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Chapter

1

Power Vacuum Tube Applications

1.1 Introduction

The continuing demand for energy control devices capable of higher operating power, higher maximum frequency, greater efficiency, and extended reliability have pushed tube manufacturers to break established performance barriers. Advancements in tube design and construction have given engineers new RF generating systems that allow industry to grow and prosper. Power grid vacuum tubes have been the mainstay of transmitters and other RF generation systems since the beginning of radio. Today, the need for new gridded and microwave power tubes is being met with new processes and materials.

Although low-power vacuum tubes have been largely replaced by solid-state devices, vacuum tubes continue to perform valuable service at high-power levels and, particularly, at high frequencies. The high-power capability of a vacuum device results from the ability of electron/vacuum systems to support high-power densities. Values run typically at several kilowatts per square centimeter, but may exceed 10 MW/cm^2. No known dielectric material can equal these values. For the foreseeable future, if high power is required, electron/vacuum devices will remain the best solution.

It is worthwhile to point out that certain devices within the realm of *receiving tubes* still continue to find application within high-end audio systems. A select group of tubes never went out of style because of their intrinsic benefits, at least as perceived by elements of the audiophile community. These “golden devices” include the 12AT7, 12AU7, 12AX7, 6L6, 6V6, and even the 5U4. These components are used today not just in classic 1960s-era audio amplifiers, but also in new microphone preamps and power amplifiers manufactured for sale to discriminating customers.

1.1.1 Vacuum Tube Development

Receiving tubes have more or less disappeared from the scene (the foregoing notwithstanding) because of the development of transistors and integrated circuits. Power grid and microwave tubes, however, continue to push the limits of technology. Power tubes are an important part of RF technology today.

From 1887—when Heinrich Hertz first sent and received radio waves—to the present, an amazing amount of progress has been made by engineers and scientists. The public takes for granted today what was considered science fiction just a decade or two ago. The route from the primitive spark-gap transmitters to the present state of the art has been charted by the pioneering efforts of many. It is appropriate to review some of the milestones in electron tube development. Much of the fundamental work on power vacuum devices can be traced to early radio broadcasting, which—along with telephone technology—has brought the nations of the world closer together than the early pioneers of the art could have imagined. More than 80 years have passed since Charles D. (Doc) Herrold founded a *voice station* (as it then was known) at San Jose, CA. Developments since have been the result of many inspired breakthroughs and years of plain hard work.

Pioneer Developers

In 1895, 21-year-old Guglielmo Marconi and his brother Alfonso first transmitted radio signals across the hills behind their home in Bologna, Italy. Born in 1874 to an Italian merchant and a Scotch-Irish mother, young Marconi had learned of Hertzian waves from August Righi, a professor at the University of Bologna. Convinced that such waves could be used for wireless communication, Marconi conducted preliminary experiments using a spark-gap source and a coherer detector. Unable to interest the Italian government in his invention, Marconi took his crude transmitter and receiver to England, where he demonstrated his wireless system to officials of the British Post Office. Marconi received a patent for the device in July 1897. With the financial support of his mother's relatives, Marconi organized the Wireless Telegraph and Signal Company that same year to develop the system commercially. Regular transatlantic communications commenced in 1903 when a Marconi station at Cape Cod, MA, sent a short message from President Theodore Roosevelt to King Edward VII in England.

The invention of the vacuum tube diode by J. Ambrose Fleming in 1904 and the triode vacuum tube amplifier by Lee De Forest in 1906 launched the electronics industry as we know it. The De Forest invention was pivotal. It marked the transition of the vacuum tube from a passive to an active device. The new "control" electrode took the form of a perforated metal plate of the same size and shape as the existing anode, positioned between the filament and the anode. Encouraged by the early test results, De Forest worked to perfect his invention, trying various mechanical arrangements for the new grid.

With the invention of the control grid, De Forest had set in motion a chain of events that led the vacuum tube to become the key element in the emerging discipline of electronics. Early experimenters and radio stations took this new technology and began developing their own tubes using in-house capabilities, including glassblowing. As the young electronics industry began to grow, vacuum tubes were produced in great quantity and standardized (to a point), making it possible to share new developments and applications. A major impetus for standardization was the U.S. military, which required vacuum tubes in great quantities during World War I. Pushed by the navy, a standardized design, including base pins and operating parameters, was forged. The economic benefits to both the tube producers and tube consumers were quickly realized.

Most radio stations from 1910 through 1920 built their own gear. For example, at the University of Wisconsin, Madison, special transmitting tubes were built by hand as needed to keep radio station 9XM, which later became WHA, on the air. The tubes were designed, constructed, and tested by Professor E. M. Terry and a group of his students in the university laboratories. Some of the tubes also were used in wireless telephonic experiments carried on with the Great Lakes Naval Training Station during 1918, when a wartime ban was imposed on wireless broadcasts.

It took many hours to make each tube. The air was extracted by means of a mercury vapor vacuum pump while the filaments were lighted and the plate voltage was on. As the vacuum increased, the plate current was raised until the plate became red-hot. This *out-gassing* process was primitive, but it worked. The students frequently worked through the night to get a tube ready for the next day's broadcast. When completed, the device might last only a few hours before burning out.

Plate dissipation on Professor Terry's early tubes, designated #1, #2, and so on, was about 25 W. Tube #5 had a power output of about 50 W. Tubes #6 to #8 were capable of approximately 75 W. Tube #8 was one of the earliest handmade commercial products.

The addition of a "screen" grid marked the next major advancement for the vacuum tube. First patented in 1916 by Dr. Walter Schottky of the Siemens & Halske Company (Germany), the device garnered only limited interest until after World War I when the Dutch firm, Philips, produced a commercial product. The "double-grid" Philips *type Q* was introduced in May 1923. Later variations on the initial design were made by Philips and other manufacturers.

Early in the use of the tetrode it was determined that the tube was unsuited for use as an audio frequency power amplifier. Under certain operating conditions encountered in this class of service, the tetrode exhibited a negative-resistance characteristic caused by secondary emission from the anode being attracted to the positively charged screen. Although this peculiarity did not affect the performance of the tetrode as an RF amplifier, it did prevent use of the device for AF power amplification. The pentode tube, utilizing a third ("suppressor") grid was designed to overcome this problem. The suppressor grid provided a means to prevent the secondary emissions from reaching the screen grid. This allowed the full capabilities of the tube to be realized.

Philips researchers Drs. G. Holst and B. Tellegen are credited for the invention, receiving a patent for the new device in 1926.

Radio Central

The first major project that the young Radio Corporation of America tackled was the construction of a huge radio transmitting station at Rocky Point, NY. The facility, completed in 1921, was hailed by President Harding as a milestone in wireless progress. The president, in fact, put the station into operation by throwing a switch that had been rigged up at the White House. Wireless stations around the globe had been alerted to tune in for a congratulatory statement by the president.

For a decade, this station—known as *Radio Central*—was the only means of direct communications with Europe. It was also the "hopping off" point for messages transmitted by RCA to Central and South America.

The Rocky Point site was famous not only for its role in communications, but also for the pioneers of the radio age who regularly visited there. The guest book lists such pioneers as Guglielmo Marconi, Lee De Forest, Charles Steinmetz, Nikola Tesla, and David Sarnoff. Radio Central was a milestone in transatlantic communications.

Originally, two antenna structures stood at the Rocky Point site, each with six 410 ft towers. The towers stretched over a 3-mile area on the eastern end of Long Island.

The facility long outlived its usefulness. RCA demolished a group of six towers in the 1950s; five more were destroyed in early 1960. The last tower of the once mighty Radio Central was taken down on December 13, 1977.

WLW: The Nation's Station

Radio station WLW has a history as colorful and varied as any in the United States. It is unique in that it was the only station ever granted authority to broadcast with 500 kW. This accomplishment pushed further the limits of vacuum tube technology.

The station actually began with 20 W of power as a hobby of Powell Crosley, Jr. The first license for WLW was granted by the Department of Commerce in 1922. Crosley was authorized to broadcast on a wavelength of 360 meters with a power of 50 W, three evenings a week. Growth of the station was continuous. WLW operated at various frequencies and power levels until, in 1927, it was assigned to 700 kHz at 50 kW and remained there. Operation at 50 kW began on October 4, 1928. The transmitter was located in Mason, OH. The station could be heard as far away as Jacksonville, FL, and Washington, DC.

The superpower era of WLW began in 1934. The contract for construction of the enormous transmitter was awarded to RCA in February 1933. Tests on the unit began on January 15, 1934. The cost of the transmitter and associated equipment was approximately $400,000—not much today, but a staggering sum in the middle of the Great Depression.

At 9:02 p.m. on May 2, 1934, programming was commenced with 500 kW of power. The superpower operation was designed to be experimental, but Crosley managed to renew the license every 6 months until 1939. The call sign W8XO occasionally was used during test periods, but the regular call sign of WLW was used for programming.

"Immense" is the only way to describe the WLW facility. The antenna (including the flagpole at the top) reached a height of 831 ft. The antenna rested on a single ceramic insulator that supported the combined force of 135 tons of steel and 400 tons exerted by the guys. The tower was guyed with eight 1-7/8-in cables anchored 375 ft from the base of the antenna.

The main antenna was augmented by a directional tower designed to protect CFRB, Toronto, when the station was using 500 kW at night. The directional system was unique in that it was the first designed to achieve both horizontal directivity and vertical-angle suppression.

A spray pond in front of the building provided cooling for the system, moving 512 gallons of water per minute. Through a heat exchanger, the water then cooled 200 gallons of distilled water in a closed system that cooled the transmitting tubes.

The transmitter consumed an entire building. Modulation transformers, weighing 37,000 lb each, were installed in the basement. Three plate transformers, a rectifier filter reactor, and a modulation reactor were installed outside the building. The exciter for the transmitter produced 50 kW of RF power. A motor-generator was used to provide 125 V dc for control circuits.

The station had its own power substation. While operating at 500 kW, the transmitter consumed 15,450,000 kWh per year. The facility was equipped with a complete machine shop because station personnel had to build much of the ancillary hardware needed. Equipment included gas, arc and spot welders, a metal lathe, milling machine, engraving machine, sander, drill press, metal brake, and a table saw. A wide variety of electric components were also on hand.

WLW operated at 500 kW until March 1, 1939, when the FCC ordered the station to reduce power to 50 kW. The station returned to superpower operation a few times during World War II for government research. The days when WLW could boast of being “the nation’s station,” however, were in the past.

UHF: A New Technical Challenge

The early planners of the U.S. television system thought that 13 channels would more than suffice. The original channel 1 was from 44 MHz to 50 MHz, but because of possible interference with other services, it was dropped before any active use. There remained 12 channels for normal broadcasting. Bowing to pressure from various groups, the FCC revised its allocation table in 1952 to permit UHF-TV broadcasting for the first time. The new band was not, however, a bed of roses. Many people went bankrupt, building UHF stations only to find few receivers were available to the public. UHF converters soon became popular. The first converters were so-called matchbox types that were good for one channel only. More expensive models mounted on top of the TV receiver and were tunable. Finally, the commission issued an edict that all TV set manufacturers had to include UHF tuning in their receivers. This move opened the doors for significant market penetration for UHF broadcasters.

The klystron has been the primary means of generating high-power UHF-TV signals since the introduction of UHF broadcasting.

Birth of the Klystron

Quietly developed in 1937, the klystron truly revolutionized the modern world. Indeed, the klystron may have helped save the world as we know it. More than 50 years after it was first operated in a Stanford University laboratory by Russell Varian and his brother Sigurd, the klystron and its offspring remain irreplaceable, even in the age of solid-state microelectronics.

The Varian brothers were unusually bright and extremely active. Mechanically minded, they produced one invention after another. Generally, Sigurd would think up an idea, Russell would devise a method for making it work, then Sigurd would build the device.

Through the influence of William Hansen, a former roommate of Russell and a physics professor at Stanford University, the Varians managed to get nonpaying jobs as research associates in the Stanford physics lab. They had the right to consult with members of the faculty and were given the use of a small room in the physics building.

Hansen's role, apparently, was to shoot down ideas as fast as the Varians could dream them up. As the story goes, the Varians came up with 36 inventions of varying impracticality. Then they came up with idea number 37. This time Hansen's eyes widened. On June 5, 1937, Russell proposed the concept that eventually became the klystron tube. The device was supposed to amplify microwave signals. With $100 for supplies granted by Stanford, Sigurd built it.

The device was simple: A filament heated by an electric current in turn heated a cathode. A special coating on the cathode gave off electrons when it reached a sufficiently high temperature. Negatively charged electrons attracted by a positively charged anode passed through the first cavity of the klystron tube. Microwaves in the cavity interacted with the electrons and passed through a narrow passage called a *drift tube*. In the drift tube, the electrons tended to bunch up; some speeded up, some slowed down. At the place in the drift tube where the bunching was most pronounced, the electrons entered a second cavity, where the stronger microwaves were excited and amplified in the process.

The first klystron device was lit up on the evening of August 19, 1937. Performance was marginal, but confirmed the theory of the device. An improved klystron was completed and tested on August 30. The name for the klystron came from the Greek verb *klyzo*, which refers to the breaking of a wave—a process much like the overtaking of slow electrons by fast ones.

The Varians published the results of their discovery in the *Journal of Applied Physics*. For reasons that have never been clear, their announcement immediately impressed British scientists working in the same field, but was almost entirely ignored by the Germans. The development of the klystron allowed British and American researchers to build smaller, more reliable radar systems. Klystron development paralleled work being done in England on the magnetron.

The successful deployment of microwave radar was accomplished by the invention of the cavity magnetron at Manchester University in the late 1930s [10]. It was one of Britain's "Top Secrets" handed over to the Americans early in the war. The cavity magnetron was delivered to the Radiation Laboratory at MIT, where it was incorporated into later wartime radar systems. During the Battle of Britain in May 1940, British defenses depended upon longer wavelength radar (approximately 5 m), which worked but with insufficient resolution. The magnetron provided high-power microwave energy at 10 cm wavelengths, which improved detection resolution enormously.

Armed with the magnetron and klystron, British and American scientists perfected radar, a key element in winning the Battle of Britain. So valuable were the secret devices that the British decided not to put radar in planes that flew over occupied Europe lest one of them crash, and the details of the components be discovered.

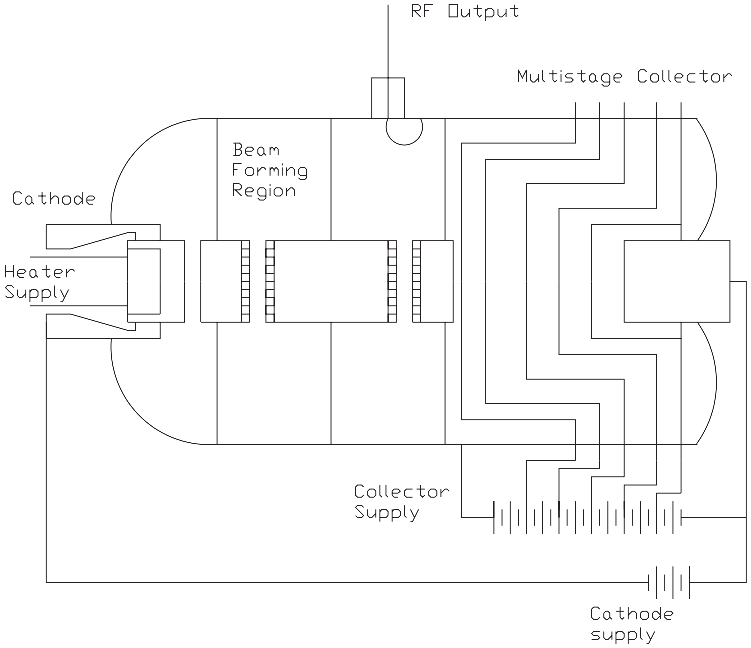

Figure 1.1 Simplified drawing of a multistage depressed-collector klystron using six collector elements.

After the war, the Varians—convinced of the potential for commercial value of the klystron and other devices they had conceived—established their own company. For Stanford University, the klystron represents one of its best investments: $100 in seed money and use of a small laboratory room were turned into $2.56 million in licensing fees before the patents expired in the 1970s, three major campus buildings and hundreds of thousands of dollars in research funding.

At about the same time the Varian brothers were working to perfect the klystron, Andrew Haeff of RCA Laboratories was developing what would come to be known as the *inductive output tube* (IOT). The crucial feature in both devices was that the electron beam, having given up a large part of its energy in a small, low-capacitance gap, tended to spread because of space-charge effects (the mutual repulsion of electrons). The characteristics of electron flow make it possible to use multiple collectors with differing potentials in tubes with large energy spread in the spent electron beam, such as the klystron and IOT. This *multistage depressed-collector* (MSDC) technique results in a considerable increase in operating efficiency. One of the earliest patents on the MSDC was issued in 1943 to Charles Litton, who later formed a company that would become Litton Industries. Figure 1.1 shows the basic MSDC structure, developed from the original Litton patent.

Nuclear Magnetic Resonance (NMR)

NMR, a technique that has revolutionized chemistry throughout the world, had its origins in experiments carried out on opposite sides of the North American continent in the late 1940s. As is often the case with basic discoveries in science, the original intent of the work was far removed from the ultimate practical application. NMR was first demonstrated during the winter of 1945 by professors Felix Bloch and William Hansen and their associates at Stanford University. At the same time another group was working independently at Harvard University, directed by Dr. E. M. Purcell. The Nobel Prize for physics was awarded to Bloch and Purcell in 1952 in recognition of their pioneering work in NMR, which allows chemists to make structural determinations of substances, and thereby see how a molecule is put together.

The Transistor Is Born

In December 1947, Dr. William Shockley of Bell Laboratories changed the course of history by demonstrating to his colleagues a newly discovered device that exhibited what he called the *transistor effect*. From this demonstration, and a later one at the Bell Labs in New York City on June 30, 1948, sprang one of the most important inventions of the 20th century—the working transistor. (The phrase “transistor” came about from a contraction of “transfer resistor.”) For their development efforts, Bell Telephone scientists John Bardeen, Walter H. Brattain, and William Shockley received the Nobel Prize for physics in 1956.

The first experimental transistor made its debut as a 3/16-in-diameter, 5/8-in-long metal cylinder. Today, transistors are fabricated in dimensions finer than the wavelength of light. The first integrated circuit, made more than 30 years ago, had two transistors and measured 7/16-in-long and 1/16-in-thick. Today, a VHSIC (very high speed integrated circuit) die with more than 10 million transistors is in production for use in desktop computer systems.

The transistor was an economical and durable alternative to receiving vacuum tubes. The tubes were big, fragile, and had a relatively short operating life. They consumed lots of power and, as a result, got very hot. Transistors offered a way to make a product that was compact, efficient, and reliable.

What made transistors distinctive was that they were fabricated from a single solid material that either insulated or conducted, depending on the purity of the base material. A solitary transistor could be scribed on nothing more than a chip of germanium (subsequently supplanted by silicon). Eager to exploit the riches of solid-state technology, engineers drew up complicated circuits, cramming boards of discrete devices into tight little islands.

Satellite Technology

The phrase “live via satellite” is commonplace today. Communications satellites have meant not only live coverage of world events, but also more service to more people at lower cost. The potential for use of satellites for communications was first demonstrated in 1960 with the launching by the United States of Echo 1 and Echo 2. These passive reflector satellites bounced radio signals across the Atlantic. This type of satellite, however, left a lot to be desired for communications purposes. Echo was superseded by Telstar 1, an active repeater satellite, launched 2 years later. Telstar demonstrated that color video signals could be reliably broadcast across the oceans and, in doing so, captured the interest and imagination of the public.

The first live transatlantic telecast was relayed by Telstar on July 10, 1962. The picture was of the American flag fluttering in front of the sending station at Andover, ME. More panoramic telecasts, showing life in widely distant places, were exchanged between the United States and Europe 13 days later.

With the potential of international communications becoming increasingly apparent, Congress passed the Communications Satellite Act in 1962. The legislation created, among other things, Comsat, which was to establish, in cooperation with organizations in other countries, a global commercial communications satellite system as quickly as possible.

U.S. initiative under the Communications Satellite Act, combined with growing international interest in the new technology, led to the formation of Intelsat in 1964. Acting as a technical manager of Intelsat during its initial growth period, Comsat developed Intelsat's first geosynchronous commercial communications satellite, *Early Bird*. The project brought to reality the concept envisaged some 20 years earlier by Arthur C. Clarke, the noted British science fiction writer.

Early Bird (also known as Intelsat 1) was launched from Cape Kennedy on April 2, 1965 and placed into synchronous orbit 22,300 miles above the coast of Brazil. The launch marked the first step toward a worldwide network of satellites linking the peoples of many nations. Early Bird, the only mode of live transatlantic television, provided in July 1965 the first live telecast (via Intelsat satellite) to the United States, an American-vs.-Soviet track meet. All of these breakthroughs relied on new, compact, efficient, and lightweight microwave power tubes.

Although a dramatic improvement over the transatlantic telecommunications facilities at the time, Early Bird was nonetheless limited in capacity and capability. For example, in order for the only TV channel to be operative, all 240 voice channels had to be shut down. Furthermore, the cost of Early Bird time was high.

Following Early Bird's introduction to service in the Atlantic Ocean region, the challenge remained to develop a global network. The next step toward that goal was taken on July 11, 1967, with the successful launch of Intelsat 2, which established satellite communications between the U.S. mainland and Hawaii. Two years later Intelsat III was launched for Indian Ocean region service, thereby completing the provisions of global coverage.

Fortunately, global coverage capacity was in place just in time for the TV audience—estimated to be the largest in world history—to see man set foot on the moon. The satellite system that had been a vision by Arthur C. Clarke two decades earlier, and a formidable legislative mandate more than a decade earlier, had emerged as a reality.

1.1.2 Standardization

Throughout the history of product development, design standardization has been critically important. To most engineers, the term “standards” connotes a means of promoting an atmosphere of interchangeability of basic hardware. To others, it evokes thoughts of a slowdown of progress, of maintaining a status quo—perhaps for the benefit of a particular group. Both camps can cite examples to support their viewpoints, but no one can seriously contend that we would be better off without standards. The standardization process has been an important element in the advancement of power vacuum tube technology.

In 1836 the U.S. Congress authorized establishment of the Office of Weights and Measures (OWM) for the primary purpose of ensuring uniformity in customs house dealings. The Treasury Department was charged with its operation. As advancements in science and technology fueled the industrial revolution, it was apparent that standardization of hardware and test methods was necessary to promote commercial development and to compete successfully in the world market. The industrial revolution in the 1830s introduced the need for interchangeable parts and hardware. Wide use of steam railways and the cotton gin, for example, were possible only with mechanical standardization.

By the late 1800s, professional organizations of mechanical, electrical, and chemical engineers were founded with this aim in mind. The American Institute of Electrical Engineers developed standards based on the practices of the major electrical manufacturers between 1890 and 1910. Because such activities were not within the purview of the OWM, there was no government involvement during this period. It took the pressures of war production in 1918 to cause the formation of the American Engineering Standards Committee (AESC) to coordinate the activities of various industry and engineering societies. This group became the American Standards Association (ASA) in 1928.

Parallel development occurred worldwide. The International Bureau of Weights and Measures was founded in 1875, the International Electrotechnical Commission (IEC) in 1904, and the International Federation of Standardizing Bodies in 1926. Following World War II, this group was reorganized as the International Standards Organization (ISO). Today, representatives of approximately 54 countries serve on the ISO’s 145 technical committees.

The International Telecommunications Union (ITU) was founded in 1865 for the purpose of coordinating and interfacing telegraphic communications worldwide. Today, its 164 member countries develop regulations and voluntary recommendations relating to telecommunications systems.

Many of the early standards relating to vacuum tubes in the United States were developed by equipment manufacturers, first under the banner of the Radio Manufacturers Association (RMA), then the Radio, Electronic, and Television Manufacturers Association (RETMA), and now the Electronic Industries Association (EIA). The Institute of Radio Engineers (the forerunner of the IEEE) was responsible for measurement standards and techniques.

Standards usually are changed only through natural obsolescence. Changes in basic quantities, such as units of length and volume, are extremely difficult for the general public to accept. In 1900 nearly all members of the scientific, commercial, and engineering communities supported the change to the metric system. But the general public finds the idea of changing ingrained yardsticks for weight and measure as unpalatable as learning to speak a new language in a native country. The effort to convert to the metric system is, in fact, still under way, with various degrees of success.

1.1.3 Transmission Systems

Radio communication is the grandfather of vacuum tube development. Amplitude modulation (AM) was the first modulation system that permitted voice communications to take place. This simple scheme was predominant throughout the 1920s and 1930s. Frequency modulation (FM) came into regular broadcast service during the 1940s. TV broadcasting, which uses amplitude modulation for the visual portion of the signal and frequency modulation for the aural portion of the signal, became available to the public during the mid-1940s. These two basic approaches to modulating a carrier have served the communications industry well for many decades. Although the basic schemes still are used today, numerous enhancements have been made.

Technology also has changed the rules by which the communications systems developed. AM radio, as a technical system, offered limited audio fidelity but provided design engineers with a system that allowed uncomplicated transmitters and simple, inexpensive receivers. FM radio, on the other hand, offered excellent audio fidelity but required a complex and unstable transmitter (in the early days) and complex, expensive receivers. It is no wonder that AM radio flourished while FM remained relatively stagnant for at least 20 years after being introduced to the public. It was not until transistors and later integrated circuits became commonly available that FM receivers gained consumer acceptance.

TV broadcasting evolved slowly during the late 1940s and early 1950s. Color transmissions were authorized as early as 1952. Color receivers were not purchased in large numbers by consumers, however, until the mid-1960s. Early color sets were notorious for poor reliability and unstable performance. They also were expensive. As with FM, all that changed with the introduction of transistors and, later, integrated circuits. Most color TV receivers produced today consist of an integrated circuit (IC) chip set numbering 8 to 15 devices.

1.2 Vacuum Tube Applications

The range of uses for power grid and microwave tubes is wide and varied. Some of the more common applications include the following:

- AM radio broadcasting, with power levels up to 50 kW
- Shortwave radio, with power levels of 50 kW to several megawatts
- FM radio broadcasting, with power levels up to 100 kW

- Television, with operating power levels up to 5 MW
- Radar, with widely varying applications ranging from airborne systems to over-the-horizon networks
- Satellite communications, incorporating the ground segment and space segment
- Industrial heating and other commercial processes

Figure 1.2 charts the major device types in relation to power and frequency.

1.2.1 Market Overview

There is a huge installed base of power vacuum tubes. Users cover a wide range of disciplines and facilities. The power tube market can be divided into the following general segments:

- *Medical*. Applications include diagnostics, such as X ray and CAT scanners, and treatment, such as radio therapy. Devices used include X ray tubes and klystrons. This important area of power tube application has seen continuous growth over the past two decades.
- *Scientific*. Applications include various types of research, including particle accelerators for nuclear research. A wide variety of devices are used in this area. Specialized units can be found in “big science” projects, such as the huge Stanford linear accelerator. The worldwide scientific market for microwave power tubes continues to grow as researchers reach for higher power levels and higher frequencies of operation.
- *Electronic Warfare*. Applications include ship- and air-based radar systems, eavesdropping systems, and radio-signal jamming equipment. Electronic warfare applications are a driving force in power microwave tube development. For example, the *Aegis* weapons system ship uses hundreds of microwave power tubes.
- *Communications*. Applications include space- and ground-based satellite systems, microwave relay, and specialized point-to-point communications systems. Power tubes play an important role in all types of high-power communications systems.
- *Radar*. Applications include ground-, ship-, and air-based radar for both commercial and military applications.
- *Industrial Heating*. Applications center on material heating and chemical processing, and environmental uses such as smokestack scrubbing.
- *Broadcasting*. Applications are TV and radio broadcasting, including shortwave. High-efficiency UHF-TV is an area of rapid development.

Despite the inroads made by solid-state technology, power vacuum tube applications continue to span a broad range of disciplines around the world.

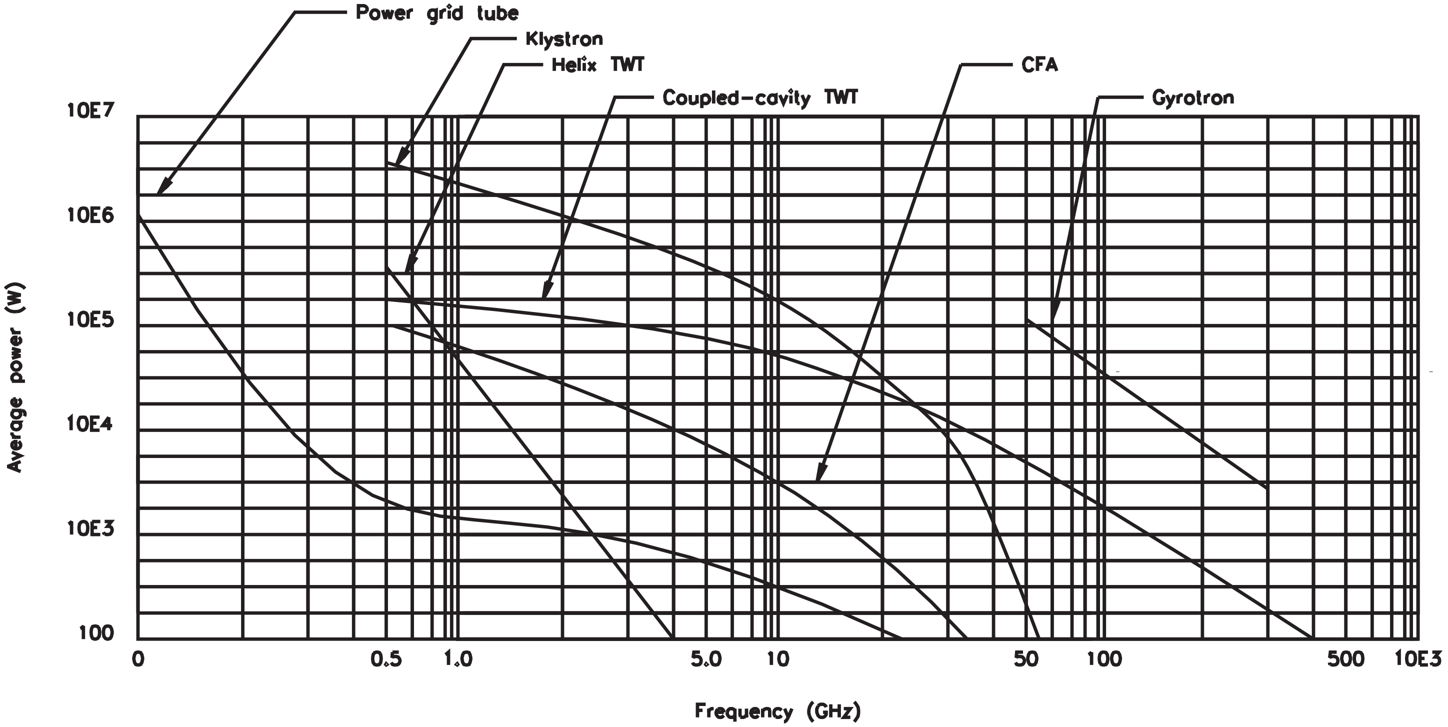

Figure 1.2 Vacuum tube operating parameters based on power and frequency.

Band A 49 meters	5.950–6.200 MHz
Band B 32 meters	9.500–9.775 MHz
Band C 25 meters	11.700–11.975 MHz
Band D 19 meters	15.100–15.450 MHz
Band E 16 meters	17.700–17.900 MHz
Band F 14 meters	21.450–21.750 MHz
Band G 11 meters	25.600–26.100 MHz

Figure 1.3 Operating frequency bands for shortwave broadcasting.

1.2.2 AM Radio Broadcasting

AM radio stations operate on 10 kHz channels spaced evenly from 540 to 1600 kHz. Various classes of stations have been established by the Federal Communications Commission (FCC) and agencies in other countries to allocate the available spectrum to given regions and communities. In the United States, the basic classes are *clear*, *regional*, and *local*. Current practice uses the CCIR (international) designations as class A, B, and C, respectively. Operating power levels range from 50 kW for a clear channel station to as little as 250 W for a local station. AM stations choosing to do so may operate in stereo using the *C-QUAM system*. (C-QUAM is a registered trademark of Motorola.) To receive a stereo AM broadcast, consumers must purchase a new stereo radio. The C-QUAM system transmits the stereo *sum signal* (in others words, the monophonic signal) in the usual manner and places the stereo *difference signal* on a phase-modulated subchannel. Decoder circuits in the receiver reconstruct the stereo signals.

1.2.3 Shortwave Broadcasting

The technologies used in commercial and government-sponsored shortwave broadcasting are closely allied with those used in AM radio. However, shortwave stations usually operate at significantly higher powers than AM stations.

International broadcast stations use frequencies ranging from 5.95 to 26.1 MHz. The transmissions are intended for reception by the general public in foreign countries. Figure 1.3 shows the frequencies assigned by the FCC for international broadcast shortwave service. The minimum output power is 50 kW. Assignments are made for specific hours of operation at specific frequencies.

High-power shortwave transmitters have been installed to serve large geographical areas and to overcome jamming efforts by foreign governments. Systems rated for power outputs of 500 kW and more are common. RF circuits and vacuum tube devices designed specifically for high-power operation are utilized.

Most shortwave transmitters have the unique requirement for automatic tuning to one of several preset operating frequencies. A variety of schemes exist to accomplish this task, including multiple exciters (each set to the desired operating frequency) and motor-controlled variable inductors and capacitors. Tune-up at each frequency is performed by the transmitter manufacturer. The settings of all tuning controls are stored in a memory device or as a set of trim potentiometer adjustments. Automatic retuning of a high-power shortwave transmitter can be accomplished in less than 30 s in most cases.

1.2.4 FM Radio Broadcasting

FM radio stations operate on 200 kHz channels spaced evenly from 88.1 to 107.9 MHz. In the United States, channels below 92.1 MHz are reserved for noncommercial, educational stations. The FCC has established three classifications for FM stations operating east of the Mississippi River and four classifications for stations west of the Mississippi. Power levels range from a high of 100 kW *effective radiated power* (ERP) to 3 kW or less for a lower classification. The ERP of a station is a function of transmitter power output (TPO) and antenna gain. ERP is determined by multiplying these two quantities together and allowing for line loss.

A transmitting antenna is said to have “gain” if, by design, it concentrates useful energy at low radiation angles, rather than allowing a substantial amount of energy to be radiated above the horizon (and be lost in space). FM and TV transmitting antennas are designed to provide gain through vertically stacking individual radiating elements.

Stereo broadcasting is used almost universally in FM radio today. Introduced in the mid-1960s, stereo has contributed in large part to the success of FM radio. The left and right sum (monophonic) information is transmitted as a standard frequency-modulated signal. Filters restrict this *main channel* signal to a maximum bandwidth of approximately 17 kHz. A pilot signal is transmitted at low amplitude at 19 kHz to enable decoding at the receiver. The left and right difference signal is transmitted as an amplitude-modulated subcarrier that frequency-modulates the main FM carrier. The center frequency of the subcarrier is 38 kHz. Decoder circuits in the FM receiver matrix the sum and difference signals to reproduce the left and right audio channels. Figure 1.4 illustrates the baseband signal of a stereo FM station.

Auxiliary Services

Modern FM broadcast stations are capable of broadcasting not only stereo programming, but one or more subsidiary channels as well. These signals, referred to by the FCC as *subsidiary communications authorization* (SCA) services, are used for the transmission of stock market data, background music, control signals, and other information not normally part of the station’s main programming. Although these services do not provide the same range of coverage or audio fidelity as the main stereo

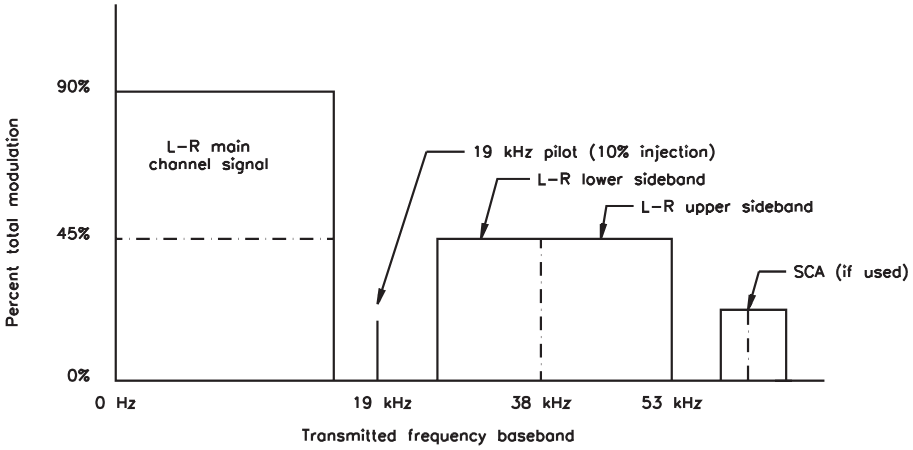

Figure 1.4 Composite baseband stereo FM signal. A full left-only or right-only signal will modulate the main (L+R) channel to a maximum of 45 percent. The stereophonic subchannel is composed of upper sideband (USB) and lower sideband (LSB) components.

program, they perform a public service and can be a valuable source of income for the broadcaster.

SCA systems provide efficient use of the available spectrum. The most common subcarrier frequency is 67 kHz, although higher subcarrier frequencies may be used. Stations that operate subcarrier systems are permitted by the FCC to exceed (by a small amount) the maximum 75 kHz deviation limit, under certain conditions. The subcarriers utilize low modulation levels, and the energy produced is maintained essentially within the 200 kHz bandwidth limitation of FM channel radiation.

1.2.5 TV Broadcasting

TV transmitters in the United States operate in three frequency bands:

- *Low-band VHF*—channels 2 through 6 (54 to 72 MHz and 76 to 88 MHz).
- *High-band VHF*—channels 7 through 13 (174 to 216 MHz).
- *UHF*—channels 14 through 69 (470 to 806 MHz). UHF channels 70 through 83 (806 to 890 MHz) currently are assigned to land mobile radio services. Certain TV translators may continue to operate on these frequencies on a secondary basis.

Because of the wide variety of operating parameters for TV stations outside the United States, this section will focus primarily on TV transmission as it relates to the United States. Table 1.1 lists the frequencies used by TV broadcasting. Maximum power output limits are specified by the FCC for each type of service. The maximum ef-

Table 1.1 Channel Designations for VHF- and UHF-TV Stations in the United States

Channel	Frequency (MHz)	Channel	Frequency (MHz)	Channel	Frequency (MHz)
2	54 – 60	30	566 – 572	58	734 – 740
3	60 – 66	31	572 – 578	59	740 – 746
4	66 – 72	32	578 – 584	60	746 – 752
5	76 – 82	33	584 – 590	61	752 – 758
6	82 – 88	34	590 – 596	62	758 – 764
7	174 – 180	35	596 – 602	63	764 – 770
8	180 – 186	36	602 – 608	64	770 – 776
9	186 – 192	37	608 – 614	65	776 – 782
10	192 – 198	38	614 – 620	66	782 – 788
11	198 – 204	39	620 – 626	67	788 – 794
12	204 – 210	40	626 – 632	68	794 – 800
13	210 – 216	41	632 – 638	69	800 – 806
14	470 – 476	42	638 – 644	70	806 – 812
15	476 – 482	43	644 – 650	71	812 – 818
16	482 – 488	44	650 – 656	72	818 – 824
17	488 – 494	45	656 – 662	73	824 – 830
18	494 – 500	46	662 – 668	74	830 – 836
19	500 – 506	47	668 – 674	75	836 – 842
20	506 – 512	48	674 – 680	76	842 – 848
21	512 – 518	49	680 – 686	77	848 – 854
22	518 – 524	50	686 – 692	78	854 – 860
23	524 – 530	51	692 – 698	79	860 – 866
24	530 – 536	52	698 – 704	80	866 – 872
25	536 – 542	53	704 – 710	81	872 – 878
26	542 – 548	54	710 – 716	82	878 – 884
27	548 – 554	55	716 – 722	83	884 – 890
28	554 – 560	56	722 – 728		
29	560 – 566	57	728 – 734		

fective radiated power for low-band VHF is 100 kW; for high-band VHF it is 316 kW; and for UHF it is 5 MW.

The second major factor that affects the coverage area of a TV station is antenna height, known in the industry as *height above average terrain* (HAAT). HAAT takes into consideration the effects of the geography in the vicinity of the transmitting tower. The maximum HAAT permitted by the FCC for a low- or high-band VHF station is 1000 ft (305 m) east of the Mississippi River and 2000 ft (610 m) west of the Mississippi. UHF stations are permitted to operate with a maximum HAAT of 2000 ft (610 m) anywhere in the United States (including Alaska and Hawaii).

The ratio of visual output power to aural power may vary from one installation to another, but the aural typically is operated at between 10 to 20 percent of the visual power. This difference is the result of the reception characteristics of the two signals. Much greater signal strength is required at the consumer's receiver to recover the visual portion of the transmission than the aural portion. The aural power output is intended to be sufficient for good reception at the fringe of the station's coverage area, but not beyond. It is pointless for a consumer to be able to receive a TV station's audio signal, but not the video.

1.2.6 Satellite Transmission

Commercial satellite communication began on July 10, 1962, when TV pictures were first beamed across the Atlantic Ocean through the Telstar 1 satellite. Three years later, the Intelsat system of *geostationary* relay satellites saw its initial craft, Early Bird 1, launched into a rapidly growing communications industry. In the same year, the U.S.S.R. inaugurated the Molnya series of satellites, traveling in an elliptical orbit to better meet the needs of that nation. The Molnya satellites were placed in an orbit inclined about 64°, relative to the equator, with an orbital period half that of the earth.

All commercial satellites in use today operate in a geostationary orbit. A geostationary satellite is one that maintains a fixed position in space relative to earth because of its altitude, roughly 22,300 miles above the earth. Two primary frequency bands are used: the *C-band* (4 to 6 GHz) and the *Ku-band* (11 to 14 GHz). Any satellite relay system involves three basic sections:

- An *uplink* transmitting station, which beams signals toward the satellite in its equatorial geostationary orbit
- The satellite (the space segment of the system), which receives, amplifies, and retransmits the signals back to earth
- The *downlink* receiving station, which completes the relay path

Because of the frequencies involved, satellite communications is designated as a microwave radio service. As such, certain requirements are placed upon the system. As with terrestrial microwave, the path between transmitter and receiver must be line of sight. Meteorological conditions, such as rain and fog, result in detrimental attenuation of the signal. Arrangements must be made to shield satellite receive antennas from terrestrial interference. Because received signal strength is based upon the inverse square law, highly directional transmit and receive parabolic antennas are used, in turn requiring a high degree of aiming accuracy. To counteract the effects of galactic and thermal noise sources on low-level signals, amplifiers are designed for exceptional low noise characteristics. Figure 1.5 shows the primary elements of a satellite relay system.

Satellite Link

Like other relay stations, the communications spacecraft contains antennas for receiving and retransmission. From the receive antenna, signals pass through a low-noise

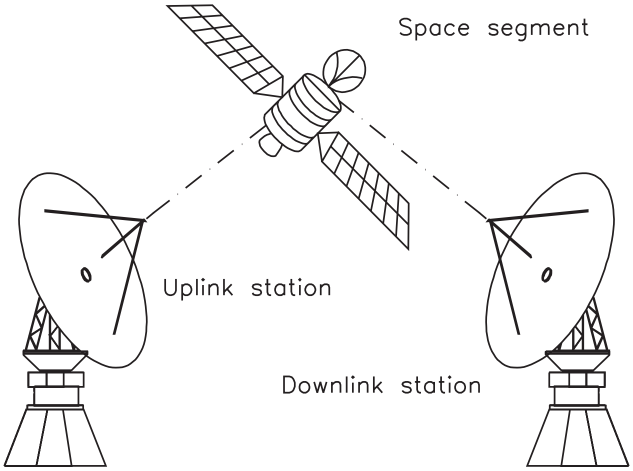

Figure 1.5 Principal elements of a satellite communications link.

amplifier before frequency conversion to the transmit band. A high-power amplifier (HPA) feeds the received signal to a directional antenna, which beams the information to a predetermined area of the earth to be served by the satellite, as illustrated in Figure 1.6.

Power to operate the electronics hardware is generated by solar cells. Inside the satellite, storage batteries, kept recharged by the solar cell arrays, carry the electronic load, particularly when the satellite is eclipsed by the earth. Power to the electronics on the craft requires protective regulation to maintain consistent signal levels. Most of the equipment operates at low voltages, but the final stage of each transponder chain ends in a high-power amplifier. The HPA of C-band satellite channels may include a traveling wave tube (TWT) or a solid-state power amplifier (SSPA). Ku-band systems rely primarily on TWT devices at this writing. Klystrons and TWTs require multiple voltage levels. The filaments operate at low voltages, but beam focus and electron collection electrodes require potentials in the hundreds and thousands of volts. To develop such a range of voltages, the satellite power supply includes voltage converters.

From these potentials, the klystron or TWT produces output powers in the range of 8.5 to 20 W. Most systems are operated at the lower end of the range to increase reliability and life expectancy. In general, the lifetime of the spacecraft is assumed to be 7 years.

A guidance system is included to stabilize the attitude of the craft as it rotates around the earth. Small rocket engines are provided for maintaining an exact position in the assigned geostationary arc. This work is known as *station-keeping*.

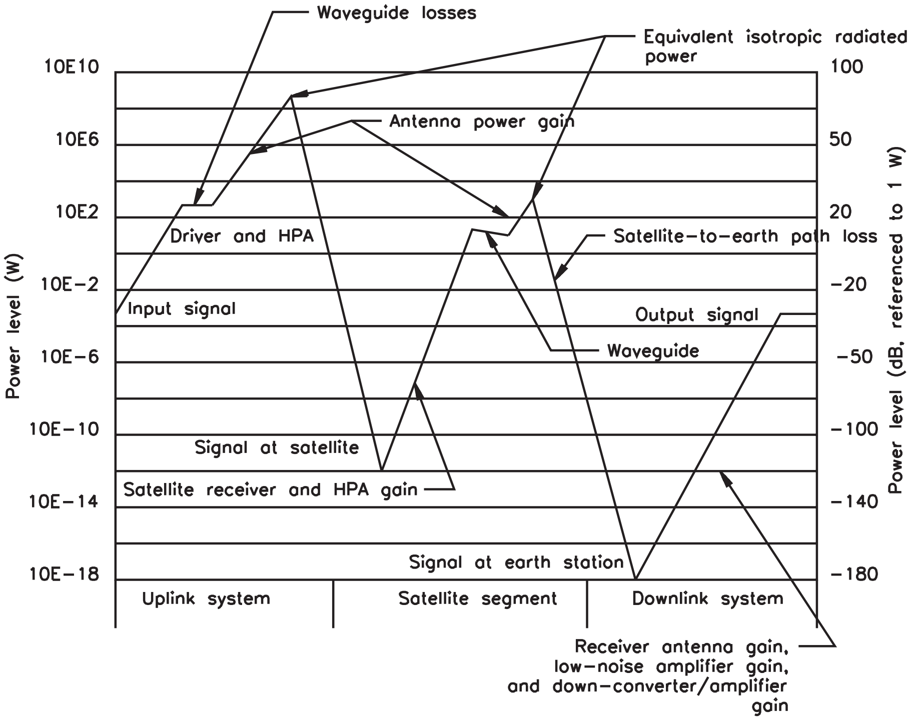

Figure 1.6 The power levels in transmission of a video signal via satellite.

1.2.7 Radar

The word radar is an acronym for *radio detection and ranging*. The name accurately spells out the basic function of a radar system. Measurement of target angles is an additional function of most radar equipment. Doppler velocity also may be measured as an important parameter. A block diagram of a typical pulsed radar system is shown in Figure 1.7. Any system can be divided into six basic subsections:

- Exciter and synchronizer: controls the sequence of transmission and reception functions.
- Transmitter: generates a high-power RF pulse of specified frequency and shape.
- Microwave network: couples the transmitter and receiver sections to the antenna.
- Antenna system: consists of a radiating/receiving structure mounted on a mechanically steered servo-driven pedestal. A *stationary array*, which uses electri-

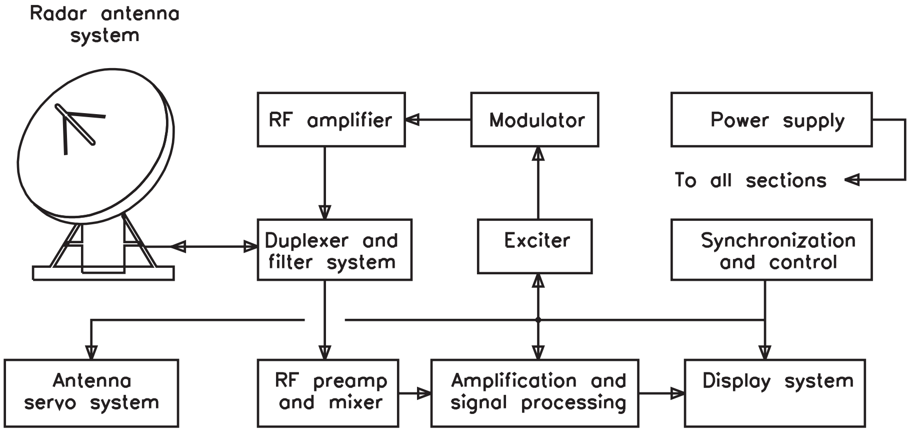

Figure 1.7 Simplified block diagram of a pulsed radar system.

cal steering of the antenna system, may be used in place of the mechanical system shown in the figure.

- Receiver: selects and amplifies the return pulse picked up by the antenna.
- Signal processor and display: integrates the detected echo pulse, synchronizer data, and antenna pointing data for presentation to an operator.

Radar technology is used for countless applications. Table 1.2 lists some of the more common uses.

Operating Parameters

Because radar systems have many diverse applications, the parameters of frequency, power, and transmission format also vary widely. There are no fundamental bounds on the operating frequencies of radar. In fact, any system that locates objects by detecting echoes scattered from a target that has been illuminated with electromagnetic energy can be considered radar. Although the principles of operation are similar regardless of the frequency, the functions and circuit parameters of most radar systems can be divided into specific operating bands. Table 1.3 shows the primary bands in use today. As shown in the table, letter designations have been developed for most of the operating bands.

Radar frequencies have been selected to minimize atmospheric attenuation by rain and snow, clouds and fog, and (at some frequencies) electrons in the air. The frequency bands must also support wide bandwidth radiation and high antenna gain.

Table 1.2 Typical Radar Applications

Air surveillance	Long-range early warning Ground-controlled intercept Target acquisition Height finding and three-dimensional analysis Airport and air-route management
Space and missile surveillance	Ballistic missile warning Missile acquisition Satellite surveillance
Surface-search and military surveillance	Sea search and navigation Ground mapping Artillery location Airport taxiway control
Weather forecasting/tracking	Observation and prediction Aircraft weather avoidance Cloud-visibility determination
Tracking and guidance	Antiaircraft fire control Surface fire control Missile guidance Satellite instrumentation Aircraft approach and landing

Table 1.3 Standard Radar Frequency Bands

Frequency Band	Frequency Range	Radiolocation Bands Based on ITU Assignments in Region II
VHF	30 – 300 MHz	137 – 134 MHz
UHF	300 – 1000 MHz	216 – 255 MHz
L-band	1.0 – 2.0 GHz	1.215 – 1.4 GHz
S-band	2.0 – 4.0 GHz	2.3 – 2.55 GHz, 2.7 – 3.7 GHz
C-band	4.0 – 8.0 GHz	5.255 – 5.925 GHz
X-band	8.0 – 12.5 GHz	8.5 – 10.7 GHz
Ku-band	12.5 – 18.0 GHz	13.4 – 14.4 GHz, 15.7 – 17.7 GHz
K-band	18.0 – 26.5 GHz	23 – 24.25 GHz
Ka-band	26.5 – 40 GHz	33.4 – 36 GHz
Millimeter	Above 40 GHz	

Transmission Equipment

The operating parameters of a radar transmitter are entirely different from those of the other transmitters discussed so far. Broadcast and satellite systems are characterized by medium-power, continuous-duty applications. Radar, on the other hand, is characterized by high-power pulsed transmissions of relatively low duty cycle. The unique requirements of radar have led to the development of technology that is foreign to most communications systems.

Improvements in semiconductor design and fabrication have made solid-state radar sets possible. Systems producing several hundred watts of output power at frequencies up to 2 GHz have been installed. Higher operating powers are achieved by using parallel amplification.

Despite inroads made by solid-state devices, vacuum tubes continue to be the mainstay of radar technology. Tube-based systems consist of the following stages:

- Exciter: generates the necessary RF and local-oscillator frequencies for the system.
- Power supply: provides the needed operating voltages for the system.
- Modulator: triggers the power output tube into operation. Pulse-shaping of the transmitted signal is performed in the modulator stage.
- RF amplifier: converts the dc input from the power supply and the trigger signals from the modulator into a high-energy, short-duration pulse.

1.2.8 Electronic Navigation

Navigation systems based on radio transmissions are used every day by commercial airlines, general aviation aircraft, ships, and the military. Electronic position-fixing systems also are used in surveying work. Although the known speed of propagation of radio waves allows good accuracies to be obtained in free space, multipath effects along the surface of the earth are the primary enemies of practical airborne and shipborne systems. A number of different navigation tools, therefore, have evolved to obtain the needed accuracy and coverage area.

Electronic navigation systems can be divided into three primary categories:

- *Long-range*, useful for distances of greater than 200 miles. Long-range systems are used primarily for transoceanic navigation.
- *Medium-range*, useful for distances of 20 to 200 miles. Medium-range systems are used mainly in coastal areas and above populated land masses.
- *Short-range*, useful for distances of less than 20 miles. Short-range systems are used for approach, docking, or landing applications.

Electronic navigation systems can be divided further into *cooperative* or *self-contained* systems. Cooperative systems depend on one- or two-way transmission between one or more ground stations and the vehicle. Such systems are capable of providing the vehicle with a location fix, independent of its previous position. Self-contained systems, housed entirely within the vehicle, may be radiating or nonradiating. They typically are used to measure the distance traveled, but have errors that increase with distance and/or time. The type of system chosen for a particular application depends upon a number of considerations, including how often the location of the vehicle must be determined and how much accuracy is required.

Because aircraft and ships may travel to any part of the world, many electronic navigation systems have received standardization on an international scale.

Virtually all radio frequencies have been used in navigation at one point or another. Systems operating at low frequencies typically use high-power transmitters with massive antenna systems. With a few exceptions, frequencies and technologies have been chosen to avoid dependence on ionospheric reflection. Such reflections can be valuable in communications systems, but are usually unpredictable. Table 1.4 lists the principal frequency bands used for radionavigation.

Direction Finding

Direction finding (DF) is a simple and widely used navigation aid. The position of a moving transmitter may be determined by comparing the arrival coordinates of the radiated energy at two or more fixed (known) points. Conversely, the position of a receiving point may be determined by comparing the direction coordinates from two or more known transmitters.

The weakness of this system is its susceptibility to site errors. This shortcoming may be reduced through the use of a large DF antenna aperture. In many cases, a multiplicity of antennas, suitably combined, can be made to favor the direct path and discriminate against indirect paths, as illustrated in Figure 1.8.

Ship navigation is a common application of DF. Coastal beacons operate in the 285 to 325 kHz band specifically for ship navigation. This low frequency provides ground wave coverage over seawater to about 1000 miles. Operating powers vary from 100 W to 10 kW. A well-designed shipboard DF system can provide accuracies of about ±2° under typical conditions.

Two-Way Distance Ranging

Automatic distance measuring can be accomplished through placement of a transponder on a given target, as illustrated in Figure 1.9. The system receives an interrogator pulse and replies to it with another pulse, usually on a different frequency. Various codes can be employed to limit responses to a single target or class of target.

Distance-measuring equipment (DME) systems are one application of two-way distance ranging. An airborne interrogator transmits 1 kW pulses at a 30 Hz rate on one of 126 channels spaced 1 MHz apart. (The operating band is 1.025 to 1.150 GHz.) A ground transponder responds with similar pulses on a different channel (63 MHz above or below the interrogating channel).

In the airborne set, the received signal is compared with the transmitted signal. By determining the time difference of the two pulses, a direct reading of miles may be found. Typical accuracy of this system is ±0.2 miles.

Ground transponders usually are configured to handle interrogation from up to 100 aircraft simultaneously.

Table 1.4 Radio Frequencies Used for Electronic Navigation

System	Frequency Band
Omega	10 – 13 kHz
VLF	16 – 24 kHz
Decca	70 – 130 kHz
Loran C/D	100 kHz
ADF/NDB	200 – 1600 kHz
Coastal DF	285 – 325 kHz
Consol	250 – 350 kHz
Marker beacon	75 MHz
ILS localizer	108 – 112 MHz
VOR	108 – 118 MHz
ILS glide slope	329 – 335 MHz
DME, Tacan	960 – 1210 MHz
ATCRBS	1.03 – 1.09 GHz
GPS	1.227 – 1.575 GHz
Altimeter	4.2 GHz
Talking beacon	9.0 GHz
MLS	5.0 GHz

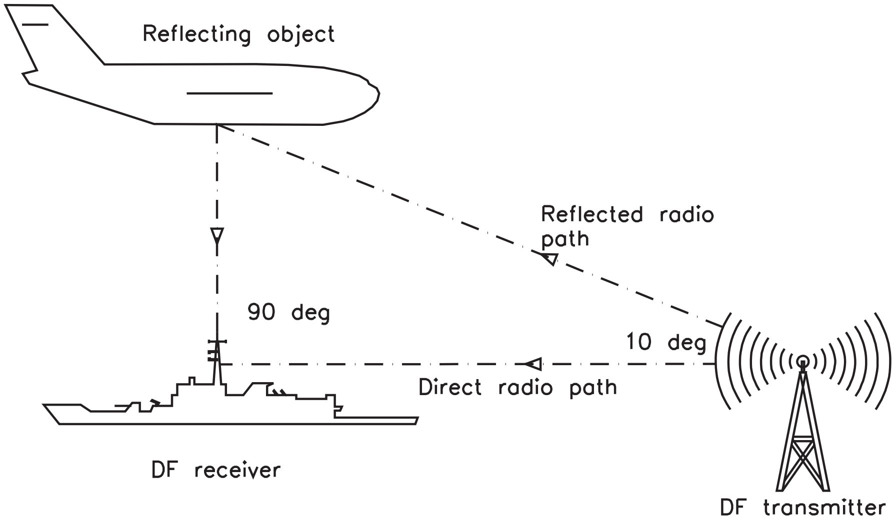

Figure 1.8 Direction-finding error resulting from beacon reflections.

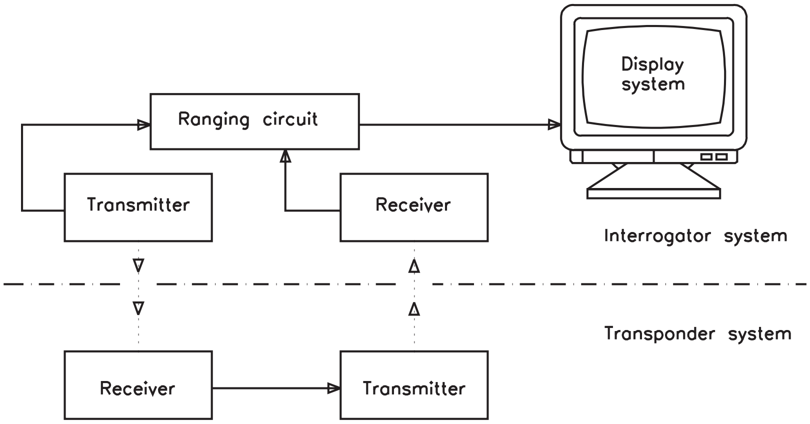

Figure 1.9 The concept of two-way distance ranging.

Differential Distance Ranging

The differential distance ranging system requires two widely-spaced transmitters, one at each end of a predefined link. By placing two transmitters on the ground, it is unnecessary to carry a transmitter in the vehicle. One transmitter is the master and the other is a slave repeating the master (see Figure 1.10). The mobile receiver measures the time difference in arrival of the two signals. For each time difference, there is a *hyperbolic line of position* that defines the target location. (Such systems are known as *hyperbolic systems*.) The transmissions may be either pulsed or continuous wave using different carrier frequencies. A minimum of two stations is required to produce a fix.

If both stations in a differential distance ranging system are provided with stable, synchronized clocks, distance measurements can be accomplished through one-way transmissions whose elapsed time is measured with reference to the clocks. This mode of operation is referred to as *one-way distance ranging* and is illustrated in Figure 1.11.

Loran C

Hyperbolic positioning is used in the *Loran C* navigation system. (Loran is named after its intended application, *long-range navigation*.) Chains of transmitters, located along coastal waters, radiate pulses at a carrier frequency of 100 kHz. Because all stations operate on the same frequency, discrimination among chains is accomplished by different pulse-repetition frequencies. A typical chain consists of a master station and two slaves, about 600 miles from the master. Each antenna is approximately 1300 ft high and is fed 5 MW pulses of defined rise and decay characteristics. Shaping of the rise and decay times is necessary to keep the radiated spectrum within the assigned band limits of 90 to 100 kHz.

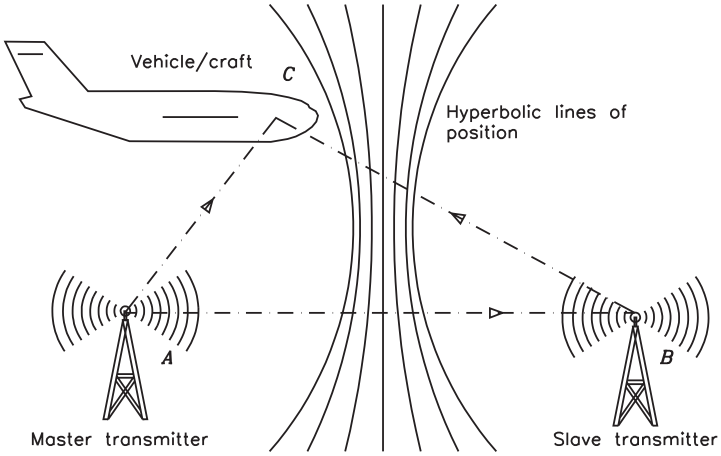

Figure 1.10 The concept of differential distance ranging (hyperbolic).

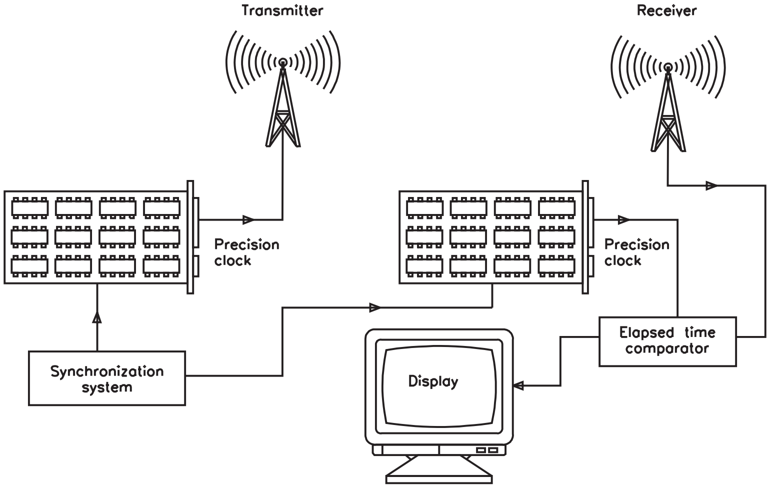

Figure 1.11 The concept of one-way distance ranging.

Pulsed transmissions are used to obtain greater average power at the receiver without resorting to higher peak power at the transmitters. The master station transmits groups of nine pulses 1 ms apart, and the slaves transmit groups of eight pulses 1 ms apart. These groups are repeated at a rate of 10 to 25 per second. Within each pulse, the phase of the RF carrier can be varied for communications purposes.

Coverage of Loran C extends to all U.S. coastal areas, plus certain areas of the North Pacific, North Atlantic, and Mediterranean. Currently, more than 17 chains employ about 50 transmitters.

Omega

Omega is another navigation system based on the hyperbolic concept. The system is designed to provide worldwide coverage from just eight stations. Omega operates on the VLF band, from 10 to 13 kHz. Skywave propagation is relatively stable for these frequencies, providing an overall system accuracy on the order of 1 mile, even at ranges of 5000 miles.

There are no masters or slaves in the Omega system; stations transmit according to their own standard. Each station has its particular operating code and transmits on one frequency at a time for a minimum of about 1 s. The cycle is repeated every 10 s. These slow rates are necessary because of the high *Q*s of the transmitting antennas.

A simple Omega receiver monitors for signals at 10.2 kHz and compares emissions from one station to those of another by use of an internal oscillator. The phase difference data is transferred to a map with hyperbolic coordinates.

Most Omega receivers also are able to use VLF communications stations for navigation. There are about 10 such facilities operating from 16 to 24 kHz. Output powers range from 50 kW to 1 MW. Frequency stability is maintained to 1 part in 10^{12}. This allows one-way DME to be accomplished with a high degree of accuracy.

GPS

The Global Positioning System (NAVSTAR GPS) is a U.S. Department of Defense (DoD) developed, worldwide, satellite-based radionavigation system. The constellation consists of 24 operational satellites. GPS full operational capability was declared on July 17, 1995.

GPS provides two levels of service—a Standard Positioning Service (SPS) and a Precise Positioning Service (PPS). SPS is a positioning and timing service that is available to all GPS users on a continuous, worldwide basis. SPS is provided on the GPS L1 frequency, which contains a coarse acquisition (C/A) code and a navigation data message. SPS provides, on a daily basis, the capability to obtain horizontal positioning accuracy within 100 meters (95 percent probability) and 300 meters (99.99 percent probability), vertical positioning accuracy within 140 meters (95 percent probability), and timing accuracy within 340 ns (95 percent probability).

The GPS L1 frequency also contains a precision (P) code that is not a part of the SPS. PPS is a highly accurate military positioning, velocity, and timing service that is available on a continuous, worldwide basis to users authorized by the DoD. PPS is the data transmitted on GPS L1 and L2 frequencies. PPS is designed primarily for U.S. military use. P-code-capable military user equipment provides a predictable positioning accuracy of at least 22 meters horizontally and 27.7 meters vertically, and timing/time interval accuracy within 90 ns (95 percent probability).

The GPS satellites transmit on two L-band frequencies: L1 = 1575.42 MHz and L2 = 1227.6 MHz. Three pseudo-random noise (PRN) ranging codes are used. The coarse/acquisition (C/A) code has a 1.023 MHz chip rate, a period of 1 ms, and is used by civilian users for ranging and by military users to acquire the P-code. Bipolar-phase shift key (BPSK) modulation is utilized. The transmitted PRN code sequence is actually the modulo-2 addition of a 50 Hz navigation message and the C/A code. The SPS

Table 1.5 Common-Carrier Microwave Frequencies Used in the United States

Band (GHz)	Allotted frequencies	Bandwidth	Applications
2	2.11 – 2.13 Hz 2.16 – 2.18 GHz	20 MHz	General purpose, limited use
4	3.7 – 4.2 GHz	20 MHz	Long-haul point-to-point relay
6	5.925 – 6.425 GHz	500 MHz	Long and short haul
11	10.7 – 11.7 GHz	500 MHz	Short haul
18	17.7 – 19.7 GHz	1.0 GHz	Short haul, limited use

receiver demodulates the received code from the L1 carrier, and detects the differences between the transmitted and the receiver-generated code. The SPS receiver uses an exclusive-OR truth table to reconstruct the navigation data, based upon the detected differences in the two codes.

The precision (P) code has a 10.23 MHz rate, a period of seven days and is the principle navigation ranging code for military users. The Y-code is used in place of the P-code whenever the *anti-spoofing* (A-S) mode of operation is activated. The C/A code is available on the L1 frequency and the P-code is available on both L1 and L2. The various satellites all transmit on the same frequencies, L1 and L2, but with individual code assignments.

Each satellite transmits a navigation message containing its orbital elements, clock behavior, system time, and status messages. In addition, an almanac is provided that gives the approximate data for each active satellite. This allows the user set to find all satellites after the first has been acquired.

1.2.9 Microwave Radio

Microwave radio relay systems carry a significant portion of long-haul telecommunications in the United States and other countries. Table 1.5 lists the major common-carrier bands and their typical uses. The goal of microwave relay technology has been to increase channel capacity and lower costs. Solid-state devices have provided the means to accomplish this goal. Current efforts focus on the use of fiber optic landlines for terrestrial long-haul communications systems. Satellite circuits also have been used extensively for long-distance common-carrier applications.

Single-sideband amplitude modulation is used for microwave systems because of its spectrum efficiency. Single-sideband systems, however, require a high degree of linearity in amplifying circuits. Several techniques have been used to provide the needed channel linearity. The most popular is *amplitude predistortion* to cancel the inherent nonlinearity of the power amplifier.

Microwave relay systems typically use *frequency-division multiplexing* (FDM) to combine signals for more efficient transmission. For example, three 600-channel master groups may be multiplexed into a single baseband signal. This multiplexing often is done some distance (a mile or more) from the transmitter site. A coaxial wireline is

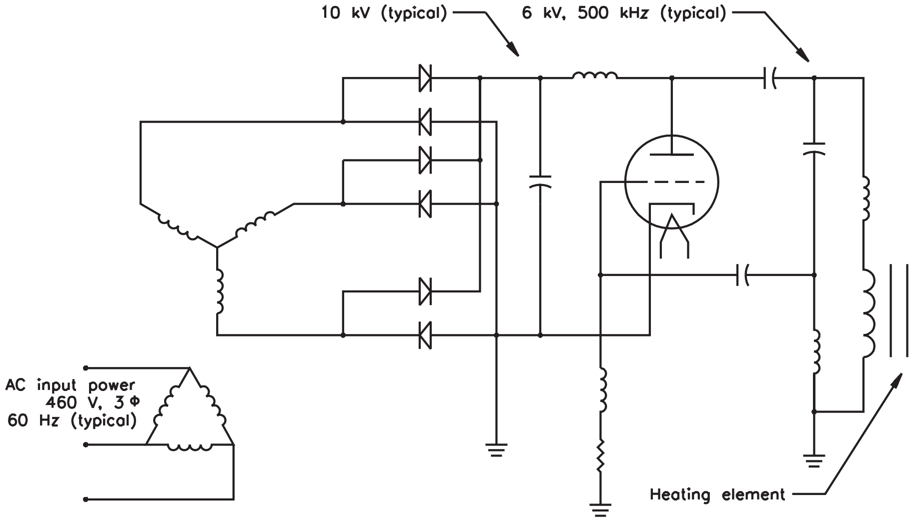

Figure 1.12 Basic schematic of a 20 kW induction heater circuit.

used to bring the baseband signal to the microwave equipment. Depending on the distance, intermediate repeaters may be used. The baseband signal is applied to an FM terminal (FMT) that frequency-modulates a carrier of typically 70 MHz. This IF signal then modulates a 20-MHz-wide channel in the 4 GHz band.

1.2.10 Induction Heating

Induction heating is achieved by placing a coil carrying alternating current adjacent to a metal workpiece so that the magnetic flux produced induces a voltage in the workpiece. This causes current flow and heats the workpiece. Power sources for induction heating include:

- Motor-generator sets, which operate at low frequencies and provide outputs from 1 kW to more than 1 MW.
- Vacuum tube oscillators, which operate at 3 kHz to several hundred megahertz at power levels of 1 kW to several hundred kilowatts. Figure 1.12 shows a 20 kW induction heater using a vacuum tube as the power generating device.
- Inverters, which operate at 10 kHz or more at power levels of as much as several megawatts. Inverters using thyristors (silicon controlled rectifiers) are replacing motor-generator sets in most high-power applications.

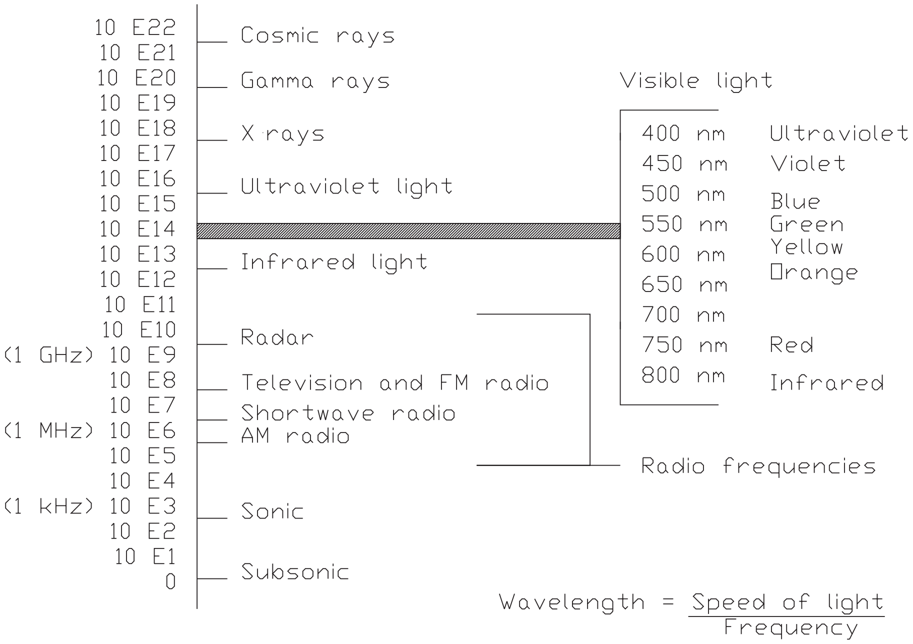

Figure 1.13 The electromagnetic spectrum.

Dielectric Heating

Dielectric heating is a related application for RF technology. Instead of heating a conductor, as in induction heating, dielectric heating relies on the capacitor principle to heat an insulating material. The material to be heated forms the dielectric of a capacitor, to which power is applied. The heat generated is proportional to the *loss factor* (the product of the dielectric constant and the power factor) of the material. Because the power factor of most dielectrics is low at low frequencies, the range of frequencies employed for dielectric heating is higher than for induction heating. Frequencies of a few megahertz to several gigahertz are common.

1.2.11 Electromagnetic Radiation Spectrum

The usable spectrum of electromagnetic radiation frequencies extends over a range from below 100 Hz for power distribution to 10^{20} Hz for the shortest X rays (see Figure 1.13). The lower frequencies are used primarily for terrestrial broadcasting and communications. The higher frequencies include visible and near-visible infrared and ultraviolet light, and X rays. The frequencies of interest to RF engineers range from 30 kHz to 30 GHz. (See Table 1.6.)

Table 1.6 Frequency Band Designations

Description	Designation	Frequency
Extremely Low Frequency	ELF (1) Band	3 Hz up to 30 Hz
Super Low Frequency	SLF (2) Band	30 Hz up to 300 Hz
Ultra Low Frequency	ULF (3) Band	300 Hz up to 3 kHz
Very Low Frequency	VLF (4) Band	3 kHz up to 30 kHz
Low Frequency	LF (5) Band	30 kHz up to 300 kHz
Medium Frequency	MF (6) Band	300 kHz up to 3 MHz
High Frequency	HF (7) Band	3 MHz up to 30 MHz
Very High Frequency	VHF (8) Band	30 MHz up to 300 MHz
Ultra High Frequency	UHF (9) Band	300 MHz up to 3 GHz
Super High Frequency	SHF (10) Band	3 GHz up to 30 GHz
Extremely High Frequency	EHF (11) Band	30 GHz up to 300 GHz
—	— (12) Band	300 GHz up to 3 THz

Low Frequency (LF): 30 to 300 kHz

The LF band is used for around-the-clock communications services over long distances and where adequate power is available to overcome high levels of atmospheric noise. Applications include:

- Radionavigation
- Fixed/maritime communications and navigation
- Aeronautical radionavigation
- Low-frequency broadcasting (Europe)
- Underwater submarine communications (10 to 30 kHz)

Medium Frequency (MF): 300 kHz to 3 MHz

The low-frequency portion of this band is used for around-the-clock communication services over moderately long distances. The upper portion of the MF band is used principally for moderate-distance voice communications. Applications in this band include:

- AM radio broadcasting (535.5 to 1605.5 kHz)
- Radionavigation
- Fixed/maritime communications
- Aeronautical radionavigation
- Fixed and mobile commercial communications

- Amateur radio
- Standard time and frequency services

High Frequency (HF): 3 to 30 MHz

This band provides reliable medium-range coverage during daylight and, when the transmission path is in total darkness, worldwide long-distance service. The reliability and signal quality of long-distance service depends to a large degree upon ionospheric conditions and related long-term variations in sunspot activity affecting skywave propagation. Applications include:

- Shortwave broadcasting
- Fixed and mobile service
- Telemetry
- Amateur radio
- Fixed/maritime mobile
- Standard time and frequency services
- Radio astronomy
- Aeronautical fixed and mobile

Very High Frequency (VHF): 30 to 300 MHz

The VHF band is characterized by reliable transmission over medium distances. At the higher portion of the VHF band, communication is limited by the horizon. Applications include:

- FM radio broadcasting (88 to 108 MHz)
- Low-band VHF-TV broadcasting (54 to 72 MHz and 76 to 88 MHz)
- High-band VHF-TV broadcasting (174 to 216 MHz)
- Commercial fixed and mobile radio
- Aeronautical radionavigation
- Space research
- Fixed/maritime mobile
- Amateur radio
- Radiolocation

Ultrahigh Frequency (UHF): 300 MHz to 3 GHz

Transmissions in this band are typically line of sight. Short wavelengths at the upper end of the band permit the use of highly directional parabolic or multielement antennas. Applications include:

- UHF terrestrial television (470 to 806 MHz)
- Fixed and mobile communications
- Telemetry
- Meteorological aids
- Space operations
- Radio astronomy
- Radionavigation
- Satellite communications
- Point-to-point microwave relay

Superhigh Frequency (SHF): 3 to 30 GHz

Communication in this band is strictly line of sight. Very short wavelengths permit the use of parabolic transmit and receive antennas of exceptional gain. Applications include:

- Satellite communications
- Point-to-point wideband relay
- Radar
- Specialized wideband communications
- Developmental research
- Military support systems
- Radiolocation
- Radionavigation
- Space research

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