NAVIGATING WEATHER

A Pilot's Guide to Airborne and Datalink Weather Radar

David Ison, Ph.D.

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About the Author

Industry expert David C. Ison has been involved in aviation for more than 35 years, during which he has flown as a flight instructor and as an ATP for both regional and major airlines flying domestic and international routes. He holds ATP Multi-Engine Land, Commercial Single-Engine Land and Sea, Gold Seal Certified Flight Instructor, Instrument Flight Instructor, Multi-Engine Flight Instructor, Ground Instructor—Instrument and Advanced, Remote Pilot, and Aircraft Dispatcher certifications.

Dr. Ison has been in aviation higher education for more than 15 years and currently holds the position of Professor, Graduate School, at Northcentral University. He graduated with a Bachelor of Science in Aviation Management from Auburn University, a Master of Science in Aeronautical Science—Operations Specialization from Embry-Riddle Aeronautical University, and a Ph.D. in Educational Studies/Higher Education Leadership with a specialization in Aviation Education from the University of Nebraska–Lincoln.

Abbreviations and Acronyms

ACARS Aircraft Communications Addressing and Reporting System
ACAS airborne collision avoidance system
ADS-B Automatic Dependent Surveillance–Broadcast
ARS automated radar summary
ATC air traffic control
CRT cathode ray tube
dBZ decibel
FIS-B Flight Information Services–Broadcast
GCS ground clutter suppression
GCT ground clutter test
GPWS ground proximity warning system
HEP height evaluation position
Hz hertz
IFF identification friend or foe
JDOP Joint Doppler Operations Project
LI lifted index
LLWAS Low-Level Wind Shear Alert System
MHz megahertz
MND magic number distance
MPEL maximum permissible exposure level
MUR maximum unambiguous range
NAP normal antenna position
NEXRAD Next Generation Weather Radar
OOOI out of the gate, off the ground, on the ground, into the gate
OWRC oceanic weather reflectivity compensation
PAC path attenuation compensation and alert
PPI plan position indicator
PRF pulse repetition frequency
PWS predictive wind shear
radar radio detection and ranging
RAREP radar weather report
RDF radio direction finding (RDF)
REACT Rain Echo Attenuation Compensation Technique
RHI range-height indicator
RRF radar reflectivity factor
RWS reactive wind shear
SATCOM satellite communication
SELCAL selective calling
STC sensitivity time control
SXM Sirius XM
TAWS terrain awareness and warning system
TCAS traffic collision avoidance system
TDWR Terminal Doppler Weather Radar
TIP threat identification position
UAT universal access transceiver
VIP video integrator and processor
VP vertical profile
VTBG variable temperature-based gain
W watts
WSD wind shear detection
WSR Weather Surveillance Radar
Z_e equivalent reflectivity
ZTD zero tilt distance

1 Radar History, Theory, Hardware, and Operation

HISTORY OF RADAR: FROM ANCIENT GREECE TO THE GLASS COCKPIT

Introduction

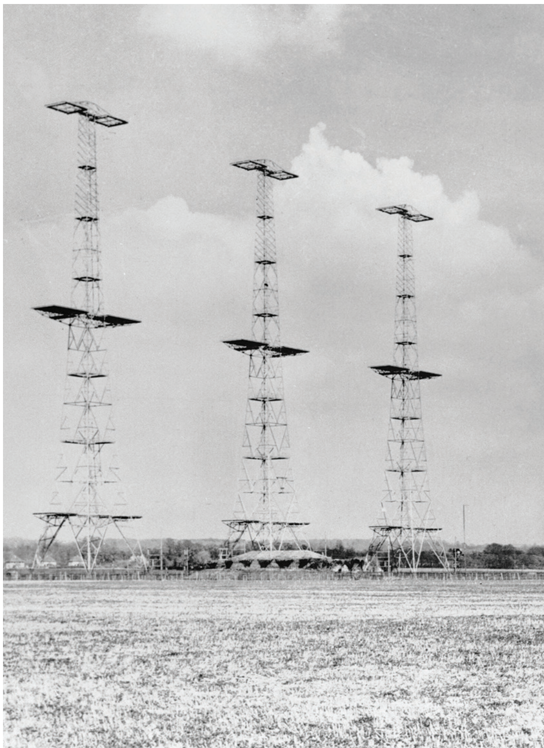
Imagine a time when hurricanes simply showed up unexpectedly. And when they did, people had little time to evacuate and minimal information about how bad things might become. Or imagine a time when heavy rains in far-off places dumped enough water to end up flooding a local river, swamping the surrounding area with little or no warning. Perhaps even more frightening is to envision yourself flying along in the clouds without any real-time weather data, unable to see outside or to avoid flinching at the frequent flashes of lightning. These scenarios used to be the daily reality across the globe. Thankfully, this is no longer the case due to a range of available technologies from computers to satellites. One of the most important discoveries that improved meteorological observation, particularly for aviation, was radio detection and ranging, known more commonly as *radar*. Radar came to be partly out of necessity and partly by accident, eventually being widely adopted by aviation for safety. Let's take a brief look into how radar was discovered and the journey it took to secure a prime place in the cockpit.

Discovering Radar

While radar itself is a recent discovery in the grand scheme of human history, essentially being a twentieth century (CE) invention, the system's principles were known as far back as the sixth century BCE. The Greeks knew of electromagnetism, the relationship between magnetic fields and electrical current, and even experimented with devices to generate static electricity. Over time, the study of electromagnetism began to become more sophisticated, yielding various benefits to science. Although there are varying claims about when the magnetic compass was invented and by whom, it is widely accepted that it came into use sometime around the thirteenth century CE, obviously revolutionizing navigation and geography.

It was not until the nineteenth century that electromagnetic concepts with which most of us today are familiar were discovered. More specific and useful details about electricity emerged at this time, such as the discovery and measurement of resistance and capacitance. By the 1830s, a metallic wire was used to transmit telegraph messages. In 1861, the United States completed a transcontinental telegraph system, followed in 1866 by the installation of a transatlantic connection.

All of this electromagnetic tinkering led German scientist Heinrich Hertz to discover how to alternate voltage to radiate electrical energy through the use of a dipole antenna. He also found that various substances could reflect this energy. By the end of the nineteenth century, inventors Nikola Tesla and Guglielmo Marconi extended Hertz's theories to develop the means of wirelessly sending telegraph messages, i.e., *radio* waves. In fact, in 1900, voice transmission via such waves was made possible due to their findings. Tesla also theorized that electrical waves could be reflected off objects, such as ships, to determine their positions and speeds. A few years later, in 1904, Christian Hülsmeyer was awarded a patent in Britain for the use of radio waves to detect objects, demonstrating the system on riverboats along the Rhine River near Köln, Germany. This early system had a range of approximately three miles, although it could not determine the actual range of objects because its transmissions were not pulsed (though British researchers in the 1920s would later solve this issue). Oddly, Hülsmeyer's invention was all but forgotten for more than two decades while other electromagnetic advances were pursued.



The 1930s saw the increasing threat of yet another war in Europe, with aircraft rapidly becoming a strategic tool in the next conflict. In response, Germany, Russia, France, Italy, Japan, the United States, Britain, and others began to research effective means of detecting aircraft and ships in earnest. By 1933, Germany revived the efforts of Hülsmeyer leading to the ability to detect ships and aircraft at a range of seven miles, laying a foundation to pursue more sophisticated recognition systems. In 1935, British researcher Robert Watts demonstrated aircraft detection with radio waves up to a range of eight miles, and soon after, in 1936, the U.S. National Research Laboratory was able to achieve the same feat using a pulsed wave system.

Because of its proximity to the growing German threat, England began building a series of radio direction finding (RDF) stations in 1936 along the English Channel coast, which became known as *Chain Home* (see Figure 1-1). Chain Home was considered operational by the outbreak of World War II, with its range extending beyond parts of the French coastline within the first year of the conflict. Information about detected aircraft was telephoned to a *filter room*, which passed the details on to scramble intercepts and to warn potential targets. The Germans, too, had a system ready for the outbreak of war named *Freya*, which was steerable and semi-mobile. Freya had a range of up to 100 miles and was used for early warning purposes (see Figure 1-2).

While undoubtedly helpful to both sides of the war, neither radar system was very operationally flexible. Chain Home required 360-foot-tall towers to broadcast its long-wavelength energy, and while Freya was more manageable and movable, it was far from small. It was quickly determined that smaller, more portable units would provide tactical advantages as they could be fitted on ships, submarines, aircraft, and vehicles. The missing link was a capable, small, high-powered, short-wavelength generator known as a magnetron. Although various countries had developed versions of magnetrons since the 1920s, it was not until 1940 that scientists at the University of Birmingham in England created the multi-resonant cavity magnetron (see Figure 1-3). This device allowed for the fine-tuning of wavelengths at high power, about one hundred times as strong as anything previously used, all within a

FIGURE 1-1.

Chain Home antennae in England along the English Channel coast.[1]

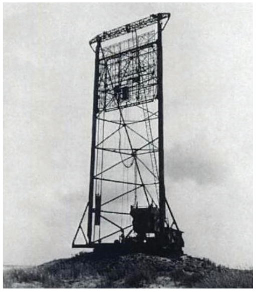


FIGURE 1-2.

Freya—the German's portable radar system.[2]

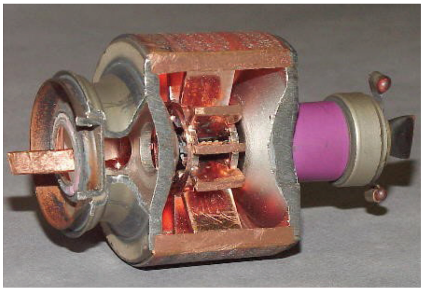


FIGURE 1-3.

Picture of a cavity magnetron such as those used in early radar systems.[3]

portable-sized box. Fearing the possible invasion by Germany and the prospect of falling behind Axis manufacturing capabilities, the British government sent an example of this new magnetron to the United States. Finding a home at the Radiation Laboratory at the Massachusetts Institute of Technology (MIT), the invention was refined and began to be produced in quantity.

With the U.S. industrial strength behind manufacturing, the use of radio waves for object detection immediately took off. The U.S. Navy quickly coined the term *radar* to describe the resulting radio detection and ranging system, and more than 150 models of radar were eventually produced for just about every kind of military application. Additionally, the radar *scope*, the circular display with range rings we often associate with radar, termed the plan position indicator (PPI), began to be put into use. While these radars were primitive compared to modern versions, they worked well enough to turn the tables of the air war in Europe. Radar even detected Japanese aircraft on their run to bomb Pearl Harbor, but they were erroneously dismissed as U.S. training aircraft until it was too late.

Toward the end of World War II, additional improvements to radar were made, including pulse-Doppler radar. The primary advantage of adding Doppler capabilities to radar is that it makes it easier to detect moving objects. However, other advantages of Doppler, such as detecting Doppler shift (movement away from or toward the transmitter), would have to wait for computer processing capabilities that were not yet available.

Use of Radar for the Detection of Weather

The initial purpose of radar was for tactical military use. Yet when the war came to an end, radar technology became declassified, thus opening it up to additional adaptations. The adoption of radar by meteorologists was not strictly purposeful, at least not initially. In actuality, weather was initially considered a nuisance to radar operations because it reduced the range of Chain Home. By 1941, the British military caught on to the ability of radar to detect weather. Both the British and MIT scientists began to accumulate knowledge on how weather appeared on radar, as well as the effects weather had on the system throughout the war. Radar's ability to assess and monitor weather helped the war effort, and it was adopted specifically for meteorological purposes later in the war. By 1945, radars were set up to monitor weather in East India, which paved the way for more widespread installation elsewhere. In 1946, the now declassified U.S. Navy radar units were given to the U.S. Weather Bureau. Weather research quickly ensued with projects in Florida and Ohio that explored thunderstorms in detail. These projects led to the detection of convective system updrafts and downdrafts and ways to improve radar range.

In the 1950s, the military developed weather-specific CPS-9 X-band radars for military bases. Unfortunately, data from these sets were not readily available to civilian outlets. The lack of weather information for non-military personnel was highlighted by severe, damaging storms that ripped across the United States in 1955, prompting the government to call for broad-coverage, civilian weather radars, which became known as the Weather Surveillance Radar-57 (WSR-57). This system required a radar operator to interpret difficult-to-view data displayed on a monochrome phosphor screen, which was then coded on teletype as a radar report, or RAREP, every hour (see Figure 1-4). By 1961, such reports were sent via facsimile and quickly became a vital enhancement to aviation safety.

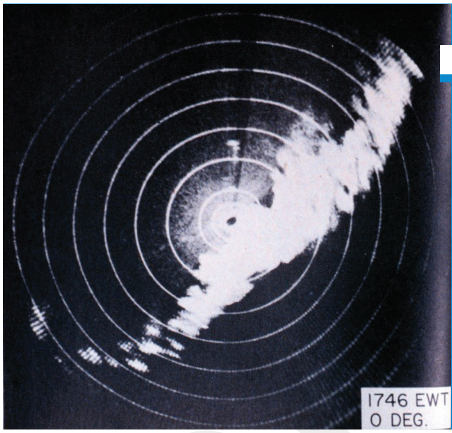


FIGURE 1-4.

Example of early phosphor radar display showing an area of severe weather (1944).[4]

The 1960s brought forth crucial improvements to weather radar features, thanks to the discovery of the "Z-R" relationship. Researchers discovered that there is a correlation between reflectivity of radar energy and the rate (i.e., intensity) of rainfall. Simply, the greater the amount of a radar signal that is reflected, the harder the rainfall. By 1968, a video integrator and processor (VIP) was added to *contour* radar images, making weather intensity much easier to discern. The VIP quantified radar returns (i.e., echoes) into groups based on intensity. There were six VIP levels of intensity available corresponding to rainfall rate estimates. Initially, the contouring was in the form of shades of white, grey, and black. The addition of the VIP system paved the way for future computer analysis and processing.

By the 1970s, computers were aiding more in image processing, making the appearances of weather easier for users to identify. Cathode ray tube (CRT) displays became more commonplace, as did color imagery and contouring. The digital VIP was introduced, which averages returns in a location for a period before displaying them to ensure images do not randomly change. During this time, radar operators still had to code echoes manually and then computers generated a graphic depiction. This soon became displaced by automated radar summary charts (ARS) in which computers converted VIP levels into images. As can be imagined, this greatly improved the information available to all weather stakeholders, including pilots. In 1974, WSR-74 was added to fill in the gaps that existed in WSR-57 coverage, significantly increasing the utility of the overall system.

The mid-1970s saw several accidents caused by weather phenomena that highlighted weaknesses in the general understanding of thunderstorms and the ability to detect storm hazards. The first was Pan Am Flight 806 in 1974. The Boeing 707 crashed on approach to Pago Pago, American Samoa, killing 97 occupants. The cause was determined to be tardy identification and response to wind shear.[5] The following year, Eastern Air Lines Flight 66, a Boeing 727, crashed on approach to New York's John F. Kennedy International Airport due to wind shear, killing 113 people.[6] These crashes, along with the rapid increase in jet aircraft traffic, prompted researchers to figure out more about thunderstorms and wind shear and, most importantly, how they potentially impact aircraft operations.

In 1976, a researcher named T. Theodore Fujita characterized microbursts—strong, small-scale wind shear events—and their danger to aviation. This research increased understanding of storm dynamics, detection, and meteorology. Additionally, these discoveries helped the

Next Generation Weather Radar (NEXRAD) systems to be developed, thanks in part to the U.S. Air Force and the National Weather Service working together in a program known as the Joint Doppler Operations Project (JDOP). Research into gust fronts, sea breeze fronts, and other forms of wind shear, in addition to the Eastern Flight 66 crash, eventually led to the development of the Low-Level Wind Shear Alert System (LLWAS) that ultimately would be installed at major airports across the United States. This system compares winds across the airport environment and alerts users to wind shear events occurring on or near the airfield.

The work of the JDOP led to the push for replacing older WSR systems with NEXRAD in the form of the WSR-88D. As can be surmised from the designation, this system was put into place in 1988 and included Doppler capabilities. Thus, the radar could identify storms but also dissect the guts of the cells plus their internal movement and winds. These efforts laid the foundation for national radar coverage in the United States (see Figure 1-5) and dramatically improved the quality and quantity of weather information available to the general public.

Additional improvements have been made over time, with another significant step occurring in 2013 in which WSR was upgraded to have dual polarization. This new polarimetric radar uses radar waves polarized in two perpendicular planes to detect particle composition and distribution within storms.

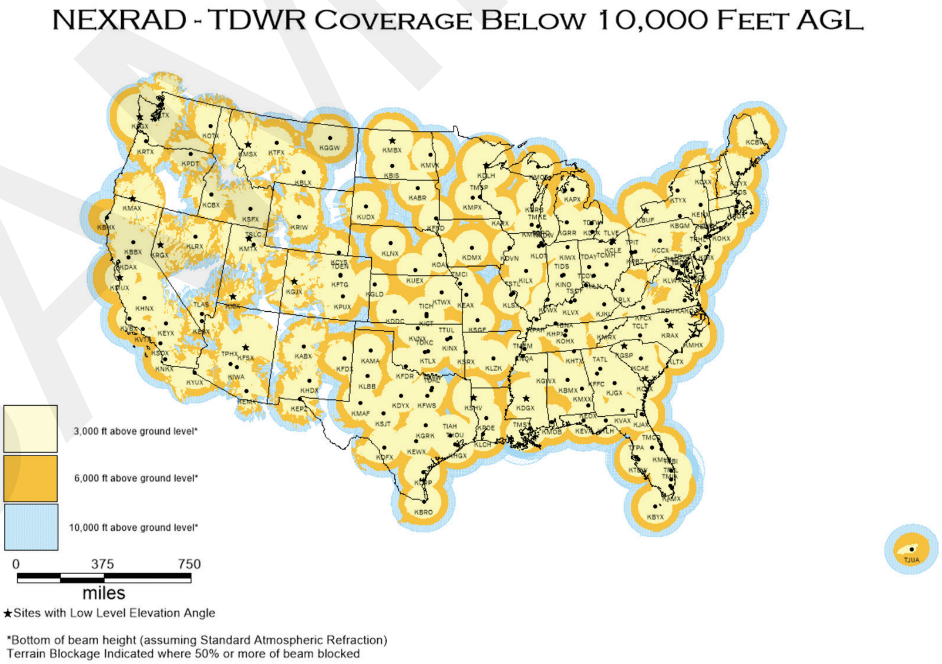


FIGURE 1-5. Map of weather radar coverage in the United States. (Note the areas blocked by terrain, especially in the Mountain West portions of the country.)[7]

The future of weather radar is likely to come in the form of advanced phased array radar. These systems do not always employ a movable antenna. Instead, they use wave interference to steer radar energy. These potential improvements are a result of the military's many years using phased array radar. Phased array systems are faster and less susceptible to mechanical breakdowns. Plans exist to add phased array systems to cellular phone towers to improve coverage in locations with significant gaps.

Weather Radar Goes Airborne

As previously mentioned, radar was initially used onboard aircraft for tactical purposes, with the weather being more of a nuisance rather than the desired target. This began to change as the utility of weather detection became more apparent during and after World War II. The primary weather concern for aviation was severe weather, namely thunderstorms, which along with their associated turbulence, hail, lightning, and heavy precipitation were one of the leading causes of crashes at the time. In 1945, U.S. airlines began to explore the use of airborne weather radar. Between 1945 and 1946, Trans World Airlines (TWA) worked with Bell Labs and West Electric to assess primitive weather radar on board a C-47 (DC-3) aircraft. From 1947 to 1949, American Airlines also flew radar-equipped C-47 aircraft with AN/APS-10 radar to detect and study thunderstorms in the Denver area. Further research conducted by United Airlines led to the idea that radar was critical to aviation safety.

The first commercial aircraft with airborne weather radar was a DC-6 that took flight in 1950. United Airlines named their radar systems "Sir Echo," complete with its own logo. The availability of airborne weather radar was quickly adopted as a marketing tool, assuring passengers of improved rides and increased safety. Following a series of crashes suspected to be associated with convective weather as well as the technological strides being made in radar systems, the FAA began to require weather radar for all air carrier aircraft, a precedent that remains to this day. A 1955 study by United Airlines found immediate dividends to the radar requirement.[8] The company reported a sharp decline in static discharge events and a decrease in turbulence incidents as well as less time spent in bumpy conditions. Further, there were 80 percent fewer weather incidents reported by flight crews as well as a reduction in delays and detours.

Although airborne weather radar use became widespread, there were still deficiencies in technology and knowledge of severe weather dynamics. Most systems in use were X-band radars, which were susceptible to attenuation, a phenomenon where precipitation absorbs, scatters, or blocks radar energy, distorting the intensity level displayed to pilots. This weakness was brought to the spotlight by the 1977 crash of Southern Airways Flight 242 in which the pilots misinterpreted the presence of attenuation on their radar display, essentially flying into an area of extreme weather.[9] This crash was instrumental in highlighting the need for better weather information provided by air traffic control, improved pilot training, and technological improvements. Soon after that, manufacturers developed and adopted attenuation compensation algorithms for radar units. Additionally, some models included indications to pilots if attenuation was suspected, assisting them in avoiding areas of severe weather.

Since the early 1980s, airborne weather radar has been incrementally improved in a variety of ways. One of the first improvements was migration from monochrome to color displays. Doppler technology was also added to airborne systems to provide better attenuation prevention and specific detection of turbulence and wind shear. More recent enhancements include automated operations such as *auto scan* and *auto tilt*. Radars have become comprised of solid-state components and have reaped the rewards of increased computing speeds and capacities. Vertical profile radar now provides three-dimensional imagery of storms, further enhancing weather awareness. Also, radar information is no longer isolated to a stand-alone radar display; instead, it is often integrated with glass cockpit avionics allowing the weather to be overlaid on navigation data, including routes, airports, procedures, and navigational aids. Computers can now analyze how fine particles are moving in a column of air to predict possible wind shear, notifying pilots visually and aurally. The amount of weather situational awareness that these improvements have brought forth in relation to earlier systems has tremendously increased aviation safety.

Summary

Since World War II, radar has become a more integral part of aviation and a critical contributor to its safety. Ground-based radar now provides significant coverage across the United States and other parts of the world to better inform meteorologists and aviation stakeholders of the location, movement, and characteristics of severe weather threats. Airborne weather radar technology has matured into sophisticated systems embedded in avionics suites, providing pilots the ability to examine and dissect proximate weather to circumnavigate hazards and maximize aircraft occupants' comfort. The availability of weather radar on modern airliners has all but eliminated the run-ins with severe weather, especially microbursts, which were much more common before radar's adoption. As technology continues to improve and prices thereof decrease, it can be anticipated that radar data will become better and more available to a broader spectrum of users. It is evident that radar has been a game changer for aviation operations and system safety.

RADAR THEORY BASICS

The premise behind radar theory is relatively simple: electromagnetic energy is emanated from a source and travels outwards, and some of this energy bounces off objects within its path and returns to the source, which has the capacity to receive it (see Figure 1-6). Some overly simplified analogies are also used to describe how radar does its work, such as bats' echolocation to find their prey or submarines' use of sonar to help pinpoint theirs. If these explanations suffice to satisfy your curiosity on the details about how electromagnetic energy is used to detect weather, then skip to the next section on hardware. Otherwise, let's dig a little deeper.

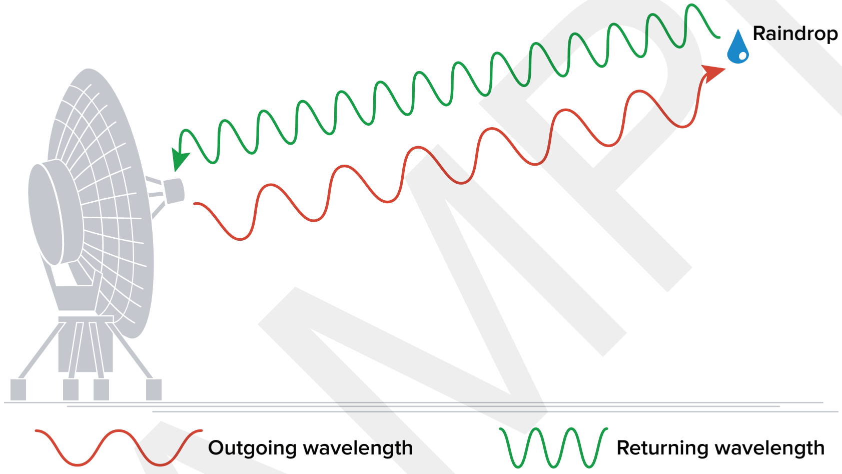


FIGURE 1-6. Basic operation of radar: transmission, backscatter, reception.

Characteristics of Electromagnetic Waves

Wavelength

Electricity and magnetic fields go hand in hand: when you have one, you always have the other. Electric motors operate on this principle as they pass electricity through coils that impart magnetic fields onto internal magnetic components, which operate the motor. An aircraft alternator uses the same principle in reverse—the engine provides the movement, which turns gears connected to the magnets in the alternator, which then impart magnetic fields on adjacent coils, creating the flow of electrons, i.e., electricity. Electromagnetic fields tend to oscillate, resulting in waves of energy that radiate outwards (thus the term *radiation*). These waves move at approximately the speed of light, or 300 million meters per second.

Waves are described in various ways, and each of these characteristics can affect the utility (and possibly the danger) of such waves (see Figure 1-7). For radar, the most critical attribute of energy waves is the wavelength—the measurement of a full cycle of a wave, i.e., the measurement from one wave peak to the next (see Figure 1-8). Atmospheric particles react disparately to different wavelengths. For example, visible light has a very short wavelength on the electromagnetic spectrum and is easily attenuated (a fancy term we use for "being blocked or absorbed") by particles. This is why clouds that produce precipitation appear dark. Thus, it is evident that radar energy needs to penetrate clouds to evaluate precipitation while not passing through without bouncing some of the energy back to the radar antenna.

Wavelengths dictate the design of the transmitter, receiver, and antenna. The selection of a suitable radar wavelength is a compromise among transmitter size, cost, and detection needs. Shorter-wave systems are smaller and less expensive and are therefore ideal for airborne applications; however, shorter waves are more susceptible to attenuation. Because size (as well as cost) is less of an issue for radar systems used by the National Weather Service (NWS), longer wavelengths are used, which allow for a more robust analysis of weather phenomena.

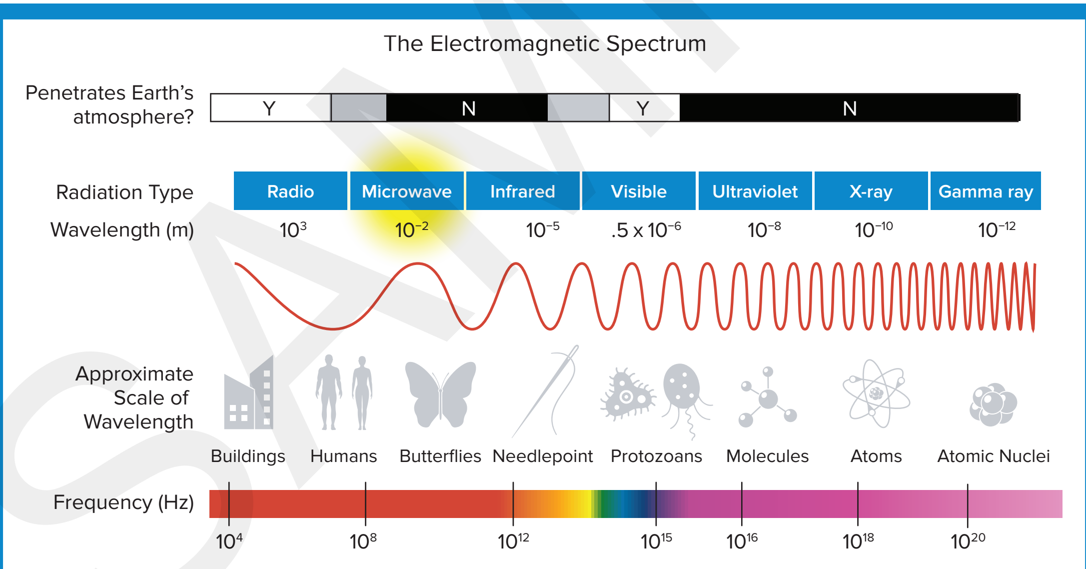


FIGURE 1-7.

Electromagnetic energy wavelengths with examples of sizes of waves.[10] (Note: radar operates in the microwave range.)

The most common type of radar used onboard aircraft falls within the X-band (3 cm wavelength). Ground-based radars are either C-band (5 cm wavelength), commonly used outside the United States, or S-band (10 cm wavelength), which is used on U.S. WSR units.

Frequency

Another measure used to describe waves is frequency, which is the number of wavelengths that pass a point within each second (see Figure 1-8). It is measured in hertz (Hz), which represents the number of cycles per second. Frequency is more of an engineering concern than an operational one, but, as one can imagine, there is an inverse relationship between wavelength and frequency: waves move at a constant speed, so with smaller (narrower) waves, a higher frequency of wavelengths will fit into a second's worth of distance traveled. Most airborne weather radars on civilian aircraft operate within the frequency range of 8,000 to 12,500 megahertz (MHz).

WHERE DID THOSE BANDS GET THEIR NAMES?

If you are ever wondering how the different radar frequency bands got their names, you came to the right place. The "X" descriptor came from the World War II era in which this frequency range was still a secret (think X-Files). "S" band stands for short wavelength, while "C" is for compromise between short and longer wavelengths.

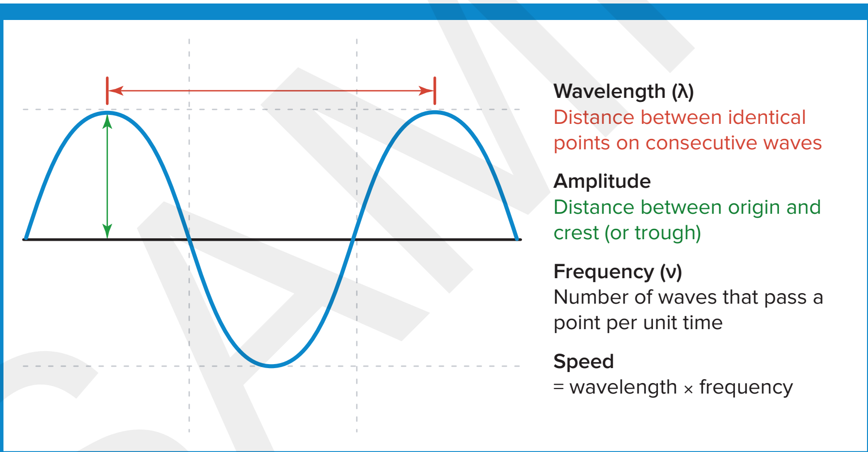


FIGURE 1-8.

Terms used to describe radio waves.

Amplitude and Phase

The term *amplitude* refers to the height of a radio wave from its origin to its crest or peak (measured either up [positive] or down [negative]) (see Figure 1-8). Amplitude is described as a measure of wave power and is indicated in watts (W). For meteorological purposes, power is vital in terms of the amount of radar energy transmitted versus the amount received back at the antenna—i.e., the amount of energy reflected. Phase refers to the synchronization of two or more frequencies and is something quite crucial to Doppler radar systems. A wave is considered to be *in phase* when the two or more wavelengths line up on top of one another, thus resonating at the same frequency. When one or more waves are *out of phase*, they are not aligned and occur at different frequencies (see Figure 1-9).

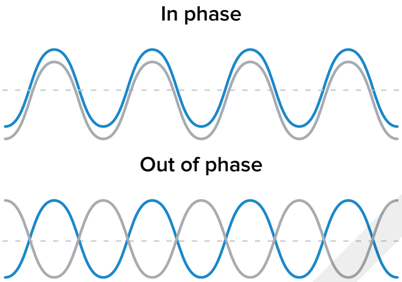


FIGURE 1-9. Wavelengths: in phase and out of phase.

Polarization

Basic radar systems transmit a signal with a fixed orientation or polarization of the radio wave crest. Usually this is aligned with the horizontal axis. On polarimetric radar systems, which are becoming more common, signals are polarized in both the horizontal and vertical axes. This allows for radars to provide insights into the size and structure of particles that reflect the radar energy. Polarimetric radar provides a view of a larger slice of the sky, allowing for more in-depth analysis and interpretation, such as estimating droplet sizes, distinguishing between rain and snow, and approximating rainfall rate (see Figure 1-10).

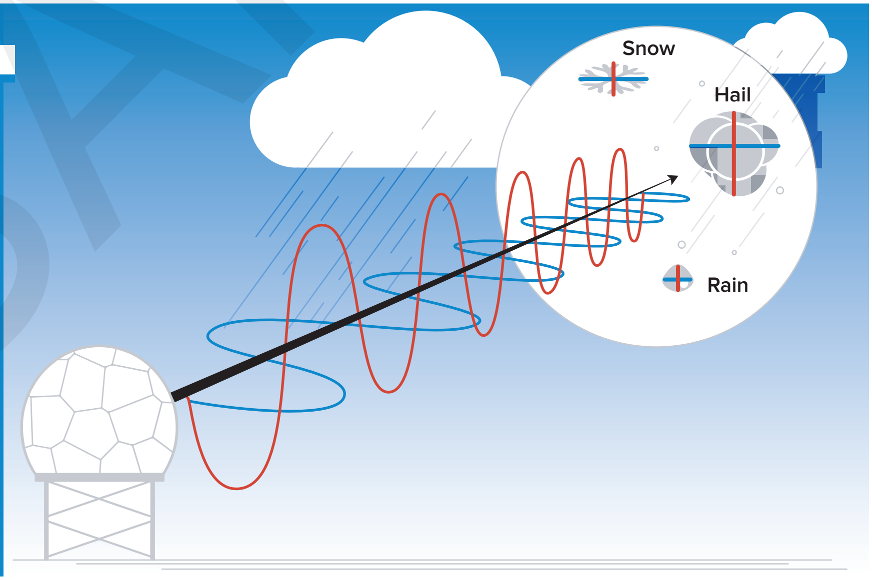


FIGURE 1-10. Polarized Doppler weather radar can measure the size of objects that are reflecting its energy to determine the type of precipitation that is falling.[11]

Atmospheric Interaction with Radar Energy

When a radar transmits energy into the atmosphere, attributes of the surrounding air mass impact that energy. For the most part, the energy essentially still travels at the speed of light, although this can vary very slightly depending on factors such as temperature and humidity. The atmosphere also plays a role in what happens to the energy and how it may be reflected.

Absorption

Some of the transmitted radar energy is absorbed as it moves through the atmosphere. Whenever the energy comes in contact with particles, it excites the molecules within, resulting in heat. An extreme example is your standard microwave, which heats your lunch by zapping it with radio waves until the food gets hot. The amount of absorption is related to radar wavelength, with shorter wavelengths being more prone to absorption (which is part of what is referred to as *attenuation*).

Scattering

As radar energy comes in contact with particles, the energy is scattered in all directions. This means little of the transmitted wave is returned to the antenna, so there is a large difference between the energy transmitted and the energy received. Only the small quantity of wave energy that reflects toward the transmitter can be detected. This direct reflection is referred to as *backscatter* and is used to determine the presence of precipitation or other objects.

Refraction and Diffraction

Although the influence is small, air mass attributes do alter the speed of radiofrequency energy. Because the atmosphere is an ocean of different combinations of temperature and humidity, these variations can cause some false reflections, or echoes, to be displayed. When there is a strong inversion layer above a WSR radar, the radar beam bends downwards, causing backscatter of the ground farther away from the antenna than normal. This “noise” appears as ground clutter (see Figure 1-11). Refraction is generally a negligible consideration for airborne systems.

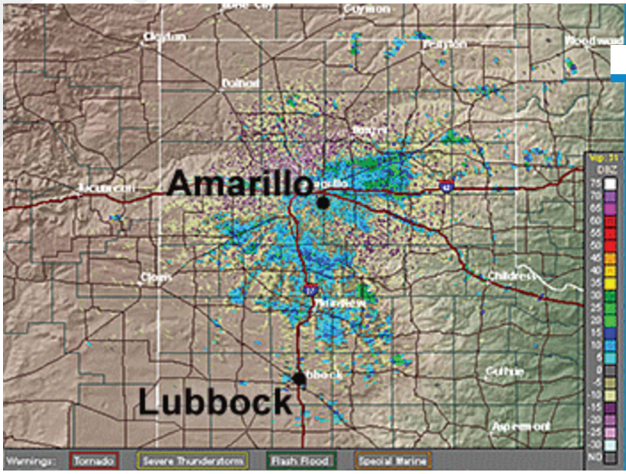


FIGURE 1-11.

Example of erroneous radar images due to refraction caused by atmospheric inversion.[12]

While refraction refers to waves' changes as they move between dissimilar mediums, diffraction is when waves are altered due to obstacles or travel paths. As radar energy is pushed away from the transmitter, some of the energy is diffracted along the edges of the antenna surface. This causes what is referred to as *side lobes* that manifest in radar energy spikes occurring at angles to the antenna. This phenomenon was more of a concern with the old dish-style (parabolic) antennas than the flat-plate types used in most aircraft today. However, regardless of the antenna design, side lobes exist, causing potential false echoes (see Figure 1-12).

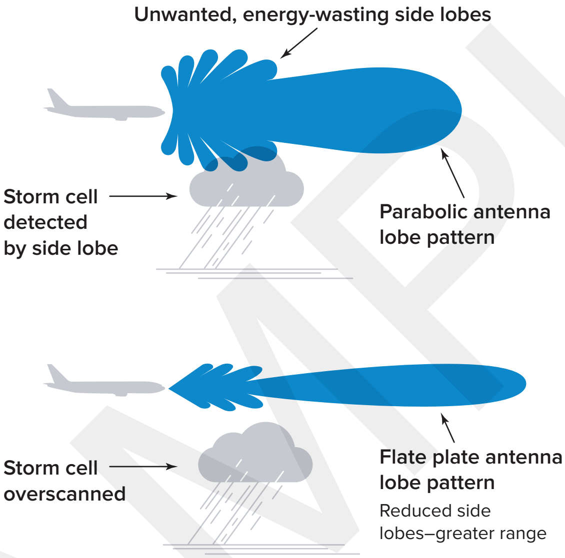


FIGURE 1-12. Weather radar energy side-lobes—parabolic versus flat-plate antenna.

HARDWARE

All radar systems have hardware components in common, though the size, shape, and capabilities may vary.

Transmitters

At the heart of every radar system is the transmitter, which is the projecting electromagnetic energy source. There are three primary types of transmitters: magnetron, klystron, and solid-state.

Magnetrons are rather complicated little contraptions but, as you recall from the historical discussion, were necessary to miniaturize microwave generation for use in mobile radar systems, such as on aircraft. Magnetrons work so well that they are still used in microwave ovens and some radar systems. A brief review of how electrical and magnetic concepts work is needed here. Both electrical and magnetic systems involve poles—a positive and a negative. When talking about the movement of electrons (electricity), the terms cathode (negative) and anode (positive) are used to describe these poles. When prompted, usually by being heated, electrons spill off the cathode and seek out the anode, following the path of least resistance. Within a magnetron, the anode has cutouts called cavities (see Figure 1-13). A strong magnet is used to impart a rotation to the electrons escaping the cathode. As these electrons swirl around, they pass by the anode cavities and resonate them, which in turn releases microwaves. It is kind of like blowing across the top of a glass bottle, which emits a sound, but in this case, the "breath" is the electron, and the "sound" is the microwave. The microwaves built up by the cavities are collected for delivery to the antenna.

Klystrons are essentially magnetrons on steroids and are used in ground-based Doppler radar systems due to their high-power requirements and size. Klystrons take advantage of the kinetic energy of electron beams to amplify them while maintaining precise control over the properties of the waves. Because of the critical nature of wave attributes to Doppler capabilities, klystrons are used in NEXRAD Doppler WSR units and by certain private weather service providers.

Modern radars incorporate solid-state transmitters in place of a magnetron. The advantages of these systems are that they require lower power inputs than magnetrons and klystrons, are less mechanically complex, are less prone to failure, provide more frequency-stable emissions, and generate a smaller radiation "danger zone" in front of the antenna. Other improvements include close-in target recognition as well as the ability to resolve small or overlapping echoes. Also, solid-state systems do not require a cathode warm-up period typical in older magnetron radars, i.e., they are instant-on systems. Lastly, the digital capabilities of solid-state systems allow for data memory and improved data processing.

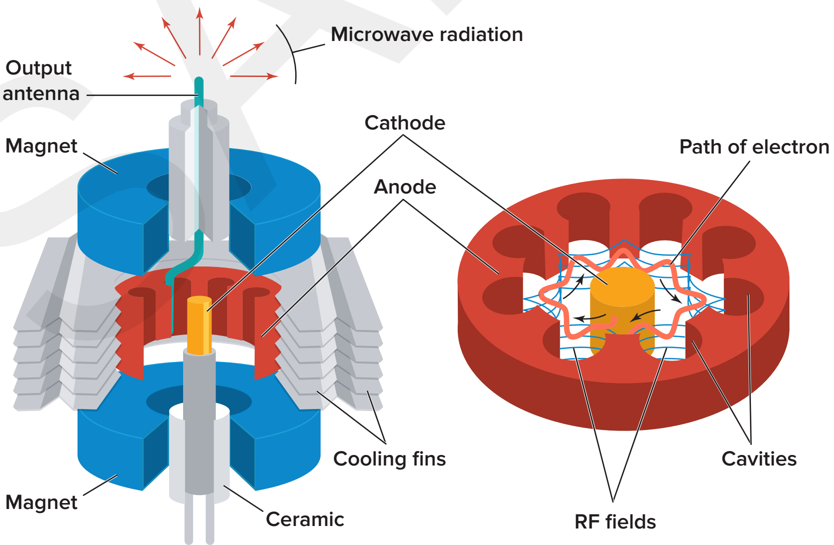


FIGURE 1-13. Detailed view of cavity magnetron.[13]

NAVIGATING WEATHER

A Pilot's Guide to Airborne and Datalink Weather Radar

David Ison, Ph.D.

Weather radar information is one of the most valuable tools available to pilots to ensure safe, efficient, and comfortable flight operations. Onboard weather radar allows pilots to tactically navigate near and around severe weather with confidence. And with the advent of datalink radar data systems, pilots of all types of aircraft and skill levels can easily access similar vital information. Yet pilots must understand how to use these technologies and their potential flaws to avoid inadvertently getting too close to or penetrating severe weather, which could obviously have detrimental outcomes.

Author Dr. David Ison takes you through the fundamental knowledge and skills necessary to operate both airborne and datalink weather radar. With a focus on simplicity and real-world application, Dr. Ison introduces and explains the essential concepts of radar operation and interpretation. Beginning with radar and severe weather theory, he covers attributes of inclement weather phenomena, how they are detected, and how pilots can evaluate these conditions through available radar sources. Airborne weather radar essentials such as attenuation, tilt management, contouring, and gain are explained with real-world examples. The text outlines advanced features including auto-tilt, turbulence detection, wind shear warning systems, and terrain mapping and provides operational strategies for all phases of flight. The detailed sections on datalink radar information explain how the system works, how to use available data, and common pitfalls. Dr. Ison describes the advantages and disadvantages of both airborne and datalink radar systems to help pilots understand the best and most effective use of each.

Each chapter provides case examples, concept questions to test your understanding, and scenarios to assess your judgment and evaluation skills. Regardless of your current skill level—and whether you are just considering adding datalink radar to your toolkit or have been flying with airborne radar for years—this book can serve as a fundamental reference on using radar data in flight.

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