontal half-loop antenna (for transponder beacons, such as the Signal Corps YH beacon used in the Pacific). After the war, the Navy recognized Wheeler's contributions by awarding him a Certificate of Commendation.



TYPE CTZ-66-AFJ ANTENNA.

Figure 7. The antenna CTZ-66-AFJ, known as the "lifesaver antenna," widely used in World War II, designed by Wheeler and other engineers of Hazeltine Corporation.

WHEELER: *. . . about the middle of the war our IFF system had been sort of compromised, and the need was recognized for a more advanced system. So in parallel with our immediate needs, a project was initiated by the Navy as a leader of all agencies, both in the government and civilian, to work on a successor IFF. After the Mark III there was one designated Mark IV that didn't go anywhere. The next was designated Mark V, and that is the one that was the subject of intensive developmental activity in the latter half of the war period.*

The Mark V was developed under cognizance of the Naval Research Laboratory located in Washington, D.C. That project involved cooperation of all the government military agencies and several companies with ambitions to manufacture the equipment. It was designated the Combined Research Group (CRG) with headquarters in a new building at the Naval Research Laboratory. I and our group spent a great deal of time on location. Our responsibility in the new project—the immediate responsibility—was to provide by a quick reaction new equipment that they perceived they needed. And so we had a shuttle between our headquarters in Little Neck and NRL in support of that activity.

. . . Now this CRG design designated Mark V was mainly distinguished by a higher frequency band, the so-called L-band, around 1 megahertz. So that involved a new set of technical problems. In the antenna area and in the area of high frequency circuits, I was a leader. So I have some patents in that field. That project came to a screeching halt when the war was over, by which I mean the ambitious program was reduced to a holding operation. It shortly resulted in a new simplified IFF, which became the keystone of our postwar IFF equipment. It was designated Mark X.

You would naturally be curious what happened to the intervening numbers. One of the leaders in the government, Gene Fubini, was at the blackboard one day and talking about the next generation of equipment. He wrote down Mark X [the letter X, indicating an unknown number], and that was transcribed to Mark Ten.

NEBEKER: *So there were no VI, VII, VIII, and IX?*

WHEELER: *None. And Hazeltine became the leader in both development and manufacture of Mark X and successor equipment.*[47]

Wheeler Laboratories

In the immediate postwar years there were exceptional opportunities for electronics engineers. Because he was well known, Wheeler knew that he would have no difficulty working as a consulting engineer and decided to leave Hazeltine Corporation. One of the first people to contact him was Robert Poole, head of the Whippany laboratory of Bell Laboratories.

In 1926 Bell Laboratories had established a small research facility at Whippany, New Jersey, about 30 miles west of New York City. The rural setting of this laboratory made it the choice for the site of top-secret research on radar that Bell Laboratories agreed to do for the Navy, and in 1938 a new engineering group was set up at Whippany.[48] After the war, the Whippany Laboratory was the site of the development of the electronic guidance equipment and other components of the Nike antiaircraft missiles.[49]

Wheeler, working with two other engineers, obtained a subcontract to design microwave circuits for the Nike System. In 1947 Wheeler Laboratories was incorporated, and the number of employees grew steadily over the next decade, most of the work being subcontracts from the Whippany Laboratory. Development of the Nike Hercules System began in 1953, and for this project Wheeler Laboratories designed microwave circuits and an innovative target-tracking antenna—a double-reflector antenna that is still in use today.[50] Wheeler said of his company, "... we enjoyed the luxury of having the primary management handled by Bell Laboratories, and we could devote almost all of our attention to creative work."[51]

Antenna design remained an area of special interest to Wheeler. He carried out a theoretical investigation of "small antennas"—antennas of dimensions much less than the wavelengths they are designed to receive—that revealed simple relationships and rules. Over the next several decades he published papers both on principles of antenna design and on particular antennas whose design benefited from the theoretical studies.[52]

For example, when consulted about the small antenna for a proximity fuse placed in the nose of a missile, he proposed a design that was much more efficient than earlier ones. As part of his work for a Navy project to use VLF (very low frequency) waves to communicate with submarines, he helped design the world's largest antenna, which was, according to the definition given above, a small antenna. Built at Cutler, Maine, and commissioned in 1961, this antenna was supported by 26 towers, each about 1000 feet tall, and extended over two square miles. A second such antenna, supported by 13 towers, was built in Australia (see Figure 8).[53]

In pondering antenna design for low-frequency radiation where the ground was one electrode of the antenna, Wheeler perceived that the earth's crust could be regarded as a parallel-plate waveguide. The surface layer was conducting because of moisture; the layer below that was nonconducting, being dry and consisting largely of silica; and at a greater depth the high temperature made the silica conducting. At a conference in 1950 Wheeler presented his idea, pointing out that this might provide "a channel for radio waves to go long distances in the earth's crust and then come out deep in the ocean...."[54] Because the Navy was searching for ways to communicate with submerged submarines, a secrecy order was placed on his patent and a project—the Navy's ELF (extra low frequency) project—was begun to investigate its possibilities.

During World War II there were some radar antennas that consisted of a small number, perhaps half a dozen, of separate radiators. These so-called array antennas were steered mechanically. A number of people began thinking about electronic steering of the radar beam, one of whom, Arthur Loughren, was at Hazeltine Corporation. Loughren devised a type of steering called frequency steering; others later devised ways to steer the radar beam by varying the phase of the radiation, and so-called "phased arrays" became widely used.

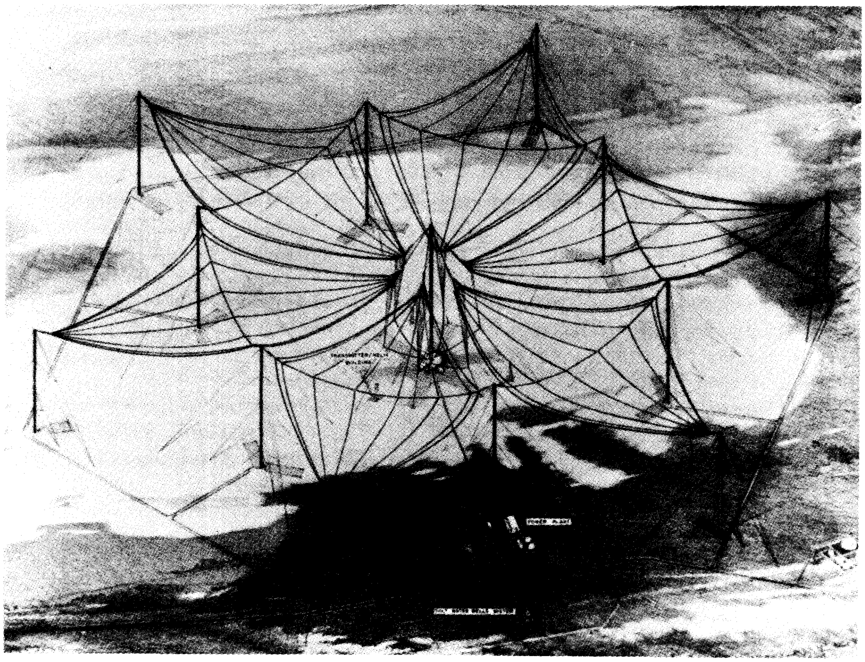


Figure 8. The U.S. Navy megawatt VLF antenna built at North West Cape, Australia.

Wheeler also became interested in array radars and published in 1948 one of his most influential papers. Entitled, "Radiation resistance of an antenna in an infinite array or waveguide,"[55] it helped to establish a scientific basis for the design of array elements. Wheeler proposed that, in the design process, the array element be treated as if it were an element of an infinite array. The idea found immediate application in work undertaken by Wheeler Laboratories for Bell Laboratories. In the 1960s Wheeler published several other papers on phased-array antennas.

Wheeler specialized also in the theory and design of transmission lines, especially strip lines, which are thin conducting strips separated from a return conductor (either another strip or a ground plane) by a nonconducting sheet. Although the idea of printed circuits goes back to the turn of the century, they did not begin to be manufactured in quantity until the 1950s. The properties of strip lines, or "microstrips," were difficult to calculate, and Wheeler made important contributions in this area, especially in the 1960s and 1970s. His paper "Transmission-line properties of parallel strips separated by a dielectric sheet," published in 1965, was named a Citation Classic by *Current Contents*.[56]

Both in Hazeltine Corporation and in his own company, Wheeler gave much attention to the continuing education of the engineers. At the laboratory of Hazeltine Corporation in Bayside, New York, in the 1930s, Wheeler organized classes and did most of the teaching himself. He did the same at Wheeler Laboratories. He also continued the Hazeltine practice of having engineers write reports, both on improvements they had made and on tests performed on a licensee's design. The resulting reports, like the ones issued by Hazeltine engineers earlier, were highly valued by the clients.

Wheeler's scientific approach to engineering problems often resulted in lengthy manuscripts. Because *Proceedings of the IRE* contained only articles of moderate length, Wheeler turned to private publication. In the years 1948 to 1954, nineteen articles, some of them more than 40 pages long, appeared in the series entitled *Wheeler Monographs*, published by Wheeler Laboratories. These were later collected in two bound volumes.

Back to Hazeltine Corporation

In the 1950s, Wheeler Laboratories prospered, and in 1959 it employed about a hundred engineers. The military had been spending a great deal of money on technological innovation, but in 1959 such money became scarcer and Bell Laboratories had less need to subcontract work to Wheeler Laboratories. This circumstance and the friendly relations Wheeler had maintained with Hazeltine management made him receptive to an offer by Hazeltine Corporation to acquire Wheeler Laboratories. The acquisition took place in 1959, and from then until late 1970 Wheeler Laboratories remained a separate part of Hazeltine Corporation. In that year it was merged with the research laboratories of the parent company. Wheeler continued as president of Wheeler Laboratories until 1968.

. . . The '50s was a period that we'll never see again and never saw before, when the Pentagon was spending all the money they could on innovation. That wasn't the name of the game in the government generally. But that period after the war, which meant especially the early days of guided missiles, was a period unprecedented and that'll never happen again. So that was a fertile field for innovation. But then at the end of that decade, in 1959, happened what you wouldn't have thought possible. The Air Force sent a letter to the contractors which said money was getting scarce, and they couldn't expect to be paid on time.

Well, that was one of many events which started to inhibit the full range of innovative activity. It among other things reduced the Bell Laboratories load to a point where they gradually had less need for our services. I might say that from some viewpoint their contracting our services should have been frowned on by their organization because essentially they were building up engineering talent to compete with their own group. But in the climate of the '50s, that was not an important consideration. Later on the people who had introduced us in their group became less involved—either higher management positions or retirement. The successor group was less personally involved in our activities, and the work for them was tapering off.

It was just at that time that MacDonald came over to see me. He said, "Shouldn't we get together again?" Well, the circumstances left me receptive to that approach, so Hazeltine acquired our company at a nominal price in stock and very thoughtfully continued our activities for another decade, semi-independent. We still operated under our name, and we still had opportunities for contracts with various other organizations.[57]

In the 1960s, subcontracting work, mainly for Bell Laboratories, continued. Wheeler and his associates made designs for antiballistic missiles (ABMs) and for ABM radar. Especially interesting was some work Wheeler did about 1960 for the Communications Products Company. The task was to design an antenna, suitable for base-station communications, that would concentrate the radiation in the horizontal plane by means of a vertical array of vertical dipoles. Drawing on his theoretical studies of antennas, Wheeler designed what became known as the Stationmaster antenna, more than a quarter-million of which have since been sold.

One of the projects on which Wheeler worked in the 1970s aimed at the design of a radar antenna that would "interrogate" the altitude-coded radar beacons carried by aircraft. This antenna had to be light in weight and be subject to very little wind loading, since it was to be mounted on the rotating antennas of the surveillance radars already in operation at airports. Wheeler started with an open, flat array of many elements and then discovered a way to reduce the required number of rods by one half. The design was a great success and can be seen at major airports today in what looks like a bedspring on top of a rotating radar.

Wheeler was employed by Hazeltine Corporation from 1924 until 1987, except for 13 years after the war. In 1958 Alan Hazeltine wrote of Wheeler, "His brilliant inventions in many branches of electronics and his training of younger engineers were of great importance to the success of the company."[58] To this must be added mention of Wheeler's contributions to the management of the company; besides directing the company's Bayside Laboratory in the 1930s and serving as chairman of the Hazeltine Board of Directors from 1965 to 1977, he was named chief executive officer at the time of the crisis brought on in 1965 by the unfavorable outcome of the Zenith litigation. He took bold actions to restore employee morale, assisted in a reorganization of the company, and in 1966 turned over management to a new chief executive, David Westermann. Wheeler stayed on at Hazeltine past the usual retirement age in the capacity of chief scientist, providing support to many of the company's projects. He worked full-time until the early 1980s, when he reached the age of 80, then worked three days a week until 1987.

Handbooks and Formulas

Since his high school days Wheeler has had a hobby of collecting formulas. Whenever he encountered a formula that he thought might be useful, he entered it in a notebook. Before any "radio-engineer's handbook" appeared, there were collections of formulas at the back of catalogs of radio components (included so that people would keep the catalogs at hand), and Wheeler remembers these as one of his sources.[59]

Like most practicing engineers, Wheeler is grateful to the compilers of handbooks. One was his first boss, John Howard Dellinger, whose *NBS Circular 74*, entitled "Radio instruments and measurements," was the standard authority for two decades after its first appearance in 1918.[60] Another was Frederick Terman, whose *Radio Engineers' Handbook* became the vade mecum for radio engineers in the post-World War II decades. In the mid-1930s, when Terman began gathering material for a new handbook, he traveled to Hazeltine's Bayside Laboratory to talk with Wheeler, which was the first of many visits between the two engineers. When the handbook was finally completed in 1943, it drew on the work of some 900 authors; Wheeler was cited more often than any of them except George H. Brown (known for his work on antennas) and Terman himself.[61]

Wheeler has always argued for understanding design principles and practices and objected to carrying out computations by the use of a "black box," such as a canned computer program or—what was common throughout most of his career—a numerical table. He sought instead a perspicuous symbolic or graphical presentation of the quantitative relationships, in order that someone using the formula or graph could gain understanding of the physical phenomena, and he preferred analysis or synthesis at what he calls the "slide-rule level," rather than at a computer level. For his own work he did adopt computer methods in the 1970s, but reports jokingly that "The saddest moment of my life was when I put away my slide rule."[62]

Wheeler, who advocated the use of "every possible shortcut to relieve the engineer of unproductive nuisance in thinking, computing, and testing,"[63] published many articles presenting design formulas, charts and other calculating aids, procedures for the slide rule, and "graphical presentation of design relations in a form suitable for analysis or synthesis."[64] His first such publication, entitled "Simple inductance formulas for radio coils," appeared in 1928.[65] Others appeared sporadically in the decades that followed, and two appeared 54 years later.[66]

For example, in 1942 Wheeler published "Formulas for the skin effect."[67] It had long been known that a so-called "skin effect" reduced the effective cross-section of a conductor carrying alternating current, and thorough mathematical treatments had been written. What Wheeler did in this article was to describe the effect in more understandable terms, deriving from this description a simple way—called the "incremental-inductance rule"—of computing the skin effect in wires of various cross sections. This rule came into wide use for the design of transmission lines, especially strip lines.

Another example is provided by the formulas in Figure 9, which are useful in analyzing and designing printed circuits. They concern the properties of a strip line (or microstrip), defined to be a conducting strip separated from a parallel ground plane by a dielectric sheet. In an article published in 1977 (almost fifty years after his first published paper), Wheeler showed that a single equation was valid (within two percent relative error) for any strip width and any dielectric constant. Moreover, the equation is reversible, which makes it easy to use it for either analysis or synthesis.[68]

A 1946 editorial entitled "The real economy in engineering," which Wheeler wrote for *Proceedings of the IRE*, contains the following statements: "The real economy in engineering is the best use of every available aid in arriving at an understanding of the problem and an expeditious solution. . . . [understanding a problem] requires concentration, enlisting the aid of th e best references and charts, practicing on examples, developing new and simpler formulas and charts, outlining the limitations. . . . The pioneering in science will always leave in its wake a great demand for reference material which will aid in the solution of engineering problems by reducing the labor of computation and especially by doing this in such a way as to contribute to the understanding of the solution and its limitations."[69]

$$R = \frac{42.4}{\sqrt{k+1}} \ln\left\{1 + \left(\frac{4h}{w'}\right)\left[\left(\frac{14+8/k}{11}\right)\left(\frac{4h}{w'}\right) + \sqrt{\left(\frac{14+8/k}{11}\right)^2\left(\frac{4h}{w'}\right)^2 + \frac{1+1/k}{2}\pi^2}\,\right]\right\}$$

$$w'/h = 8\frac{\sqrt{\left[\exp\left(\frac{R}{42.4}\sqrt{k+1}\right) - 1\right]\frac{7+4/k}{11} + \frac{1+1/k}{0.81}}}{\left[\exp\left(\frac{R}{42.4}\sqrt{k+1}\right) - 1\right]}$$

Figure 9. The wave resistance R (or characteristic impedance) of a strip line on a dielectric sheet above a ground plane can be computed using the formula at the left, where w' is the effective width of the strip, h is the thickness of the dielectric sheet, and k is the dielectric constant. The mathematically equivalent formula below is useful in designing a strip line that is to have a given wave resistance.

Professional Activities, Family Life, and Historical Writing

Wheeler counts himself fortunate in having worked almost all of his career in the vicinity of New York City, which was the focal point of the radio profession. Offices and laboratories of RCA, Bell Telephone, ITT, and other companies were located in the area; important electronics research was done at Columbia University, City College of New York, and Polytechnic Institute; the Radio Club of America and the Institute of Radio Engineers were both based in the city. Wheeler attended meetings of the Radio Club, sometimes presenting his own work; in 1936 he was named Fellow, and in 1964 he received the highest honor of the Radio Club, the Armstrong Medal. Especially during the period he was working on circuit theory, he was also an active member of the American Institute of Electrical Engineers.

IRE activities, especially the meetings of the New York Section and the annual meeting, he found particularly valuable. Wheeler, who was named an IRE Fellow in 1935, served on several committees, notably the Technical Committee on Radio Receivers and the Standards Committee, for both of which he served as chairman.[70] From 1940 to 1945 he was a director of the IRE, and after the war he helped establish a Long Island subsection. During this time he proposed that all members be assigned to "Sections," geographically defined, and that the annual directory include biographies of the Fellows. These practices were adopted by the IRE and have been continued by the IEEE.

The family Wheeler started when he married Ruth Gregory (shortly after her graduation from George Washington University in 1926) is a great source of pride to him. Harold and Ruth, with their three children, Dorothy, Caroline, and Alden Gregory, formed a close-knit and harmonious family (see Figure 10). Wheeler had the advantage himself of having grown up in such a family. He writes: "Our father and mother were a wonderful team and our family relations were as nearly ideal as could be imagined. Kindness and love, respect and admiration, were the cornerstones. There was a spirit of cooperation and enough discipline. Good habits and cleanliness were taken for granted, by the example of our parents" and "The family built by my parents proved to be a remarkable accomplishment. . . . It offered us children a generous ration of nurture, protection, confidence, ambition and opportunity. With the strength of our family ties, none of us is ever alone."[71]

Wheeler reminds one of the Enlightenment rationalists in his efforts to reshape traditional practices according to reasoned design. He was a proponent of the MKS (meter-kilogram-second) system of units as preferable to the CGS (centimeter-gram-second) system.[72] He has championed what he calls the "logical date code," in which the temporal units are given

Figure 10. Dorothy, Harold, Alden, Ruth, and Caroline Wheeler in 1936.

in decreasing order: 1934 DEC 23, or 34 12 23, or, in Wheeler's usual style, 341223.[73] He has argued for including journal name, volume number, and date on each page of an article so that photocopies would automatically contain that information. He has suggested innovative ways to refer to sources and given thought to the best form of the many abbreviations used in technical writing.[74]

The honors accorded Wheeler include, in addition to those already mentioned, a twenty-dollar gold piece won as a paperboy in Mitchell, South Dakota, honorary doctorates from George Washington University, the Stevens Institute of Technology, and Polytechnic University, election to the National Academy of Engineering, the Pioneer Citation of the Radio Club of America, and the Microwave Career Award of the Microwave Theory and Techniques Society. Wheeler has been an advisor to the Department of Defense—he served on the Guided Missile Committee from 1950 to 1953 and on the Defense Science Board from 1961 to 1964. In 1964 he received the most prestigious award of the Institute of Electrical and Electronics Engineers, the Medal of Honor, "For his analyses of the fundamental limitations on the resolution in television systems and on wide-band amplifiers, and for his basic contributions to the theory and development of antennas, microwave elements, circuits, and receivers."

Wheeler has written three historical books, *Hazeltine the Professor* (1978), *The Early Days of Wheeler and Hazeltine Corporation—Profiles in Radio and Electronics* (1982), and *Hazeltine Corporation in World War II* (1993). The first of these Wheeler felt a responsibility to write in order to make known the great impact Louis Alan Hazeltine had on electronics engineering, an impact that a person judging solely by inventions and publications would not suspect. The second book is largely autobiographical and deals with the period up to World War II. The third book concerns the activities of Wheeler and of Hazeltine Corporation during the war.

NEBEKER: *You've also kept a diary much of your life.*

WHEELER: *By accident, but very fortunately, someone presented me with a little pocket diary in my high school years for Christmas. I started very casually to jot down things I was doing each day. I was enough interested to continue the next Christmas and bought a diary for myself. I engaged in entries more and more over the years until I graduated to a normal-size diary, bound volume. It is interesting that I did not do what the stories in the literature describe about diaries. My diary was not an exposition of my current emotional problems and other things, just a fragmentary entry of things I did. Sometimes I have a hard time remembering what it was when I read the diary. But I continued that so I have a complete set of diaries that track my daily activities pretty much from high school to the present time.*

NEBEKER: *Without large gaps?*

WHEELER: *One year I just didn't bother to get a new diary. I've regretted it ever since. So one year was missing. I think it was 1930. That convinced me that I shouldn't allow gaps.*

NEBEKER: *You used these diaries in your historical writings?*

WHEELER: *Oh, very much. And in matters of personal interest. What year did I take a first trip to the West Coast? What was the airport when I began to fly west? When I arrived in L.A., the airport was Burbank. Just a friendly little shack. So that's one of my treasures that I keep within reach all the time when I'm working.*[75]

In looking back over his seven decades of work with radio receivers (AM, FM, and shortwave), test equipment, television, radar, transmission lines, and antennas, Wheeler has commented that his fields of specialization "progressed with the growth of technology in my profession. . . . "[76] He appreciates his good fortune to have been born at about the same time as the field of electronics, for it was only in the early decades, he points out, that the learning rate of a professional could keep up with the growth of the field.

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[1] George H. Douglas, *The Early Days of Radio Broadcasting* (Jefferson NC: McFarland & Company, 1987), and Christopher H. Sterling and John M. Kittross, *Stay Tuned: A Concise History of American Broadcasting*, second edition (Belmont CA: Wadsworth Publishing Company, 1990).

[2] Alan Douglas, *Radio Manufacturers of the 1920's*, vol. 2 (Vestal NY: Vestal Press, 1989), p. 231. If a Philco advertisement (in *Collier's*, 14 September 1929, reproduced in Douglas, p. 237) can be taken at face value, then the roughly simultaneous appearance of the Model 95 and of regular symphonic broadcasts was not merely coincidental. According to this advertisement, the officials of the Philadelphia Orchestra, directed by Leopold Stokowski, "steadfastly refused until the present time to send its glorious music out over the air," but that the level of radio reception had been raised so much, especially by Philco, that "Stokowski has consented to go on the air for the first time." (In the following year Stokowski began a 10-year collaboration with scientists and engineers of Bell Laboratories for improving sound reproduction; see the article by Robert E. McGinn in *Technology and Culture*, vol. 24, 1983, pp. 38–75.)

[3] Photos courtesy of Alan S. Douglas.

[4] Douglas, *Radio Manufacturers of the 1920's*, p. 231.

[5] The information about Harold Wheeler contained in this article comes mainly from the following sources: (1) an extensive oral history interview of Wheeler conducted by the author 29–31 July 1991 (from which an edited transcript has been prepared); (2) Wheeler's books *Hazeltine the Professor* (Greenlawn NY: Hazeltine Corporation, 1978) and *The Early Days of Wheeler and Hazeltine Corporation—Profiles in Radio and Electronics* (Greenlawn NY: Hazeltine Corporation, 1982); (3) Wheeler's other published writings; (4) copies of personal papers provided to the author by

Wheeler; and (5) a manuscript autobiography prepared in 1990 for Project LMS (Life Members' Stories), sponsored by the IEEE Life Member Fund Committee. (Items 1, 4, and 5, as well as a full list of Wheeler's publications, are available at the IEEE Center for the History of Electrical Engineering.) An earlier version of this article appeared in *Proceedings of the IEEE*, vol. 80, 1992, pp. 1223–1236.

[6] Wheeler used a regenerative detector with 2-stage audio amplification and a single Baldwin receiver connected to the horn of a phonograph.

[7] At that time radio was already being used to bring to farmers another type of information that needed to be disseminated rapidly—weather forecasts. In 1917 Earle M. Terry at the University of Wisconsin began transmitting weather bulletins to farmers (Douglas, *The Early Days of Radio Broadcasting*, p. 83).

[8] Interview 1991, p. 17.

[9] Dellinger, a Princeton physics Ph.D. and president of the Institute of Radio Engineers in 1925, contributed greatly to the establishment of the science of radio engineering. His "Principles of radio transmission and reception with antenna and coil aerials," read at a meeting of the American Institute of Electrical Engineers in 1919, was a landmark paper (see Donald McNicol, *Radio's Conquest of Space* [New York: Murray Hill Books, 1946], pp. 154–155). A rich source of information about Dellinger is Wilbert Snyder and Charles Bragaw's *Achievement in Radio: Seventy Years of Radio Science, Technology, Standards, and Measurement at the National Bureau of Standards* (Boulder CO: National Bureau of Standards, 1986).

[10] Between the time of the first meeting of Hazeltine and Wheeler and the time of this agreement, Wheeler invented another form of neutralization, known as "capacity-bridge neutralization," for which Wheeler obtained the first of his many US patents. (See *Early Days*, pp. 166–169.)

[11] See Wheeler's *Hazeltine the Professor*, which contains two autobiographical sketches by Hazeltine.

[12] *Proceedings of the IRE*, vol. 6, 1918, pp. 63–98.

[13] W. Rupert Maclaurin, *Invention and Innovation in the Radio Industry* (New York: Macmillan Company, 1949) (reprinted in 1971 by Arno Press, New York), pp. 127–129.

[14] *Hazeltine the Professor*, p. 106.

[15] *Hazeltine the Professor*, p. 87.

[16] *Early Days*, p. 117.

[17] G. Breit and M. A. Tuve, "A radio method of estimating the height of the conducting layer," *Nature*, vol. 116, 1925, p. 357. A more complete report is Breit and Tuve's "A test of the existence of the conducting layer," *Physical Review*, vol. 28, 1926, pp. 554–575.

[18] H. A. Wheeler and F. D. Murnaghan, "The theory of wave filters containing a finite number of sections," *Philosophical Magazine*, vol. 6, 1928, pp. 146–174.

[19] Interview 1991, pp. 35–36.

[20] "Automatic volume control for radio receiving sets," *Proceedings of the IRE*, vol. 16, 1928, pp. 30–39.

[21] "Classic circuits," *Electronics*, vol. 53, no. 9, 1980, pp. 436–442. Another

section of the same issue of *Electronics* was entitled "Great innovators," and one of the people thus honored was Harold Wheeler.

[22] Interview 1991, pp. 4–6.

[23] Interview 1991, p. 11.

[24] Interview 1991, p. 6.

[25] Wheeler's work was first publicly presented in a paper given in 1934 by Hazeltine engineers Daniel Harnett and Nelson Case, "The design and testing of multirange receivers," *Proceedings of the IRE*, vol. 23, 1935, pp. 578–593. Wheeler gives a full account of the history and his role in it in Wheeler Monograph Number 8, "The piston attenuator in a waveguide below cutoff" (Great Neck NY: Wheeler Laboratories, 1949). As this monograph points out, independently of Wheeler's work and slightly earlier, John Dreyer, an engineer working for Atwater Kent, invented a form of the piston attenuator, but he was unable to calculate the rate of attenuation, so he had to rely on measurements.

[26] H. A. Wheeler and V. E. Whitman, "Acoustic testing of high fidelity receivers," *Proceedings of the IRE*, vol. 23, 1935, pp. 610–617; and H. A. Wheeler, "RF inductance meter," *Electronics*, vol. 20, no. 9, 1947, pp. 105–107.

[27] "Microwave measurements," *Proceedings of the IRE*, vol. 50, 1962, pp. 1207–1214.

[28] Interview 1991, p. 8.

[29] See *Early Days*, pp. 229–231.

[30] H. A. Wheeler and W. A. MacDonald, "Theory and operation of tuned radio-frequency coupling systems," *Proceedings of the IRE*, vol. 19, 1931, pp. 738–805.

[31] Most important were "Two-signal cross-modulation in a frequency-modulation receiver," *Proceedings of the IRE*, vol. 28, 1940, pp. 537–540, and "Common-channel interference between two frequency-modulated signals," *Proceedings of the IRE*, vol. 30, 1942, pp. 34–50. When Wheeler was presented the Armstrong Medal of the Radio Club of America in 1964, the award citation read, in part, ". . . it is particularly appropriate that this year which marks the 25th Anniversary of FM broadcasting, the Armstrong Medal is awarded to one who also pioneered in the field of frequency modulation. His theoretical analysis of frequency modulated signals helped outline the boundaries of this new discipline."

[32] In a history of radio, Gordon Bussey comments that the rate of progress in radio design in the late 1920s in the United States was slowed by "time-wasting legal arguments over patents" (*Wireless: The Crucial Decade* [London: Peter Peregrinus, 1990, p. 49].) An example of how time-wasting the legal actions could be is provided by Edwin Armstrong's 1949 suit against RCA and NBC for infringement of his FM patents, for which Armstrong spent, in sum, one year on the witness chair (John D. Ryder and Donald G. Fink, *Engineers & Electrons: A Century of Electrical Progress* [New York: IEEE Press, 1984, p. 82].)

[33] The story is much more complicated than is here suggested. Two patents were actually involved: the original diode AVC patent (US Patent 1879863) and a reissued patent (Reissue 19744). In response to several unfavorable court decisions concerning the original patent, Wheeler filed a reissue

application that made more specific claims. The cases referred to in the text concerned the reissue. (A fuller account of the litigation is contained in Wheeler's *Early Days*, pp. 232–248.)

[34] Quoted on page 182 of W. Rupert Maclaurin's *Invention and Innovation in the Radio Industry*.

[35] Floyd L. Vaughan, *The United States Patent System* (Norman OK: University of Oklahoma Press, 1956) (reprinted by Greenwood Press, Westport CT; 1972), p. 22.

[36] Quoted on page 10 of Steven Lubar's "New, useful, and nonobvious," *American Heritage of Invention and Technology*, vol. 6, no. 1, 1990.

[37] As mentioned above, the AVC circuit was honored by the journal *Electronics* as one of twelve classic circuits. Frederick Terman, in *Radio Engineers' Handbook* (New York: McGraw-Hill, 1943, p. 639) credits Wheeler with the invention of diode AVC. The perception that the courts were not protecting patent rights and a 1939 speech by President Franklin Roosevelt condemning further inventions (Roosevelt said they reduced employment) prompted the National Association of Manufacturers to argue publicly for the value of inventions and of patent rights. In 1940 the NAM honored about 100 inventors with the "Modern Pioneer Award"; Wheeler was one of those honored.

[38] Additional information about the two cases settled by the Supreme Court is contained in the interview conducted by the author and in an 8-page manuscript, headed "U.S. Supreme Court," that Wheeler wrote on 27 July 1991, a copy of which is available at the Center for the History of Electrical Engineering.

[39] Albert Abramson, *The History of Television, 1880 to 1941* (Jefferson NC: McFarland & Company, 1987).

[40] H. A. Wheeler and A. V. Loughren, "The fine structure of television images," *Proceedings of the IRE*, vol. 26, 1938, pp. 540–575.

[41] H. A. Wheeler, "The interpretation of amplitude and phase distortion in terms of paired echoes," *Proceedings of the IRE*, vol. 27, 1939, pp. 359–385.

[42] H. A. Wheeler, "Wide-band amplifiers for television," *Proceedings of the IRE*, vol. 27, 1939, pp. 1078–1086. This paper was reprinted for its historical importance in the August 1984 issue of *Proceedings of the IEEE*.

[43] Interview 1991, p. 64.

[44] See Leslie Curtis, "Detectors for buried metallic bodies," *Proceedings of the National Electronics Conference*, vol. 2, 1946, pp. 339–351.

[45] A different system, the Mark IV, was developed in the United States, but a Combined Communications Board decided to adapt the British Mark III for use by all the Allies. See Henry Guerlac's *Radar in World War II* (Tomash Publishers and American Institute of Physics, 1987), pp. 367–374.

[46] Interview 1991, p. 10. In 1936 he published "The design of doublet antenna systems" (*Proceedings of the IRE*, vol. 24,1936, pp. 1257–1275), and in 1937 he applied for a patent on a horizontal figure-eight antenna.

[47] Interview 1991, pp. 103–104.

[48] M. D. Fagen, editor, *A History of Engineering and Science in the Bell System: National Service in War and Peace (1925-1975)* (Bell Telephone Laboratories; 1978), p. 24.

[49] Ibid., pp. 370–383.

[50] Interview 1991, p. 54. The antenna is described on page 389 and pictured in its radome on page 390 of Fagen, *A History of Engineering and Science.*

[51] Interview 1991, p. 74.

[52] Especially important are the following papers: "Fundamental limitations of small antennas," *Proceedings of the IRE*, vol. 35, 1947, pp. 1479–1484; "Small antennas," *IEEE Transactions*, vol. AP-23, 1975, pp. 462–469; "Antenna topics in my experience," *IEEE Transactions*, vol. AP-33, 1985, pp. 144–151.

[53] Richard C. Johnson and Henry Jasik, *Antenna Engineering Handbook*, 3rd edition (New York: McGraw-Hill, 1993), Chapter 6.

[54] Interview 1991, p. 51.

[55] *Proceedings of the IRE*, vol. 36, 1948, pp. 1392–1397.

[56] The article is in *IEEE Transactions*, vol. MTT-13, 1965, pp. 172–185; the designation of it as a Citation Classic is in *Current Contents*, 2 June 1980, p. 16.

[57] Interview 1991, pp. 89–90.

[58] In *Hazeltine the Professor,* p. 94.

[59] Interview 1991, p. 40.

[60] National Bureau of Standards, *Circular 74* (Radio instruments and measurements), first edition 1918, second edition 1924. In 1932 Frederick Terman wrote (in *Radio Engineering*, p. 669), "This book is the standard authority on the subject [of calculating inductance, mutual inductance, and capacity] and contains formulas for making calculations of any desired accuracy for almost every case than can be encountered in practice." For information about *Circular 74*, see pages 52 through 55 of Wilbert Snyder and Charles Bragaw's *Achievement in Radio*.

[61] See the author index (pp. 997–1004) of *Radio Engineers' Handbook* (New York: McGraw-Hill, 1943).

[62] Interview 1991, p. 33.

[63] H. A. Wheeler, "The real economy in engineering," *Proceedings of the IRE*, vol. 34, 1946, p. 526.

[64] The quotation is from a 17-page manuscript, written by Wheeler, entitled "Selected papers by Harold Alden Wheeler," a copy of which is available at the Center for the History of Electrical Engineering.

[65] "Simple inductance formulas for radio coils," *Proceedings of the IRE*, vol. 16, 1928, pp. 1398–1400.

[66] "A simple formula for the capacitance of a disc on dielectric on a plane," *IEEE transactions*, vol. MTT-30, 1982, pp. 2050–2054; "Inductance formulas for circular and square coils," *Proceedings of the IEEE*, vol. 70, 1982, pp. 1449–1450.

[67] *Proceedings of the IRE*, vol. 30, 1942, pp. 412–422.

[68] H. A. Wheeler, "Transmission-line properties of a strip on a dielectric sheet on a plane," *IEEE Transactions on Microwave Theory and Techniques*, vol. MTT-25, 1977, pp. 631–647.

[69] *Proceedings of the IRE*, vol. 34, 1946, p. 526.

[70] Wheeler's chairmanship of the Technical Committee on Radio Receivers, which lasted from 1932 to 1938, ended with the issuance of a report that soon became the standard guide, used in many countries, for testing radios.

[71] *Early Days*, pp. 16, 20.

[72] Wheeler argued as follows: The CGS system has a set of electromagnetic units and a separate set of electrostatic units, so the practitioner often had to convert from one set to the other; the MKS system had the additional advantage that wavelengths of electromagnetic radiation were being measured in meters (Interview 1991, p. 23).

[73] See H. A. Wheeler, "A logical date code for communications and records," *Journal of Industrial Engineering*, vol. 18, no. 4, 1968, pp. ix–x. Wheeler considers his form preferable to the usual European form of day-month-year because it is already the established practice to put the units in decreasing order when expressing magnitudes (as a number of three digits gives hundreds, tens, and ones).

[74] See *Early Days*, pp. 9–10.

[75] Interview 1991, p. 191.

[76] Manuscript autobiography prepared for Project LMS (1990), p. 8.