CRUCIBLE OF COMMUNICATIONS: HOW AMATEUR RADIO LAUNCHED THE INFORMATION AGE AND BROUGHT HIGH TECH TO LIFE

PART 2: HAMS BRING REAL-TIME COMMUNICATIONS TO THE WORLD

INVITED ARTICLE

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ABSTRACT

Until the birth of wireless at the end of the 19th century, the world had never known real-time ubiquitous communications. Printed newspapers of the day contained information that was often days, if not weeks, old with little hope of widespread verification of reported events. Part 1 of this series [1] gave an overview of the fascinating hobby of ham radio, and showed how the grass roots effort of hobbyists and the sinking of the Titanic opened up the airwaves for the world's first amateur radio operators. Now, in Part 2, we see how amateur radio was at the forefront of the wireless revolution that brought AM and FM radio broadcasting, television, and mobile communications to the world. As shown here, it was the ingenuity and tenacity of hams that brought forth the information age in all of its forms.

UNIVERSITIES SPAWN THE ART OF RADIO

When Prof. Jerome Green of the University of Notre Dame published the first easy-to-build wireless transmitter and receiver circuits in 1899 [1, 2] the potential for ubiquitous real-time communication among citizens presented itself for the first time in history. Although free space optical communications using smoke signals and semaphore existed for very specific applications for centuries, at the dawn of the 20th century, a person had to be within earshot or in plain sight of an event to instantly know any of the particulars. Before 1900, information was communicated globally through telegraph relay lines, or through postal carriers, or via the fledgling and extremely sparse telephone networks. It was the tinkerers and experimenters — the first ham operators — that harnessed the potential of wireless communications and spread it across the world.

President Taft of the United States in 1912 signed into law the world's first legislation that gave amateur radio operators their own spectrum at the unexplored wavelengths below 200 meters (frequencies above 1.5 MHz), and other governments around the world, particularly Great Britain, Germany, Brazil and Australia, were moving quickly to foster the ham radio hobby in their own countries. Indeed, there was keen awareness, after the sinking of the Titanic in 1912, that a trained citizenry of wireless experts would be of great value to any country, and to society as a whole [1].

Pioneering physicists and experimenters such as Heinrich Hertz, Guglielmo Marconi, Sir Oliver Lodge, and John Ambrose Fleming had discovered electromagnetic waves, and had begun to perfect their transmission and detection through air by creating the early foundational devices for harnessing wireless for end users in the late 1800s (Fig. 1).

These electronic developments paved the way for wireless at the turn of the 20th century, and spawned the development of radio. The somewhat supernatural ability to transmit information invisibly and ubiquitously through air captivated the world's attention at a time when Alexander Graham Bell's wired telephone, discovered in 1876, was just being deployed aggressively by AT&T throughout the USA and by other upstart telephone companies around the globe.

Not surprisingly, universities became hosts for exploration of this new medium of radio, with hobby clubs sprouting up on campuses world-wide. Just as so many of today's internet and networking giants such as Alphabet (previously known as Google), Meta (previously known as Facebook), Cisco and Akamai can trace their roots to founders who tinkered on the college campuses of Stanford, Harvard and MIT, it was universities at the turn of the 20th century that enabled students — the bulk of the earliest amateur operators - to explore and develop the radio art which brought forth the information age.

One of the first faculty members to promote the hobby of ham radio was Reginald Audrey Fessenden. Born in Quebec, Canada in 1866, Fessenden was hired in 1892 by Purdue University as a professor of Electrical Engineering, but was soon lured to the Western University of Pennsylvania (now University of Pittsburgh) in part because of the electrification and wireless research being sponsored by Westinghouse. Fessenden remained an active professor until 1900, at which point he left academia to pursue entrepreneurial opportunities in the revolutionary concept of voice transmission over wireless, something that was not believed to be possible at the time. He always remained dedicated to students and universities throughout his life, as evidenced by his life-long use of the title "professor," and his willingness to help clubs such as the Junior Wireless Club (e.g, Radio Club of America, for which he was a club advisor) [1, 4].

The world's earliest collegiate amateur radio stations were built at Harvard University in the 1905-1908 timeframe [5]. In 1905, Harvard upperclassman Robert F. Gowen (Fig. 2) built an apparatus in Quincy Hall, and was a leader of the amateur radio movement at Harvard. By 1906, five stations in various dormitories and buildings had been built by students around the Harvard campus, and many more were under construction. On April 2, 1906, the enterprising young ham radio enthusiasts formed a company, The Weld Phonepterogram Company (Limited), involving over a dozen students, and they began to offer the entire student body a service of sending telegraph messages to other students throughout the Harvard campus using the slogan "Wireless Messages to all Parts of the Yard and Vicinity." The new company was headquartered at 37 Weld Hall on the Harvard campus, and derived its name from the term "phonepterogram" which meant "to write with winged sounds." It is remarkable to consider the fact that Harvard student Mark Zuckerberg initiated his now ubiquitous company, The Facebook, in 2004 on the very same campus with a similar intent to connect students — almost 100 years after the first student ham stations set out to pursue a similar mission across "The Yard." This stunning fact further demonstrates how ham radio was the world's first social media enterprise, a century before it became commonplace over the internet.

In 1907, a young Harvard professor named George W. Pierce taught a new course, Physics 17, that dealt with high frequency currents and wireless telegraphy, and was named honorary president of the Harvard Wireless Club 1AF in 1909 after building a 5 kilowatt station in Jefferson Hall to teach the new class with experiments in wireless. This same professor would soon revolutionize the world with his discovery of the crystal oscillator.

Many articles and internet postings assert that the Harvard amateur radio club 1AF was founded by students Albert S. Hyman, Bob Almy, and Peggy Murray in 1909, and that the first letters of their three last names were used to create the term "ham," but this cannot be verified by the author and is refuted by evidence. In private communication with Harvard historian Paul Burchsted who consulted the "Quinquennial catalogue of the officers and graduates" [6], Harvard student Albert Solomon Hyman was born in Boston in 1893 and obtained a B.A. degree in 1915 and a M.D. degree in 1918, implying that he would not have likely been a student at Harvard in 1908. Hyman became a cardiologist in New York City and in 1928 was the first to introduce the use of a pacemaker to revive a heart that had stopped beating [7]. Robert Forbes Almy was born in New Bedford, MA in 1901 and would have been seven years old at the time of the founding of Harvard's radio club. Almy attended Harvard for his MA and Ph.D. degrees, which he obtained in 1925 and 1935, respectively, and became a beloved English professor at Miami University in Oxford, Ohio, where he studied American writers. While he enjoyed sailing and woodworking, no evidence can be found regarding his involvement with radio [8].

Regarding Peggy Murray, women were not admitted to Harvard until 1920, so it would have been odd for a woman to be a member of the Harvard radio club in 1908 (at that time, women attended Radcliffe University, its sister campus). Furthermore, a 1902 publication refers to "hams" as poor operators of the telegraph key, further dispelling the myth that student initials were used to form the term. It is possible, however, that the term "ham" was created by a shortening of the term "home amateur," as a disparaging comparison to professional telegraph operators at the turn of the century [1, 9].

Two other very early college amateur radio clubs include the Wireless Telegraph Club of Columbia University in New York City, which was launched in 1907 and 1908 with 25 student members and with the strong support of Professors Pupin and Crocker. In November 1908, students of Columbia's ham club made headlines in The Sun newspaper by stringing a 300′ wire antenna at a height of 100′ between the smoke stacks of University Hall and Havemeyer Hall [10]. This was just a year before its most famous wireless student, a lad by the name of Edwin Howard Armstrong, became a part of that campus club.

Meanwhile, students at the Massachusetts Institute of Technology (MIT) established the MIT Radio Society in 1909 using callsign 1MX, and liberally shared ideas and compared notes with the hams at Harvard. College ham radio clubs with on-campus radio stations began to spring up throughout the United States, including stations at Texas A&M University (1912), University of California (1914), Union College (1915), University of Arkansas (1916), and Purdue University (1919).

In Australia, radio enthusiasts young and old began meeting in Melbourne and Victoria between 1905 and 1910, forming the New South Wales Institute of Telegraphy in 1910 and the Wireless Institute of Victoria in 1911 (these eventually merged into the Wireless Institute of Australia). In Europe, the British Wireless Relay League and the Manchester Wireless Society had members before 1911, and the Radio Society of Great Britain (RSGB) was formed in 1913 from the London Wireless Club. All of these English clubs likely had college student members, but records are thin.

It is highly probable that Tohoku Imperial University became the home of Japan's first amateur radio club in the early 1920's, when Dr. Hidetsugu Yagi joined that school as an electrical engineering professor with vast experience and hands-on knowledge. While the Japan Amateur Radio League (JARL) was launched in 1926 by 37 hams, it is likely that the research and experiments led by Prof. Hidetsugu Yagi and his graduate student Shinatro Uda planted the seeds for amateur radio at Tohoku several years before then.

Yagi, born in Osaka, Japan in 1886, learned electrical engineering by first traveling to Europe, where he studied under the celebrated physicist and first German professor of electrical engineering, Heinrich Barkhausen. Barkhausen began his academic career in Dresden in 1911 and had just pioneered the generation of continuous wave (CW) oscillations by electric arcs. Later, Yagi joined the research program of Professor J.A. Fleming, the inventor of the vacuum diode pictured in Fig. 1.

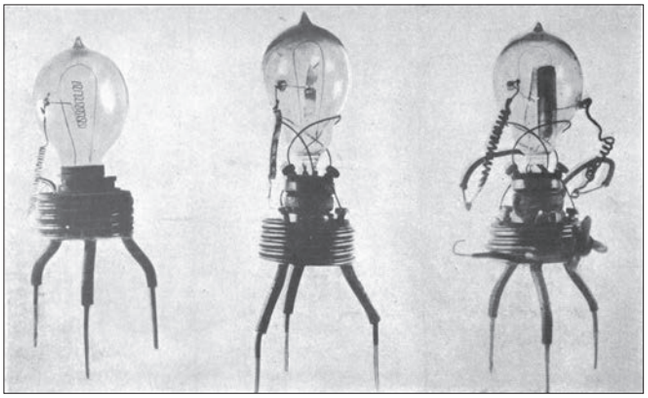
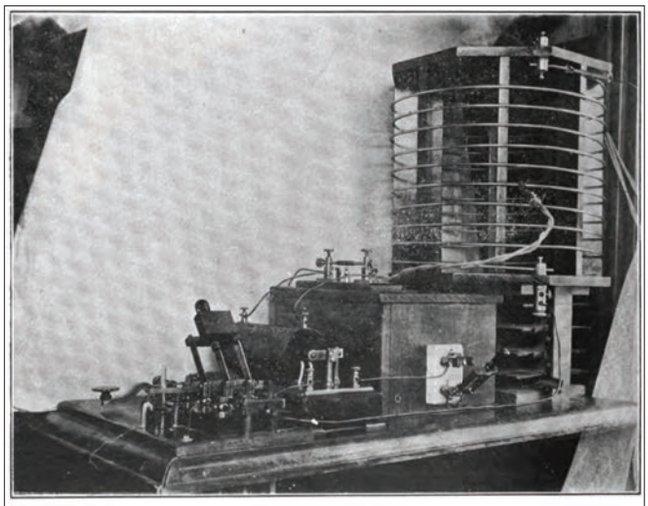


FIGURE 1. A photograph of the Fleming valve, the world's first vacuum tube invented in 1904 by John Ambrose Fleming. These tubes were used to receive radio waves by rectifying the current from the receiver antenna, and were also the first thermionic diodes. The tubes used an evacuated glass bulb that contained two electrodes: an extremely hot wire filament cathode that carried current within the tube, and a flat metal plate or coil which served as the anode. Functioning as the world's first tube diode, electrons flowed only in one direction, from filament to anode [3].



Station in Quincy Hall

FIGURE 2. Believed to be the first amateur radio station on a college campus, this wireless set was built by student Robert F. Gowen in 1905 at Quincy Hall at Harvard University [5].

Fleming was also the creator of the "right hand rule" to describe how the E-field and H-field propagate in free space, having been a student of James C. Maxwell (creator of Maxwell's equations).[1] After working with Fleming, Yagi then traveled to Harvard University to work with Prof. George W. Pierce who was in the midst of inventing his famous single-stage crystal oscillator that generated a continuous wave. The Pierce oscillator is a mainstay of telecommunications, even to this day. Yagi returned to Japan and earned his doctorate from Tokyo Imperial University in 1921, while teaching and building a wireless laboratory at Tohoku Imperial University in Sendai. Yagi was inter-

[1] John A. Fleming, the creator of the first vacuum tube, was a valued consultant at Edison Electric and Marconi, as well as a popular teacher at University College in London.

FIGURE 3. Professor Hidetsugu Yagi displays an example of the Yagi-Uda antenna that he and Shintaro Uda invented in 1924–25. (Photo copyright of HYS Engineering Services, Inc., used with permission).

ested in creating directional antennas, and found a particularly clever graduate student by the name of Shintaro Uda who was a tireless and brilliant experimenter. It was Uda who discovered the world's most popular directional antenna in Yagi's lab in 1924, and perfected it in 1925 [11].

Patented in 1926, the Yagi-Uda antenna (or more commonly called the Yagi, see Fig. 3 and Fig. 4) uses a driven dipole element and various parasitic elements called directors (positioned in front of the dipole and of slightly shorter length than the dipole) and reflectors (positioned behind the dipole and of slightly longer length than the dipole). The mutual coupling and phase differences caused by the parasitic elements focus the energy in a major boresight direction while creating broad nulls in other directions. The Yagi is still today the most commonly used directional antenna for HF, VHF, and UHF frequencies, and is used extensively for over-the-air television reception, police radio, utility communications, public safety, wireless internet service, HF communications at embassies and remote locations, as well as throughout the amateur radio hobby.

A fascinating account of the very slow adoption of the Yagi antenna inside of Japan after its discovery, the surrender of Singapore to the Japanese army in 1942, and the adoption of the Yagi and its use by allied forces in radar systems for advantage in World War II, is given by Prof. Sato of Sophia University in his article "A secret story about the Yagi Antenna," which appeared in the June 1991 issue of *IEEE Antennas and Propagation Magazine* [12].

The Yagi is used extensively by hams throughout the radio spectrum as it can be easily steered by a mechanical rotator to point to a particular direction for maximum gain with good front-to-back and sidelobe rejection (see Fig. 4 for a typical installation of Yagi antennas, as used by the author at his amateur radio station, N9NB, located on a ridge-top of the Blue Ridge mountains in Riner, Virginia).

The experiences of Yagi and Uda, and the pilgrimage of students and engineers worldwide who flocked to universities with active ham clubs and engaged professors to learn about the emerging field of radio, were a common theme in the early part of the 20th century. Thousands of young pioneers, inventors, and entrepreneurs honed their wireless communications and electronic skills as college students at college amateur radio stations, and as shown subsequently, perhaps none so famously as Edwin Howard Armstrong, the world's most influential wireless engineer who attended Columbia University from 1909–1913.

From Spark Gap to Continuous Wave to Voice Transmissions

Professor Reginald Fessenden and Lee de Forest had successfully pushed the wireless art away from its origins in Morse code and spark gap to a medium that could communicate voice and music. In fact, Fessenden, a Canadian radio pioneer, ham radio enthusiast, and inventor, had been working on voice transmissions by modulating a radio frequency wave since 1900, and reportedly stunned the world when he transmitted voice and music on December 24, 1906 from his radio station in Brant Rock, Massachusetts to boats at sea. Additionally, he had told newspapers he had made telephonic transmissions as early as 1900 as well as in 1905 [13, 14]. Such transmissions used amplitude modulation, since detectors in those days relied purely on rectification (e.g. envelope detection using devices such as shown in Fig. 1). Note that frequency tuning, filtering, and the use of mixers (also known as "heterodyning") were not well understood until around 1917 after Armstrong's first two major inventions.

During his historic radio broadcast on the eve of Christmas in 1906, Fessenden played "O Holy Night" on his violin, creating the world's first radiotelephone and symphonic broadcast, and ushering in the concept of radio broadcasting that would eventually take the world by storm until the advent of television decades later. Meanwhile, Lee de Forest, an avid tinkerer and showman, followed closely the work of the early pioneers, and filed a patent in 1906 on his Audion tube, the world's first triode vacuum tube which became the mainstay of radio circuits for most of the 20th century, even after the invention of the transistor in 1947. With the Audion, it became possible to move beyond simple rectification or switching, thus enabling amplifiers with a wide range of amplitude and phase characteristics to be manufactured, although de Forest didn't necessarily understand how to harness these capabilities at the time [15–17].

Lee de Forest sold his patents, including his pioneering Audion tube patent, to AT&T in 1913 just as the telephone company was rapidly expanding its national coverage. Not only did AT&T need the Audion to efficiently amplify voice signals across the thousands of miles of its cables, but it was also weary of the possibility that radio could displace its capitally-intensive wired telephone infrastructure. Even in these early days, AT&T was intrigued about the idea of using wireless to replace wires for long distance communication to lower its infrastructure costs, something that has indeed happened over the course of history. As shown subsequently, AT&T would soon rely on the breakthrough work of hams to provide the first international long-distance telephone service using high-frequency (HF) ionospheric propagation across the Atlantic Ocean.[2]

By the mid-1920s long distance lines connected every part of the United States, and were popping up in developed nations across the world [18].

The most spectacular wireless innovator and ham radio operator, who contributed the most to the global adoption of wireless, was Edwin Howard Armstrong, W2XMN. Born in New York

[2] In 1913, a Bell Telephone physicist named H. D. Arnold showed that the vacuum tube dictated the performance of long-distance telephone calls over wire. Arnold and his colleagues designed superior tubes and related circuitry, relying upon patents acquired from de Forest and Fessenden, to amplify long-distance telephone transmissions. Transcontinental telephone service between New York and San Francisco began in 1915, with Alexander Graham Bell making the first transcontinental phone call to Thomas Watson, his pioneering partner who had helped him develop the telephone four decades earlier. This first-of-its kind transcontinental phone line used 130,000 telephone poles, 2,500 tons of copper wire, and three vacuum-tube devices placed along the path to strengthen the signals. A 3-minute phone call cost $20.70 in 1915 ($617 in 2023 US dollars) [18].

City in 1890, Howard Armstrong became the most impactful experimentalist and inventor at the dawn of radio, and to this day the world relies upon his many inventions. Armstrong (see Fig. 5) was a member of the Radio Club of America from its very early days, and graduated from Columbia University with an electrical engineering degree in 1913.

Working with Professors John Morecroft and Michael Pupin at Columbia during his undergraduate studies, Howard Armstrong became an expert on vacuum tube technology and wireless communications, and in his junior and senior years of college, became the first to realize that de Forest's Audion tube was not only useful as a detector or rectifier, but importantly, that it could also be used as an amplifier when positive feedback was applied to the input. This discovery catapulted the radio field virtually overnight, as tubes could now be used to amplify weak wireless signals by hundreds or thousands of times. Armstrong's invention, known as regeneration, or the regenerative circuit (see Fig. 6), was awarded US patent 1,113,149 in October 1914, and was to become the first of Armstrong's 42 patents which greatly aided the wireless revolution that was to come. The Radio Corporation of America, the Marconi company, and Westinghouse Electric & Manufacturing all eventually licensed Armstrong's patents, which allowed radio equipment to be reduced from the size of a squash court to a small vacuum tube [17].

While serving as a major and captain in the US Signal Corps in France during World War I, Armstrong made his second great discovery in 1917 — the supersonic heterodyne, shortened to superheterodyne — which is still the mainstay of wireless transmitters and receivers today. Howard Armstrong's superheterodyne invention, US Patent 1,342,885, used an oscillating Audion tube to mix together signals of two different frequencies, resulting in a high- gain multiplication effect that produced sum and difference frequencies of the two applied signals. German inventor Walter Schottky independently discovered the same effect and received Deutsche Reich Patent 368,937 within the same year. With the invention of the superheterodyne, radios could now be adjusted in frequency and filtered for ultra-sensitive and very selective frequency tuning for both radio transmission and reception.

Throughout his lifetime, Armstrong made headlines due to his ingenuity, inventions, entrepreneurship, spectacular perseverance, and, ultimately, his tragic death. As discussed subsequently, Armstrong invented Frequency Modulation (FM) in 1933 and convinced the Federal Communications Commission to open up what are now globally known as the commercial FM radio bands, first allocated in the US to the very high frequency range (at the time) of 42–50 MHz, and later moved to 88-108 MHz after World War II. In the non-technical realm, Howard Armstrong was known for his death-defying acts of climbing large radio towers without using a belt or harness. While in his 20's, he famously proposed to his wife Marion while climbing atop the tallest radio towers in New York City, and sometimes celebrated major events throughout his career by perching himself atop the tallest tower steeples owned by the Radio Corporation of America in New York City [17]. In the end, Armstrong took his own life after suffering severe stress from decades-long patent litigation against Lee de Forest and AT&T, which became all-consuming and caused his marriage to deteriorate. He jumped to his death from his 13th floor Manhattan apartment building in 1954.

E. Howard Armstrong was the first person ever to receive electrical engineering's highest honor, the Medal of Honor (originally known as the "Gold Medal") from the Institute of Electrical and Electronic Engineering (IEEE, formerly known as the Institute of Radio Engineers, or IRE) in 1917, based on his earth-shattering regenerative and superhetrodyne discoveries. Because of restrictions on travel and meetings during World War I, his medal was not awarded in person until 1919. No medal was given in 1918, and Ernst Alexanderson, pioneering creator of a high-power alternating generator for radio wave transmissions, received the honor in 1919 at the same time Armstrong was given his 1917 award. Guglielmo Marconi, a licensor of Armstrong's patents, became the 3rd recipient of the Medal of Honor in 1920, and was most likely nominated or selected by a committee that included Armstrong. Reginald Fessenden received the honor in 1921, and in 1922 Lee de Forest, most likely nominated or supported by Fessenden (as both had sold patents earlier to AT&T), received the medal. John Stone Stone, an early telephone and radio inventor who sold patents to Lee de Forest and AT&T more than a decade earlier, was honored with the medal in 1923, having likely been nominated or selected by a committee that included de Forest and Fessenden. Armstrong's professor, Michael Pupin, received the honor in 1924. These early winners of the very top prize in electrical engineering belie the influence and rivalry that existed between Armstrong and de Forest, and between AT&T (the acquiror of de Forest and Fessenden patents) and the Radio Corporation of America and Marconi Company (who had licensed Armstrong's patents at the dawn of the wireless revolution).

Amateur radio operators rapidly adopted the new inventions of the Fleming valve, the Audion, the Pierce oscillator, and Armstrong's revolutionary discoveries, and began to incorporate regenerative receiver circuits and superheterodyning concepts

FIGURE 4. Installation of four Yagi antennas on the author's amateur radio tower on a ridge- top at station N9NB in Riner, Virginia. The lowest Yagi is a 4-element tri-band Yagi (10 m, 15 m, and 20 m bands) fixed towards Europe (NE direction), and the largest Yagi (by number of elements) is a rotatable tri-band Yagi at a height of 65' (shown here beaming towards Asia in the NW direction). The smallest Yagi is a dual-band VHF/UHF (6 m and 2 m bands) at a height of 68' that is also rotatable on the same mast, and the tallest Yagi is a rotatable two element mono-band 40 m Yagi at a height of 70', also rotated on the same mast. The height of a Yagi above ground and the nearby ground slope both impact the elevation angles with the greatest antenna gain. (Photo (c) T. S. Rappaport).

E. H. ARMSTRONG
The discoverer of the "feed-back" circuit, in the uniform of a major in the Signal Corps during the war

FIGURE 5. Photo of E. Howard Armstrong [19].

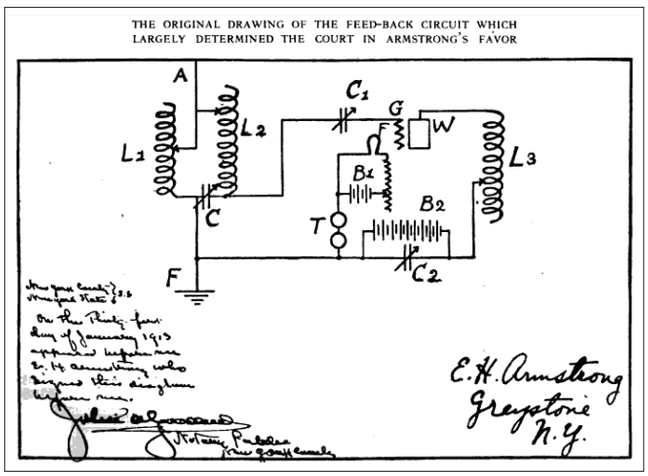


FIGURE 6. While a college undergraduate student at Columbia University, Armstrong invented the Regenerative Circuit that revolutionized wireless communications [19].

in their homebrew equipment. Magazines geared to hams and electronics hobbyists, such as *The Model Engineering and American Electrician*, *Amateur Work*, *Electrical Review*, *Western Electric*, *Scientific American*, *QST*, *Modern Electrics*, *The Electrical Experimenter*, and *Popular Science* advertised the new radio products, as amateur radio clubs touted the new inventions and rapidly disseminated the designs of new circuits [20, 21]. The pioneering inventors, themselves, such as Fessenden, Armstrong, and Marconi, met with amateur radio clubs on college campuses and in cities across the world to explain their inventions and the circuits that could use them. Hams had easy access to the very latest in radio innovation, and employed these new findings in their radio stations.

World War I and the Wireless Age

World War I erupted suddenly when Austria's Archduke Franz Ferdinand and his wife Sophie were assassinated by a Bosnian Serbian nationalist during an official visit to Serbia's capital, Sarajevo, on June 28, 1914. For the next five years, the global war effort would lean heavily upon the expertise of amateur radio operators, with governments enlisting ham radio operators to serve as military communications specialists, navigators, and researchers at government and industrial laboratories that were developing radio systems and jamming technologies at a feverish pace. Yet, the fledgling hobby would face challenging times as governments moved to assure no radio transmissions could be used by the enemy.

The electronics companies that had sprung up to serve the rapidly growing hobby and the new technology of wireless were immediately redirected to provide supplies and innovations for the war effort. Governments around the world suspended or terminated licenses for all amateur radio stations, requiring existing ham stations to be dismantled, and mandating a blanket of radio silence so that enemy eavesdroppers could not intercept messages or detect radio signals of any kind. Just two years earlier, the hobby of ham radio had become legitimized and was growing rapidly after President Taft in the United States signed the Radio Act of 1912 giving ham operators their own spectrum below 200 meters. Now, the hobby came to a dead stop because of WWI.

Given the rapid escalation of WWI, governments did not have time to train radio operators, and in a most fortuitous set of circumstances for the ham radio hobby, military units were forced to issue broad open calls for volunteers with radio skills to join the war effort. The skills and knowledge base of amateur radio operators of the day proved immense and effective, providing an instant talent pool. As an example, when the United States entered the war in 1917, it faced an extreme shortage of, and urgent need for, radio officers, instructors, operators, wireless engineers, and technicians. The US Navy, which had earlier been against the budding amateur radio enthusiasts before the Radio Act [1], now found itself in desperate need for help, at a time when there were about 6,000 US amateur operators. In a desperate plea, officials from the US Navy asked the newly formed national amateur radio club, the American Radio Relay League (ARRL), if it could immediately find 500 radio operators within a 10-day period. A last broadcast went out over the amateur radio airwaves across the US, just days before all ham stations were dismantled under the executive order for radio silence, and — voila — the Navy had its operators! It is estimated that over half of the US amateur radio operators, as many as 3,500–4,000, saw service in WWI, as the total number of Navy radiomen increased from 979 on January 31, 1917 to a total of around 6,700 at the time of Armistice on November 11, 1918.

Guglielmo Marconi, who became Commendattore of radio signaling for the Italian Army during the war, said "America is fortunate in having perfected its organization in the amateur field," while the US Secretary of Commerce William C. Redfield commented at war's end: "The officers in charge of the wireless operations of our armies in France commend highly the skill, ingenuity, and versatility of the licensed amateur radio operators who volunteered in large numbers for military service and served in dangerous and responsible positions" [16]. It is widely

believed that the advances made in the relatively new discovery of wireless during WWI set the stage for strategies for air and sea communications used in WWII [22].

Radio Goes Mainstream

After WWI, wireless communications became a fundamental part of society, as radios quickly filled homes, businesses, and vehicles throughout the world. In fact, the purchase of radios made them the world's most rapidly adopted technology in history at the time. In the early 20th century, the term "wireless" was used to describe over-the-air communications, but that term soon gave way to the word "radio," as broadcasting and the sale of radios became mainstream after WW I. Interestingly, it wasn't until the early 1990's, more than 75 years later, that the term "wireless" was used regularly by this author and came back into widespread use by mainstream society and the engineering and scientific communities, and we have been using "wireless" ever since [23, 24]. Amazingly, as now shown, the phenomenon of mainstream adoption of radio broadcasting was initiated exclusively by the commercialization of amateur radio stations and their operators.

From a ham radio station created originally by amateur operator Frank Conrad, with call sign 8XK in 1916, the world's first publicly celebrated amplitude modulated (AM) radio station, KDKA of Pittsburgh, Pennsylvania, made its commercial broadcast debut on November 2, 1920 by announcing the results of the US Presidential election between Warren Harding and James Cox. Westinghouse Electric and Manufacturing Company, a major wireless and power company headquartered in Pittsburgh, had acquired the ham station and saw the medium of radio as a new vista for growth. H.W. Harlin was hired as the world's first permanent radio announcer, later termed a "disc jockey," for playing phonograph records over the air at KDKA.

Lesser known is the fact that there were at least two other AM stations that preceded KDKA as the world's earliest broadcast station, including a ham station in 1912 operated by Charles "Doc" Herrold and his wife Sybil, owners of the Herrold College of Wireless and Engineering. The Herrolds operated an experimental station and taught radio operators beginning in 1909 in San Jose, California, using callsigns FN, SJN, 6FN, (which eventually became KQW, and finally the west coast CBS flagship station KCBS). This station was the world's first broadcasting station, and Doc Herrold is credited with coining the term "broadcast," that has been used in common language for over a century [25]. In Detroit, Michigan, ham station 8MK was called the "Radiophone' station, making broadcasts as early as August 20, 1920. Radiophone was purchased by the Detroit News to became station 8ZZ, later assigned callsign WBL, until it finally became known as it is today — Detroit's venerable all-news AM radio station WWJ [26, 27].

As was typical in the early days of radio, and still holds true today, young hams would tinker with components and build receivers to listen to these new AM broadcast stations that were popping up on the airwaves. Dubbed short wave listeners (SWLs), would-be ham radio enthusiasts would often first design and construct a receiving station to listen to far away broadcasters before applying for their "ticket" (e.g. amateur radio license). In fact, in 1920 during its first year of broadcasting, WWJ was the radio station that a boy named John Kraus listened to after making his first crystal radio set at the age of 10. That boy became the legendary Professor John Kraus, W8JK, a world-renowned researcher, educator, author, and ham radio operator in the field of antenna engineering. Kraus spent his entire career at Ohio State University, and stated often that his early experiences in building his first crystal radio set and listening to WWJ ignited his life-long interest in antennas, wireless and amateur radio [28]. As described in [1], a vast number of entrepreneurs and notable communications pioneers have similarly found their life-long interest in communications to be kindled from their early experiences as children when dabbling in amateur radio or tinkering with electronics. The author is personally aware of pioneering electrical engineers such as Leonard Kleinrock, a father of the Internet, and Henry Samueli, co-founder of Broadcom, as two of the many examples of child tinkerers, and this author similarly was captivated by his grandfather's shortwave radio at the age of 5 — and the passion has never left.

The power of radio ushered in a new era where people could hear news, music, sports, and entertainment in real time, well before anything would appear in the local newspaper. With the end of WWI, military leaders now realized the incomparable and vital capabilities of wireless communications, and the public's appreciation for wireless communications swelled. Savvy technical bureaucrats also realized the importance of the amateur radio hobby for the national good, particularly during war-time, and fostered public policy that would allow the amateur radio hobby to grow. Following WWI, almost overnight, radio became the most popular personal entertainment medium in the world, only to give way to television by the 1950s. Most of society had no idea of the role ham radio had played, and was yet to play, in this wireless revolution. In the 1920s, households around the world were purchasing radio receivers to listen to broadcasts being sent over the air in cities across the world. In fact, Westinghouse Corporation reported that in the USA alone, it could not keep up with demand for radio sets, producing 25,000 receivers a month in 1921, as revenues for receivers and radio parts in the USA ramped from $60 Million in 1922 to $358 Million in 1924 ($6.3 Billion in 2023 dollars). The golden age of radio was born [29]. While it is a little-known fact, history shows that the early commercial AM broadcast industry was spawned from individual amateur radio stations which were engineered, designed and often operated by hams. As AM broadcast stations began to spring up around the globe, ham operators began to explore the potential of long- distance wireless communications (DX) that would ultimately connect the planet.

Hams Go Global

Until 1921, no common citizen had ever communicated in real time with another person across an ocean. Sending messages overseas through ocean cables or radio telegraph using companies such as the Marconi Company was expensive. This all changed when a grand challenge was issued to the amateur radio community. In 1920, the fledgling periodicals and ham radio organizations that were springing up throughout the world were eager to foster experimentation in the hobby, while equipment vendors — the sponsors of these publications and organizations — wanted to advertise their latest electronic components in hopes that hams would purchase them to build superior radio stations [1]. Wireless World magazine and ARRL publicized the idea of transatlantic tests throughout 1920, in an effort to spur on focused efforts of hams to communicate across the Atlantic (Fig. 7). While Marconi had heard the letter "S" sent in 1901 from across the Atlantic, this was done with extremely high power and tall antennas, and there was skepticism that entire messages could ever be communicated over such distances by modest means. The amateur radio transatlantic tests were heralded as the unifying event that would allow the hobby to perfect the radio art for greater capabilities.

On a few well-publicized winter weekends from 1920 through 1922, certain evenings were set aside for amateur operators all over the USA and Europe to attempt to cross the Atlantic Ocean. The first contests were to have stations in the USA transmit in Morse code continually for hours, while stations in Europe were to log what they received. At the same time, hams throughout the world were encouraged to make long distance

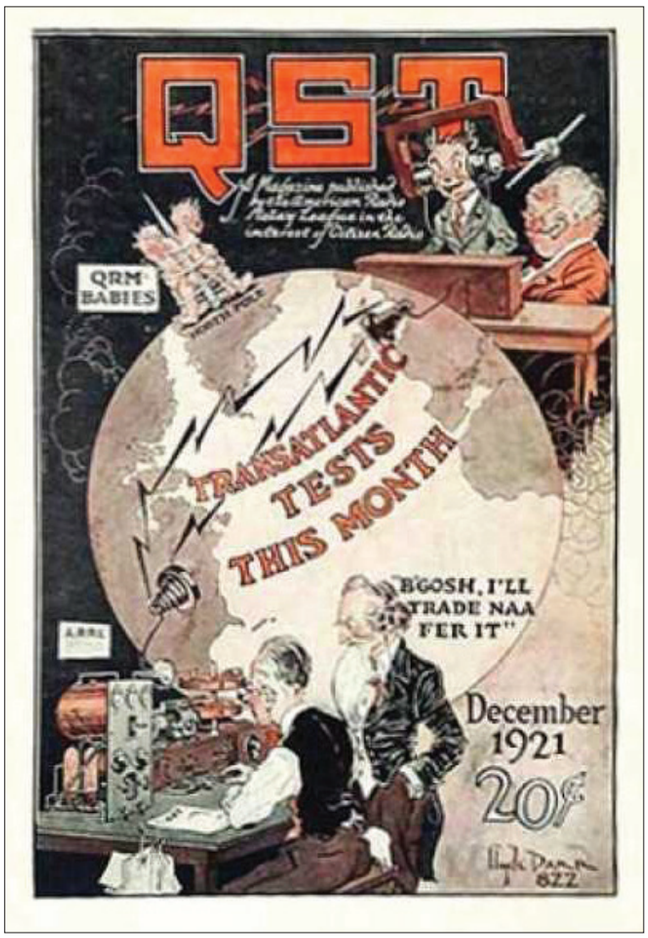


FIGURE 7. The cover of the December 1921 QST Magazine, promoting the transatlantic ham radio contest of late 1921 and early 1922.

two-way contacts with as many stations as possible, and as far away as possible. These transatlantic tests were sponsored by the American Radio Relay League and the Wireless Society of London (later renamed the Radio Society of Great Britain, or RSGB) [30, 31] and set the stage for competitive contesting, an aspect of the hobby which is still very popular today. Although the contests in 1920 and the week of February 1921 failed to provide any concrete one-way transatlantic contacts, the second test of 1921, conducted in December, unequivocally proved to the world that intercontinental real-time communication was viable with modest amateur radio stations [32, 33, 34].

Paul F. Godley, 2ZE, a young American engineer employed with the American Radio Relay League (or simply called "the League"), was viewed to be one of the world's best radio operators, and was sent to England by boat by his employer in the Fall of 1921. At the young age of 23, Godley had earlier helped build an "Amazon to the Andes" radio service for Brazil in 1913, and had established his own electronics components business under the name Paragon Paul. Now, at age 32, Godley was working for the League using his custom-designed 9-tube superhetrodyne receiver and flexible receiving circuits for the 200–250 meter bands, and was sent on a mission by the ARRL to detect the first-ever transatlantic transmission by ham operators in the second transatlantic test held in the winter of 1921–22. On the ship to England, Godley happened by chance to meet a young engineer who worked for the Radio Corporation of America (RCA). This engineer, Harold H. Beverage, also a ham, had just invented a traveling wave antenna that provided remarkable long-range low-noise reception — the ideal antenna for DX reception! Beverage shared his design with Godley on the boat, hoping with confidence that it would enable successfully reception of many ham stations across the Atlantic ocean.

H. H. Beverage's breakthrough antenna, a wave antenna made of just a simple piece of wire that is several wavelengths (several hundreds of meters) long and runs in a straight line along the direction of desired reception situated only a couple of meters above ground, is still used by hams around the world more than 100 years later, and is still the gold standard antenna for low noise High Frequency (HF) reception. Godley used this directional antenna, which has become famously known as the "Beverage Antenna" for his receiving station that he used in Scotland with great success for the second contest [15].

Harold Beverage's antenna was later used by AT&T, RCA, and telephone companies around the world to facilitate long distance telephone calls throughout much of the 20th century (until the deployment of undersea coaxial cables in the late 1950s, satellites in the 1970s, and undersea fiber optic cables in the late 1980s) [35, 36]. Long distance telephone companies such as AT&T would purchase dozens of acres of land near the sea to fabricate miles and miles of Beverage antennas which were oriented to point towards the continent of desired interest, in order to receive ionospheric telephone transmissions throughout much of the 20th century. Large vertical transmitting antenna arrays were often deployed on the same plot of land, but several acres away from the receiving system in order to provide isolation when operated in full duplex mode to support two-way telephone calls.

Working with RCA, Beverage helped engineer the famous RCA Radio Central station at Rocky Point, Long Island, New York, which was inaugurated on November, 5 1921, as the world's most powerful transoceanic radio facility at the time (Fig. 9 shows an antique radio shack from this site). Located at Rocky Point and Riverhead, New York, its Alexanderson 220 kW, 18.3 kHz transmitters and Beverage long-wire receiving antennas provided reliable worldwide radio communications. In succeeding years, RCA's research laboratory also developed diversity radio reception, rhombic and folded-dipole antennas, the first transoceanic single side-band (SSB) channels, and commercial facsimile service.

Yet, through his career at RCA, and even when serving as president of the IRE in 1937, Harold "Bev" Beverage, 2BML remained a ham at heart and was an active member of the venerable Radio Club of America [37], spending free time experimenting and talking with other ham radio operators who desired to improve their stations.

As the telephone industry was just building out equipment and vast transmitter and receiver systems to test, improve, and establish voice telephone circuits that would cross the globe using wireless communication over shortwave frequencies, hams were already conducting regular transatlantic communication with each other using very modest stations and antennas. The first regular successful two-way transatlantic communications occurred with Connecticut USA station 1MO and French station FAB. The hams conducted regular, hour-long Morse code two-way communications. After the transatlantic tests of December 1921 and January 1922 showed remarkable success, the hobby of amateur radio had a new quest — to more reliably communicate over long distance (DX) paths using even smaller wavelengths (higher frequencies) and more modest stations [38].

The ionosphere had not yet been formally discovered or explained, but it was found and already used by hams! It wasn't until 1924, when Edward Appleton conducted foundational experiments to show that radio waves could refract, and bend around earth thanks to an ionized layer of the atmosphere several hundred kilometers above earth, that the ionosphere would become known and understood. Appleton developed the theory

of the ionosphere, still used today, that showed how the particular radio frequency and the time of day (which dictates the ionization density and height above earth due to the relative strength of sun) can facilitate global shortwave communications. Appleton received the Nobel Prize for his ionospheric work in 1947, yet hams had conquered the ionosphere years before its discovery.

Global radio broadcasts sprung onto the scene once it was revealed by hams that global communication was viable with modest equipment. The British Broadcasting Company (BBC) was founded on October 18, 1922 with the backing of leading wireless manufacturers including Marconi. Shortwave stations used the newly discovered global reach of wireless to beam programming into homes around the world at a time when electricity, indoor plumbing and running water was not available in most homes. Radio receivers of the time were powered primarily by batteries purchased at the local hardware store. Global shortwave stations sprung up throughout the world to broadcast news, music, entertainment, religious teachings, and propaganda, following on the footsteps of the rapid adoption of commercial AM radio. Radio receivers began incorporating both AM and shortwave bands in their offerings, as the world began to tune in for real-time global news, sports and entertainment [29].

Hams to the Rescue

The dramatic rescue at sea of 700 of the 2,200 passengers of the HMS Titanic in 1912 opened the world's eyes to the value of wireless communications and the capabilities of ham radio. Now, with a proven ability to communicate around the world, hams served a vital early role for long distance and global communications when commercial services either did not exist or were not readily available.

The discovery of the ionosphere in the 1920s led to deep knowledge of how the various ham bands would work at different times of day and in different seasons of the year. Night time was ideal for local and regional communications of up to a few hundred km on the low bands after sunrise (e.g. frequencies below 7 MHz, or wavelengths greater than 40 meters) since the ionosphere collapsed in density and height above earth. Broad daylight was best for local and regional communications up to several hundred km on 7 MHz (i.e., 40 meters), whereas long distance (DX) global communications was best supported on the high bands (e.g. 14 MHz and above, which are at wavelengths of 20 meters or shorter) when the sun was shining over half the earth and the ionosphere was rapidly expanding. Remarkable but albeit somewhat rare long-distance contacts could also be achieved via the grey line, a propagation path made across the circumference of the earth which divides sunlight and darkness.

Hams continually improved their stations, their knowledge of HF propagation, and engaged in new antenna designs to maximize their ability to communicate anywhere in the world, with good likelihood they could communicate wherever they wanted, as long as the ionosphere and their equipment cooperated. Regularly scheduled message passing networks, called "traffic nets" were set up between hams throughout the world on the various ham bands, to maintain a regular forum to relay messages (called "traffic") that citizens, or hams themselves, might wish to send. The regularly scheduled nets across the world gave assurance to the ham community that if there was ever a local, regional, national, or global disaster, there would always be scheduled times for amateur radio operators to maintain communications throughout the world.

The children's book *Radio Rescue* is based upon true-life experiences and describes how in 1923 a young boy with the call sign 2AKZ used ham radio to rescue a family caught in a flood 1000 miles away. It gives a very realistic account of the world of communications in the 1920s and how ham radio played a vital role in emergency situations [39]. Since the advent

FIGURE 8. In January 1922, the cover of QST Magazine proclaimed the early successes of transatlantic communications by ham operators.

of the hobby, hams have been famous for providing support for rescue operations, or providing emergency communications (known as EmComm) when commercial means were non-existent or unavailable. Today, hams can be found providing support of community and sporting events throughout the world, as well as for emergencies of all kinds.

In the United States and Canada, the Amateur Radio Emergency Service (ARES) is an extensive organization of volunteer hams throughout North America who participate in on-line training, and then offer free EmComm services for virtually any cause that needs non-business communications support, using the copyrighted motto "When all else fails" [40]. Countries all over the world have well organized EmComm groups of amateur operators dedicated to providing voluntary and emergency communications.

Another of the many facets of amateur radio, closely related to EmComm at the formation of the hobby, is known as *contesting*, also called *radiosport*. Contesting evolved in the 1920s as the number of amateur operators around the world began to swell. Contests were held over one or several weekends, in a non-stop 48-hour period per weekend, and were generally announced through global ham publications and at ham clubs a year in advance. These days, contests do not last longer than 48 hours over a single weekend.

Contests allow any amateur radio operator in the world to make as many radio contacts with other amateur radio operators, using a very brief, emergency-like message exchange for each contact during the contest. Winners are those with

FIGURE 9. A photo of Guglielmo Marconi (L) and Edward Howard Armstrong taken by Harold Beverage in 1933 at RCA's Babylon Shack in Rocky Point, NY. The photo shows the two pioneers standing at the famous wireless shack originally constructed for Marconi's company in 1902, and subsequently purchased by Armstrong, who gave it to David Sarnoff as a gift when Sarnoff was president of Radio Corporation of America [35] (Photo Courtesy of North Haven Historical Society, used with permission)

the greatest number of contacts and the greatest number of unique or farthest away countries. Various categories allow different types of stations (e.g. high power, low power, single operator, multi-operator) to compete with similarly-designed stations in their own country and throughout the world. From the very early contests, score multipliers (known as "mults") were provided to bring a strategic element to contesting, and to incentivize the design and construction of improved equipment and antennas. Mults boost the score with greater points per contacts made on particularly difficult frequency bands (such as the low bands of 7 MHz, 3.5 MHz or 1.8 MHz, where static is greatest at night and high gain antennas are more difficult to build). Duplicate contacts ("dupes"), where the same station is contacted more than once on a particular band, are not included in the scoring, and in the early days created scoring penalties, since volunteers had to manually cross check by hand all of the submitted paper logs for accuracy and adjudication — today, computers handle this chore, and logs are submitted electronically immediately at the end of the contest by email or over an internet webpage. Amateur radio contests of a wide range of varieties can be found on the airwaves virtually every weekend of the year, and are extremely helpful in allowing amateurs to test and improve their station design while improving their operating prowess under difficult conditions, with little sleep, on crowded bands (e.g, with a great deal of QRM due to widespread participation on the band). The CQ World Wide (CQWW) contest is one of the most popular global DX contests today, with over 50,000 amateurs participating during the last full weekend of September using radioteletype (RTTY), the last full weekend of October for SSB, and end of November for CW. The World Radiosport Team Championship (WRTC) is known as the "ham radio Olympics." WRTC typically involves the top 100 contesters in the world who compete every 4 years during the global International Amateur Radio Union (IARU) radiosport contest [41]. WRTC was most recently held in Bologna, Italy in July 2023, delayed a year by the Corona virus epidemic.

Hams in amateur radio clubs around the world also hone their EmComm and operating skills by participating in an annual *field day*. Field day is a special weekend for every amateur radio operator, as well as would-be hams, as it offers a chance to set up and operate virtually every communications mode and frequency band during a simulated emergency event, using tents, emergency power, and hastily erected antennas. The first national field day is believed to have been held during a summer weekend in 1933 in the United States, and amateur radio clubs throughout the world have been setting up in the field every year since. The public is always encouraged to participate in field day operations, and special stations at most field day sites are created to allow the public to try their hand at operating a radio and making a contact while learning about the hobby.

The use of the amateur radio spectrum for emergency communications is and has always been a main theme of the hobby since inception. It is simply impossible to account for all of the ways that amateur radio has played a vital role in protecting the health and safety of citizens, but there are a few legendary examples that are noteworthy, as they vividly demonstrate how the decentralized, non-commercial nature of ham radio offers unique capabilities when commercial or military means are not available.

One of the earliest and most public display of amateur radio's amazing ability to offer unique communications to remote regions of the world was during the 1925 American expedition to Greenland sponsored by the US Navy Bureau of Aeronautics. The expedition involved airplanes and ships, and was led by Admiral Richard E. Byrd, a famed aviation explorer who would eventually become the first person to fly over both the north and south poles, and Donald Baxter MacMillan, a renowned civilian explorer who had been at the North Pole in 1909 as part of an early expedition to conquer the arctic. Byrd and MacMillan were joined together on a unique military/civilian expedition, despite objections of some in the Navy to involve a civilian counterparty. MacMillan prepared his famous ships, the Bowdoin and the Perry, to set sail with supplies, dogs and dogsleds, and crew (which included radio operator John L. Reinartz and Admiral Byrd) from Maine in early 1925.

The plan was for the Bowdoin to make daily radio reports to the U.S. Naval radio station as it sailed to and around Greenland, but because of atmospheric problems, the Navy receiving station in Washington, D.C., was unable to consistently receive transmissions from the Bowdoin. Ham radio came to the rescue, and made global headlines when a 15-year-old boy in Cedar Rapids, Iowa by the name of Art Collins, the grandnephew of A. Frederick Collins (an early pioneer of wireless [42]), was able to consistently make radio contact with the expedition [43]. Throughout the summer of 1925, the Collins boy accomplished a task that even the U.S. Navy found difficult. Using a ham radio that had built himself, the boy talked by Morse code with Reinartz in Greenland, consistently night after night. His signals reached the expedition more clearly than any other, and after every broadcast, young Collins took the messages from the expedition down to the Cedar Rapids telegraph office, and relayed to Washington the scientific findings that the exploratory group had uncovered that day.

Collins' exclusive and reliable radio contact with the expedition soon became a nationwide news story that won him acclaim as a radio wizard. The August 4, 1925 *Cedar Rapids Gazette* told the story:

> "The mysterious forces of air leaped the boundary of thousands of miles to bring Cedar Rapids in touch with the celebrated MacMillan scientific expedition at Etah, Greenland, and wrote a new chapter into the history of radio. Sunday, Arthur Collins, 514 Fairview Drive, 15-year-old radio wizard, picked up the message from the expedition's ship Bowdin, at twenty meters (wavelength), at about 3 o'clock and conversed in continental code for more than one hour. It was the first time the expedition and any United States radio station had communicated at that wavelength. Messages were received by Collins for the National Geographic Society, which is sponsoring the expedition, and for others, and were sent out from here by telegraph.
>
> Arthur Collins is the son of Mr. and Mrs. M.H. Collins and is a student at Washington High School. He has been a radio fan for years, and has himself constructed most of his apparatus. His equipment is in a small room on the third floor of the Collins home. His station is known as 9CXX. The local boy told a Gazette reporter today that although he had been in wireless communication with Australia, Scotland, England, India, Puerto Rico, Guam, and Mexico, he never had received a greater thrill than when he talked to his friend on the famous expedition bound northward to explore a mystic continent."

Excerpt from Aug. 4, 1925 Cedar Rapids Gazette Newspaper, describing the heroic radio feats of young Art Collins.

One week later, a follow-up article in the *Gazette* concluded: "Though only 15, he is true to his trust. For he hopes to realize great radio ambitions, by and by."

At the age of 16, Collins was asked to write a technical article for *Radio Age* which was published in the May 1926 issue. One statement in that article foreshadowed the motivational force which was to lead him to great radio ambitions. The young Art Collins penned: "The real thrill in amateur work comes not from talking to stations in distant lands ... but from knowing that by careful and painstaking work and by diligent and systematic study you have been able to accomplish some feat, or establish some fact that is a new step toward more perfect communication."

Collin's reputation in the radio world grew dramatically. Radio operators around the country who had heard about his contacts with the MacMillan expedition wrote to him to ask how he did it. Unselfishly, typified by the ham spirit, Art Collins shared eagerly and often his experiences and expertise with anyone who cared to learn, well into adulthood. His passion for improved radio communications drove him to launch the famed Collins Radio Company, which became a global manufacturer of military, aeronautical, space, and amateur radio communications gear.

Collins had a particular fascination in Single Side Band (SSB) voice communications and personally invested time and resources to create a novel mass-produced mechanical filter that made commercial SSB possible, and his amateur radio and military products pioneered the use of SSB throughout the world. Collins Radio was acquired by Rockwell International to form Rockwell-Collins in 1973.

Another fascinating example of ham radio coming to the rescue was on April 2, 1982, when a junta from Argentina led by General Leopoldo Galtieri invaded and held the Falkland Islands for over two months by first taking control of the capital city, Port Stanley. The Falklands is a group of several hundred islands located in the South Atlantic Ocean, about 500 km south of the southern tip of South America. During the invasion and throughout the occupation, amateur operator and farmer Tony Pole-Evans of Saunders Island in the Falklands was able to use his clandestine ham radio station and antenna to maintain the only link that Britain would have to fight and win the war. Pole-Evans would send very brief radio transmissions (so as not to be detected by Argentinian troops) to Les Hamilton, GM3ITN in Scotland over HF frequencies in the ham bands, and Les would relay vital real-time British air and ground troop information to the military [44].

On the day of the invasion, local hams in the Falklands reported on a local net that ground troops and warships were invading the capital yet the world had no idea, and upon hearing this, well-known Falkland ham radio operator Bob McLeod, VP8LP, was able to make contact over HF with Laurie Margolis, G3UML, at the BBC News Service in London. Bob was able to give eye-witness accounts of the invasion, and urged the BBC to alert its listeners as well as the British military of the attack. A video and audio reenactment of the first amateur radio contact after the invasion can be found on the web, simply search for "Falklands invasion contact reconstructed," or visit https://www.youtube.com/watch?v=9ulDliwfjyQ. Over 1,000 lives were lost during the invasion of the Falklands, but the death count would likely have been much greater had it not been for ham radio.

Hams aided thousands of citizens who were stranded up and down the east coast of the United States in August 1955, when back-to-back hurricanes hit the Delaware Valley [45]. In the face of the fiercest cyclones Idia and Kenneth ever to hit Africa, the government of Mozambique recently turned to investing and encouraging amateur radio for emergency communications services. The Emergency Telecommunications Cluster (ETC), the World Food Programme's Technology division in Mozambique, and the National Institute for Disaster Risk Management and Reduction, have supported the National Institute of Communications in Mozambique (INCM) to set up a prototype ham radio station in the port city of Maputo, capable of connecting with any location in the country. The investment in ham radio stations will follow across Pemba, Beira, Niassa, Lichinga, Tete, Zambezia and Inhambane provinces, with a goal of providing emergency backup communications while encouraging technical exploration and learning [46].

The Invention of FM Unleashes the Mobile Phone Industry

About a decade after hams had mastered the art of routinely communicating across the globe on HF frequencies, E. Howard Armstrong was about to stun the world with his genius once again. On December 26, 1933, Armstrong, W2XMN, a giant in the world of wireless as well as in ham radio, (https://www.qrz.com/db/w2xmn) received US patent 2,630,497 for his invention of Frequency Modulation (FM) using multiplexing (e.g. left and right stereo channels for each ear). Armstrong by this time was already known as a founding father of wireless through his inventions of the regenerative oscillator circuit in 1913 (US Patent 1,113,149 issued in 1914), and the superhetrodyne cir-

FIGURE 10. Motorola (then called Galvin Manufacturing) created the world's first FM handie-talkies for combat use before WW II. This product was a prelude to the cellphone revolution that amateur radio operators enabled using FM repeaters they deployed across the world throughout the 1960's and 1970's.

cuit in 1917 (US Patent 1,342,885 issued in 1920), a technique still used in most wireless transceivers to this day. He became wealthy by selling the rights to some of his patents to Westinghouse in 1920 just before Westinghouse launched the operation of KDKA. In 1923, on his honeymoon, Armstrong gave his wife Marion the world's first portable superheterodyne receiver, which resides in the Henry Ford museum collection [47]. It was Armstrong's invention of super-regeneration, the ability to control oscillations at great amplitude in both transmission and reception, that made Armstrong a household name, as he sold that patent to Radio Corporation of America (RCA) in 1922, making him the largest shareholder of RCA at the time.

While RCA was originally founded in 1919 as a patent trust owned by General Electric (GE), Westinghouse, AT&T and United Fruit Company, it was through Armstrong's involvement that it became one of the world's largest manufacturers of radios and televisions.[3] A fascinating and well-prepared account of the life and ingenuity of Edwin Howard Armstrong, as well as the epic personal and professional trials that surrounded the formative years of the radio art and the exploits of two other giants at the dawn of wireless, Lee de Forest and David Sarnoff, is found in the book by Tom Lewis, *Empire of the Air — the Men who Made Radio* [17]. A powerful tribute to Armstrong appeared in Columbia University's Columbia Magazine in 2002 [48]. The author, to this day, shows the movie rendition of "Empire of the Air," produced by Ken Burns and Public Broadcasting Corporation (PBS), as the very first lecture in his semester-long college course on wireless communications.

Armstrong's invention of wideband FM, and his tenacious, in fact relentless, efforts to popularize it with a chain of FM broadcasting stations that he built across the east coast of the USA in the late 1940's and early 1950's, not only ushered in the era of FM radio broadcasting that we know of today, but also launched the television industry and the embryonic mobile radio industry, both which relied upon FM for high fidelity audio quality. It was FM that became the backbone of all audio transmissions, due to its immunity to amplitude variations created by lightning, car ignitions, or signal fading due to motion. Armstrong's invention and commercialization of FM came more than a decade after AT&T researcher John R. Carson (of "Carson's rule" and single sideband fame) had initially discovered narrowband FM and declared it an inefficient modulation. Just like with his invention of superheterodyning and the regenerative oscillator, Armstrong's new discovery of wideband FM set off another massive frenzy of investment, research, and product development, as the world rushed to understand and commercialize this newfound approach to sending high fidelity voice and music via a radio carrier, albeit with wider channel bandwidths than ever known before.

Because of the wider bandwidth required of FM, carrier frequencies that were much higher than the existing spectrum had to be used in order to "find space on the bands" and avoid creating interference to incumbent narrowband users. Amateur operators were among the very first to experiment with the new modulation of FM by creating portable handheld devices at the much higher carrier frequencies of UHF or VHF. Miniaturization of equipment in the 1930's and 1940s required extremely rigorous designs, as vacuum tubes were the key active components of the day. The transistor had not yet been invented — it would not be discovered and adopted until the late 1940's and early 1950's. Despite the limitations of vacuum tubes, the walkie-talkie came into being, with nicknames such as "handie-talkie," and "HT." These devices had short battery lifetimes with a weight of several pounds primarily due to the battery. It was mostly hams who comprised the engineering teams led by Don Mitchell and Dan Noble at Galvin Manufacturing (later to be named Motorola) that designed the world's first widely distributed hand-held VHF portable radios in 1940: the SCR-536 (which used AM, led by Mitchell) and SCR-300 (which used FM, led by Noble). These HT's were used widely during WW II with great success by allied ground troops. Even before WW II, Motorola's founder Paul Galvin saw great potential in FM and the coming age of mobile and portable communications, and successfully recruited Dan Noble away from the faculty of Connecticut State College in 1940 after reading that Noble had developed the first FM radio system for police cars in the Connecticut State Police force. After joining Galvin, Noble went on to convince the military complex, and then police and public safety users throughout the world, to adopt FM for mobile and portable communication systems. In 2000, the IEEE created the Daniel E. Noble Technical Field Award by renaming the IEEE Morris N. Liebmann Memorial Award in Noble's honor.

Another ham, Al Gross, W8PAL, a teenager at the time, had developed a prototype hand-held walkie-talkie two years earlier in 1938, using miniaturized tubes mounted on special bakelite ceramic substrates and with circuits crafted by Nobel laureate Jack Kilby, W9GTY. Kilby would go on to become the creator

[3] An antitrust settlement by the US Government forced RCA to become an independent company in 1932 because of the enormous growth and influence of radio.

of the integrated circuit after the transistor was invented [1]. The original Al Gross walkie talkie operated above 250 MHz, quite a feat for the era, and well above any known operating receivers at the time, but was kept top-secret and out of the public eye for decades. The original working Al Gross UHF walkie-talkie prototype is on permanent exhibit on the campus of Virginia Tech in Blacksburg, VA, where he occasionally lectured at the invitation of the author in the latter years of his life [1].

One of the more important developments made by FM enthusiasts in the ham radio hobby was the creation of the *FM repeater* (also called a *digipeater*) and the use of an *autopatch* (an automated phone patch) that would serve a local geographic area the size of a large city or county. Repeaters had already been developed for the commercial land mobile radio industry after the discovery of FM to facilitate mobile fleet and public safety applications, leading to the creation of trunked mobile radio systems [24]. Yet, until the advent of FM, virtually all of the spectrum used by hams had been between the range of 1.8 to 30 MHz (the HF bands, also known as the shortwave bands). FM provided superior audio quality, eliminated the fading that was commonplace on the already popular CW, AM and single-sideband (SSB) modes, and allowed hams to experiment with television and data signals using much greater bandwidths than was allowed at HF. Greater bandwidths required spectrum allocations at much higher frequencies than the existing shortwave bands, causing hams to successfully petition their governments to allocate new spectrum in the VHF, UHF and microwave bands for amateur radio use. In addition to wider permitted bandwidths above HF, hams were granted authority by their governments in the 1960s to use the amateur spectrum to operate remote, automated relay stations for the first time [49].

An amusing account of the exploration and early design of ham radio repeaters in 1963 is given by repeater pioneer Gene Mitchell, K3DSM, when he was a high school and college student [50]. These new amateur radio privileges unleashed a rapid infrastructure development phase with rich technical learning that would catapult the hobby into new realms, changing the world yet again.

With new spectrum and automated remote relay station privileges, VHF and UHF ham radio repeater stations suddenly began proliferating rapidly across the globe. A repeater was typically owned by a local amateur radio club, and provided all hams with open radio access across a large city or county. The repeater allowed hams to use their low power VHF or UHF FM radio sets to communicate over a large geographic area, typically with a range of 25 miles or more. Ham clubs across the world began to set up repeaters in the 2 m band (144–148 MHz) with repeater antennas mounted atop tall buildings, towers, or hilltops. Using very tall repeater stations, a club could facilitate the communications of a wide range of users throughout a city or county, since the repeaters could receive weak signals from a large constituency of mobile or portable ham users in the geographic region, and then retransmit the station's signal with a powerful signal on a different frequency over the same large geographic region. Ham clubs across the US and other countries in the world blanketed the earth with individually operated repeaters, so that traveling hams could easily remain in communication with other hams while driving in their cars for long distances. In this manner, it became possible for hams from all over a county or city, or newcomers to the area, to acquaint themselves with other hams in the area.

Each repeater base station consisted of a dual frequency (frequency division multiplexing, half- duplex) FM high-power transmitter and ultra-sensitive receiver, and employed cavity resonators to provide strong isolation between the sensitive receiver uplink and powerful downlink transmission frequencies. The most common early repeaters, still in use today, used a 600 kHz frequency split between the uplink and downlink channels, and operated at a carrier frequency of about 145 MHz. Finding a good repeater site was always a hot topic at amateur radio club meetings, with the goal of finding the very best building or hilltop so that an omnidirectional antenna could be used to provide maximum coverage distance during transmission along with good reception for low power mobile users in all possible directions [51].

The rollout of repeaters allowed any local ham in earshot of the repeater to have instant access to the entire geographic area when transmitting on the repeater's uplink frequency and listening on the repeater's downlink frequency. Traveling hams, driving through a particular community, could access the repeater and instantly communicate with other amateur operators who were monitoring the repeater. In this manner, ham operators became accustomed to global mobile communications using portable FM radios and handie-talkies. In just a few years, by the late 1960's, the entire planet was blanketed with UHF repeaters run by hams sponsored by ham clubs, that allowed any amateur operator, anywhere, to have instant voice communication with local hams over a repeater [52]. One of the truly amazing features about the global ham radio repeater buildout is that many of these repeaters were equipped with an autopatch feature, which allowed ham operators to make automated touch-tone telephone calls from their car or mobile walkie-talkie. The birth of the cellphone industry, and as shown in Part 3 of this series, in fact much more, can be traced to this global repeater buildout by the ham radio community.

Hams had for decades used long distance HF frequencies to provide *phone patch* capabilities to friends, family members, and strangers. Missionaries, volunteer workers, and other non-business global travelers relied on the international goodwill of amateur radio operators and the free airways of ham radio for global telephone calls, in lieu of paying exorbitant long-distance telephone prices, so they could economically stay in contact with their families while traveling to remote places on earth. A phone patch was a piece of audio switching equipment that a ham operator would use to connect the ham station to his or her landline telephone to enable a two- way audio connection between the ham radio set and the telephone line. The phone patch provided a telephone-to-radio interface to the ham station, allowing a ham radio operator to offer a pivotal relay service for two-way communication between a landline user and a remote ham radio station. A remote traveler could find or call (over the telephone) a ham radio operator in their toll-free vicinity, who could then make an over-the-air DX contact via the ionosphere to a ham radio operator in the traveler's home country. As long as both ham operators had phone patches in their shacks, and the two hams were each in a toll-free local calling area of the two non-ham citizens, the two ham operators could host a phone call QSO between the traveler and the traveler's family at absolutely no cost, with two ham stations serving as over-the-air relays.

This was one of the many services offered by amateur radio, and was meaningful in its day since international long distance telephone charges could run as high as several dollars per minute before the birth of the internet and Voice over Internet Protocol (VoIP).

Now, with new regulations that allowed automated remote control, it became possible for hams to use FM repeaters to automatically initiate landline calls while in their car or on the move.

Beginning in 1971, the ARRL began publishing a repeater directory that provided a listing of all the locations and frequencies of FM repeaters in the United States, and other countries had similar publications that gave all hams the access information to any repeater, wherever they traveled. Today, such listings are provided on-line and in cellphone applications by many sources, such as the one hosted by IZ8WNH [53]. This was a game changer for amateur radio, and for the world of mobile communications.

Using an autopatch on an UHF FM repeater, any operator could make local phone calls over the repeater. Using a dual tone multi-frequency (DTMF) touch tone keypad, a ham could bring up the repeater and then use the repeater's autopatch to place a local telephone call over the air, a harbinger to the cellular telephone revolution that would soon follow. The autopatch allowed the repeater station to automatically initiate an outbound telephone call over a landline telephone connection, thereby allowing any mobile user of the repeater to originate a telephone call that would be carried over the airwaves to the repeater, and then connected over a telephone line to a landline user. In essence, hams had the ability to originate mobile telephone calls wherever they were in the world, using their HTs. There was generally a restriction imposed by the repeater owner that all calls had to be local to the repeater, so that no long-distance landline toll charges were incurred by the repeater operator. Also, since all repeater traffic was broadcast over the entire coverage area of the repeater — open for eavesdropping — and restricted for non-business use, anyone listening to the repeater downlink frequency could hear both sides of the conversation, so the calls were purely for hobby use.

By the late 1960s, hams around the world had embraced mobile phone communications and were using it in their daily lives. It is without question that the global ham radio FM repeater buildout provided a great deal of the engineering prowess and expertise, as well as a certain confidence and "can-do" spirit, while providing the human capital that enabled the rapid buildout of the world's first cellular telephone networks of the 1980s and 1990s. To this day, virtually all of the very early engineers who got their start in the cellphone revolution can trace their roots to exposure to ham radio and the early use or development of FM repeaters. We shall see in Part 3, the final article in this series, how the incredible infrastructure buildout of FM repeaters and the use of mobile communications by hams around the globe played a major role in launching breakthroughs in the fields of digital communications, computing, packet radio, satellite communications, and environmental sensing. This major adoption of a mobile communications architecture — the FM repeater, and a mobile communications device, the HT — by the global amateur radio community was just the start of an entirely new phase of innovation for the hobby that would shape our world today and for decades to come.

Conclusion

Part 2 of this series has demonstrated the immense impact that the hobby of amateur radio and its enthusiastic cadre of operators have had in the creation and establishment of real-time wireless communications throughout history. The ham spirit of experimentation, a quest for knowledge, and a passion for sharing ideas and tinkering with, and then adopting, the most recent technological developments, is seen to have brought us the information age that we enjoy today. Were it not for hams around the globe, and their indominable spirit, the adoption and use of radio would have been much greatly delayed, and certainly not likely to have happened in such a grand and ubiquitous manner.

As with most high-tech breakthroughs, universities, with their youthful, engaged students and visionary faculty, played a vital role as crucibles for the creation and dissemination of the principles and practice of wireless. Yet, it was the ham radio inventors and pioneers, and the innumerable ham radio clubs who made themselves available to others and shared their insights, that perpetuated the fundamental understanding and adoption of real-time communications using the medium of wireless. This article has attempted to document how radio, and the allure of its invisible magic, captivated the hearts and minds of all hams throughout history, no matter what their status, their station in life, their country of origin, or their perceived importance on the world stage.

We have seen in Part 2 the triumphs of just a sliver of the many ham radio pioneers who persevered and labored tirelessly, relentlessly, to understand and then to master the electronic breakthroughs that comprise the myriad communication devices and architectures that we take for granted in our daily lives. By understanding the ingenuity and impact that past pioneers, many of them ham radio operators, have had on the electrical engineering field, we begin to better understand in a larger context just how their ingenuity enabled new realms of innovation and new waves of investment, all which have continued to propel the information age. We also are able to better understand the significance of the individuals named on the various major technical awards given by the IEEE and other technical societies as a means to honor modern day innovators.

As discussed in the final article, Part 3 of this series, the global buildout of FM repeaters by hams not only created the workforce and technical knowledge that enabled the cellular telephone revolution, but also gave great confidence to the ham community as it continued to lead the way, as pioneers, in packet radio networking, digital communications, computing, satellite communications, software defined radios, ionospheric sounding, and space weather, all which have a prominent impact on our daily lives today and into the future.

References

[1] T. S. Rappaport, "Crucible of Communications: How Amateur Radio Launched the Information Age and Brought High Tech to Life; Part 1: The Birth and Breadth of the Ham Radio Hobby," (Invited Article), *IEEE Commun. Mag.*, vol. 60, no. 10, Oct. 2022, pp. 6–10; https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9928087.

[2] J. Green, "The Apparatus for Wireless Telegraph," *American Electrician*, July 1899.

[3] IEEE Milestone, Fleming Valve, 1904. See: https://ethw.org/Milestones:Fleming_Valve,_1904 and https://en.wikipedia.org/wiki/Fleming_valve#/media/File:Fleming_valves.jpg.

[4, J. S. Bellrose, "Fessenden and Marconi: Their Differing Technologies and Transatlantic Experiments During the First Decade of this Century," *Proc. 1995 Int'l. Conf. 100 Years of Radio*, 5–7 Sept. 1995

[5] R. A. Morton, '11, "The Wireless at Harvard," *Harvard Illustrated Magazine*, 1909, vo. 10, p. 131–35; https://hdl.handle.net/2027/nyp.33433076016132 see also: https://web.archive.org/web/20220216171322/http://w1af.harvard.edu/php/history.php.

[6] Author Correspondence with Paul Burchsted, Research Librarian for Harvard University, Aug 7-10, 2023.

[7] "ALBERT HYMAN, 79, CARDIOLOGIST, DIES," *New York Times*, Dec. 9, 1972.

[8] "Memorial to Robert F. Almy," The University Senate of Miami University, Feb. 6, 1969.

[9] G.M. Dodge, The Telegraph Instructor, self-published by the author, c. 1903, Valparaiso, Indiana, USA.

[10] "Wireless Club at Columbia: Disputes with the Aero Club the Monopoly of Morningside Air," *The Sun*, New York, NY, Nov. 25, 1908. Chronicling America: Historic American Newspapers. Lib. of Congress; https://chroniclingamerica.loc.gov/lccn/sn83030272/1908-11- 25/ed-1/seq-2/.

[11] M. Ishuguro *et al.*, "Highlighting the History of Japanese Radio Astronomy: 1: An Introduction," *J. Astronomical History and Heritage*, Nov. 2012, vol. 15, no. 3, 2012, pp. 213–31.

[12] G. Sato, "A Secret Story About the Yagi Antenna," *IEEE Antennas and Propagation Magazine*, vol. 33, no. 3, June 1991, pp. 7–18. DOI: 10.3724/SP.J.1440-2807.2012.03.06.

[13] "Wireless Telephone Has Been Perfected," Pittsburgh Press, May 20, 1902, 9.8.

[14] D. Halper, C. Sterling. "Fessenden's Christmas Eve Broadcast: Reconsidering an Historical Event," *Antique Wireless Association Review*, vol. 19, 2006, p. 127.

[15] R. A. Bartlett, *The World of Ham Radio, 1901–1950*, McFarland and Company, Inc., c. 2007

[16] C. B. DeSoto, *Two Hundred Meters and Down, The Story of Amateur Radio*, The American Radio Relay League, Inc, c. 1936

[17] T. Lewis, *Empire of the Air: The Men Who Made Radio*, Harper Collins, New York, 1991.

[18] G. Constable and B. Somerville, *A Century of Innovation: Twenty Engineering Innovations that Transformed our Lives, Telephone History Part 3 — Long Distance*, Joseph Henry Press, c. 2003, see also http://www.greatachievements.org/?id=3633.

[19] E. H. Armstrong, *Radio Broadcast*, Vol. 1, No. 1, 1922

[20] T. H. White, *United States Early Radio History*, an on-line book about the early history of radio in the United States. www.earlyradiohistory.us

[21] A. F. Collins, "How to Construct an Efficient Wireless Telegraph Apparatus at a Small Cost," *Scientific American Supplement*, Feb. 15, 1902, pp. 21,849–21,850, and also in *Scientific American*, Sept. 14, 1901.

[22] H. J. S. Tworek, "Wireless Telegraph," *Int'l. Encyclopedia of the First World War*, Version 1, Oct. 14, 2014, online encyclopedia https://encyclopedia.1914-1918-online.net/article/wireless_telegraphy.
[23] T. S. Rappaport, "The Wireless Revolution," *IEEE Commun. Mag.*, vol. 29, no. 11, Nov. 1991, pp. 52–71.
[24] T. S. Rappaport, *Wireless Communications: Principles and Practice*, 1st Edition, Prentice-Hall, New Jersey, c. 1996.
[25] R. L. Hillard and M. C. Keith, *The Broadcast Century and Beyond, 5th Edition*, Focal Press, 2010.
[26] T. L White, "The Broadcaster's Desktop Resource: High Powered History, WWJ's Beginnings, 95 Years Ago," Aug. 2015; https://www.thebdr.net/wp- content/uploads/PDF/Profiles/Broadcast-History/wwjs-beginnings-95-years-ago.pdf.
[27] C. B. Young, "WWJ — Pioneer in Broadcasting," Michigan History, Dec. 1960, vol. 44, no. 4.
[28] J. D. Kraus, *Big Ear*, 1976, Cygus-Quasar Books, Powell, Ohio, USA, c. 1976.
[29] S.J. Douglass, *Listening In, Radio and the American Imagination*, Chapter 2 "Ethereal World," University of Minnesota Press, c. 2004.
[30] "Transatlantic Sending Tests," *QST Magazine*, Feb. 1921, ARRL, p. 20.
[31] "QRV for the Transatlantics?," *QST Magazine*, Nov. 1921, ARRL, p. 10.
[32] P. F. Goldely, "Official Report on the Second Transatlantic Test," *QST Magazine*, Feb. 1922, p. 14.
[33] Transatlantic Tests, RSGB; https://rsgb.org/main/activity/transatlantic-tests/.
[34] M. Marinaro, WN1M, "The Transatlantic Tests," *QST Magazine*, May 2014, pp. 72–73.
[35] A. I. Wallen, *Genius at Riverhead, A Profile of Harold H. Beverage*, North Haven Historical Society, North Haven, Maine, c. 1988.
[36] G. Huston, "At the Bottom of the Sea: A Short History of Submarine Cables," Feb. 12, 2020, Asia Pacific Network Information Centre (APNIC); https://blog.apnic.net/2020/02/12/at-the- bottom-of-the-sea-a-short-history-of-submarine-cables/.
[37] *Proc. Radio Club of America*, Diamond Jubilee issue, 75th Anniversary of the Radio Club of America, 1984. In this issue, it shows that H. H. Beverage became a member of the Radio Club of America in 1920, a Fellow in 1926, a Life Member in 1971, received the club's prestigious Armstrong Award in 1938, and the rarely issued Pioneer Award in 1976.
[38] Transatlantic Tests, Part 4, RSGB; https://rsgb.org/main/activity/transatlantic-tests/tests-4/.
[39] L. Barasch, "Radio Rescue," Frances Foster books, c. 2000.
[40] Emergency Communications, American Radio Relay League, Newington, Connecticut, USA; https://www.arrl.org/emergency-communications-training.
[41] J. K. George, *Contact Sport: A Story of Champions, Airwaves, and a One-Day Race around the World*, c. 2016.
[42] A. Frederick Collins, "The Collins Wireless Telephone," *Scientific American*, July 19, 1902, pp. 37–38.
[43] A. Perry, "Riding the SHORT WAVES," Radio Age, Nov. 1925, pp. 11–12; https://earlyradiohistory.us/1925col.htm.
[44] "Clydebank Radio Ham Helped to Win Back the Falklands," *The Scotsman*, March 24, 2002.
[45] G. Hart, W1NJM, "The Great Flood of 1955: Amateurs by the Thousands Come to the Aid of Stricken Communities," *QST Magazine*, Oct. 1955, pp. 11–18.
[46] E. Millership, "Tuning in to 'Amateur' Radio Airwaves in Mozambique: Ham Radio Strengthens Emergency Telecommunications Preparedness in Disaster-Stricken Mozambique," *World Food Program*; https://www.wfp.org/stories/tuning-amateur-radio-airwaves-mozambique.
[47] THF156549, " First Portable Superheterodyne Radio Receiver, "Made by Edwin Howard Armstrong, 1923, Gifted to The Henry Ford by Marion Armstrong;" https://www.thehenryford.org/collections-and-research/digital-collections/artifact/256388/
[48] Y. Tsividis, "Edwin Armstrong: Pioneer of the Airwaves," *Columbia Magazine*, April 1, 2002, Columbia University.
[49] The History of the Northeast FM Repeater Association; http://nfmra.org/nfmra-history/.
[50] Gene Michael, K3DSM; http://www.g-c-o.com/k3dsm/repeater.htm
[51] K. W. Sessions, "The Radio Amateur's F-M Repeater Handbook," Editors and Engineers, Ltd; c. 1969.
[52] B. Pasternak, *The Practical Handbook of Amateur Radio FM & Repeaters*, c. 1980, TAB Books, Blue Ridge Summit.
[53] WWW.IZ8WNH.IT: "Let's Map Together Ham Radio Repeaters and Beacons;" https://www.iz8wnh.it/.

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