RADAR

The Electronic Eye

by

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To My Friends

among the engineers and physicists
of the
Western Electric Company
and the
Bell Telephone Laboratories
who designed much and built most
of the radar of World War II

Preface

This book has been written for the millions of radio fans and radio owners who are slightly acquainted with the important components of their radio sets.

To those that are familiar with the accomplishments of radar in World War II, it will not seem exaggeration to say that we won the war with radar. Not even the atomic bomb equaled it in importance. In the opening chapter of this book, I have set forth with strict brevity a few of the uses of radar in World War II.

To the electrical engineer familiar with power and low-frequency currents, microwave phenomena present a topsy-turvy world; copper and silver become perfect insulators (quarter-wave stubs); a perfect insulator becomes an excellent power transmitter (dielectric wave-guides). Our concepts of conductors and resistances no longer seem to apply in the realm of extremely high frequencies; yet the contrast is only apparent. Actually, as the following pages will reveal, the differences become clear if we follow the transition from ordinary house currents through the intermediate stages to ultra-high frequencies.

In order to understand microwave radar, the ordinary radio fan and layman should acquire a knowledge of wave guides and fields. For this reason, the reader will find these subjects treated at considerable length. Though some parts may appear unduly technical, I would suggest that the general reader pass over them on a first reading. After going through the remainder of the book, the average interested reader will find the more involved passages not too difficult.

In view of its importance in past, present, and future, radar should be presented to the general public in its most palatable form—without higher mathematics. This is the aim of the present volume.

New York MAURICE RUBIN

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INTRODUCTION

Accomplishing miracles in war and peace, radar is the code name for "RAdio Detecting And Ranging". Spelled backward or forward, the word is the same. This gives us a clue to what radar is: a radio echo device. In brief, radar is an electronic instrument capable of projecting radio impulses in a beam at the speed of light, 186,000 miles a second. Not unlike an automobile headlight, whose beam can reveal an obstruction ahead, radar impulses disclose the presence of distant objects by reflecting the pulses as echoes to the observer. Usually, a cathode ray tube serves as an interpreter and presents on its screen the electronic echoes made visible to the human eye.

Directed toward a distant object such as an airplane, the radar reports the elements of its position in space, to wit, the distance, the elevation and the deflection, that is, its position to the right or left.

As a child you have undoubtedly shouted at a cliff or a wall and timed the return of the echo to find how far away you were. This is very similar to the method used in radar. Your echo was made up of sound waves, whereas the radar employs high-frequency radio waves measured in centimeters.

The radar transmitter sends out radio waves with the speed of light. The waves travel in straight lines and when they hit an object, such as a ship, a plane, a fort, they bounce back, or are reflected, not unlike a beam of light hitting a mirror. The total time for the radio wave to start on its trip and to come back gives us a measure of the distance to the object. To the moon and back (it has been done) requires about 2·5 seconds for the round trip.

Distance alone is insufficient. We should know the direction of the object and its height above the ground. The direction is known from the directional transmitter antenna; the height, by the angular distance the beam makes with the horizon. If the object is a hostile plane or ship, with the foregoing data we can plot its exact position in space.

A radar unit can be built so small that it will fit into the palm of one's hand. Usually, the transmitter and the receiver employ a single directional antenna. From the transmitter, high-frequency waves are emitted and beamed by the antenna in the general direction we wish to explore. On striking an object, some of the energy is reflected back to the receiver. From the receiver, it is fed to the cathode ray tube where the visual display occurs on the screen.

Objects produce characteristic specks of light on the screen of the cathode ray tube. A cloud appears as one form of echo, the surface of water in another form, a ship in motion or a plane, still another which will vary or change because of the motion. Only experience will enable an operator to interpret in a split second what he sees on the screen.

Next in importance to the cathode ray tube perhaps the reflex klystron ranks a close second. Unlike an ordinary radio tube, the klystron groups electrons as they pass through resonant cavities (to be explained in the text) and produces amplification at frequencies entirely beyond the capability of ordinary tubes. The reflex klystron generates waves of very high frequency which combine with the incoming echo waves to produce high-frequency beats. These are amplified by a superheterodyne similar to that of radio but equipped with many more stages of amplification.

In aerial warfare, radar reached its highest degree of wartime usefulness. Coupled to automatic pilots of planes, it is possible to fly the plane to an invisible target. Joined to a computing bomb-sight, a bombardier can release bombs at a precise moment and get results often better than he could with visible bombing. By means of radar, pilots are shown the way back home, flying blind through overcast and clouds or fog to their home bases at night.

One antenna usually serves for both transmitter and receiver. So that the echo may be detected, it is necessary that the transmitter be silent during reception. A tube of special design serves as an electronic switch which cuts off the transmitter and allows the echo to be received between the pulses given out by the transmitter. This electronic switch can operate in a hundredth of a microsecond (a hundred millionth of a second).

Nothing has been said about the transmitter. It was only when a special tube called the magnetron was invented that we were able to generate extremely high power pulses at centimeter wave lengths. The magnetron consists of a solid block of copper in which has been drilled a series of holes or chambers circularly disposed about a central emitting cylinder. Electrons from the cylinder (heated by a filament) are driven to the walls of the chambers by high voltages applied between the filament and the walls of the magnetron. The entire magnetron is placed between the poles of a powerful magnet and the electrons are forced to assume spiral paths, building up energy at a frequency determined by the voltage, the magnetic field, and the size of the cavities. A magnetron easily held in the palm of one's hand can generate hundreds of kilowatts.

The superheterodyne in a radar receiver has many more stages than in an ordinary radio. A little thought will reveal why this is necessary. In radio, a receiver gets its energy from a broadcasting radio transmitter. In radar, the receiver is affected by the extremely small amount of energy *reflected* from a distant object. In consequence, the energy received by a radar receiver is millions of times smaller than that of a radio receiver.

Despite the extreme sensitiveness of the radar receiver, it must be able to function unimpaired in the presence of the radar transmitter which generates hundreds or thousands of kilowatts of energy. It is the electronic switch that accomplishes the task of protecting the receiver from the enormous pulses sent out by the transmitter.

As to the means of connecting radar components, at ultra-high frequencies (centimeter wave lengths) wires are no longer satisfactory. Because of "skin effects", which become conspicuous at very high frequencies, less and less current passes through the interior of a solid conductor, and it is only the outer shell of the conductor that carries the current. For this reason, we must resort to hollow wave guides. The high-frequency components of centimeter wave radar must be connected by hollow wave guides. These take the form of piping of round or rectangular cross section. Engineers have come to use the term "plumbing" which is an apt description of hollow wave guides.

Ordinary radio tubes cannot be used in the high frequency circuits of microwave radar. Fast though we may consider the speed of light (186,000 miles a second), it is too slow for the operation of radio tubes at very high frequencies. The transit time or the time required for electrons to pass from filament to grid to plate is greater than the duration of an oscillation. For this reason, no build-up can occur within ordinary radio tubes at ultra-high frequencies because the phase relationships are not cooperative. As a consequence, new tubes had to be invented such as the klystron, the reflex klystron, and the magnetron.

In brief, then, radar is essentially a radio. Because it must receive extremely small amounts of electromagnetic energy, it must be highly sensitive, requiring many stages of amplification. Even so, the transmitter must be very powerful to ensure that the echoes will be perceptible. Customarily, radar employs a highly directional antenna capable of rotation both in horizontal and vertical planes. The antenna concentrates the energy transmitted, not unlike the beam of a searchlight. Because of the very high frequencies employed, hollow wave guides must be used in the connection of parts and components. Finally, instead of converting electromagnetic energy into sound as in radio, radar transforms its received energy, after amplification, into visual signs on the screen of a cathode ray tube.

In the following pages, the author has attempted to explain the components, circuits, and operation of microwave (centimeter) radar in detail and in logical sequence.

Chapter 1

RADAR IN WAR

1.1. *What radar is*

Before we show what radar did for us in the late wars, it may be well to dispel some of the atmosphere of mystery that surrounds it.

What is radar? The word is a contraction for "RAdio Detection And Ranging". It is a kind of television in which the transmitter and the receiver are usually built into the same unit with one antenna. The transmitter sends out powerful bursts of energy (pulses) in less than a millionth of a second. The transmitter is then shut off for a long interval—several thousands of a second (which is long in radar). The receiver functions between the pulses sent out by the transmitter. Echoes from the objects struck by the pulses are returned to the receiver. The nearer the reflecting object is, the sooner will the echo manifest itself; the farther away the object is, the longer will it take for the echo to return. The time between the transmission of the pulses and the return of the echo is a measure of the distance of the object from the radar observer. Pulse and echo both travel with the speed of light (186,000 miles a second). Radar sets employed for aiming artillery and anti-aircraft guns are accurate within five or ten yards in several miles; or, reduced to time measurements, 1/30,000,000 of a second.

1.2. *Radar used by bats*

Long before we knew anything about electromagnetic waves, certain members of the animal kingdom were employing the principles of radar in their daily movements. For many years, scientists were puzzled by the way bats could fly about and avoid obstacles in pitch black caves. Investigation revealed that a bat emits a supersonic tone with his vocal organs that is far beyond the audible range of human beings. The notes sounded by a bat range from about 30,000 vibrations a second to well over 70,000. Assuming a mean of 50,000 vibrations a second, and remembering that sound travels about 1100 feet a second through air, the wave length of such sound waves would be 1100/50,000 or 0.02 feet, approximately. This is about one-quarter of an inch. Such small waves are easily reflected by obstacles that are comparable in size. The bat's ears are tuned to the pitch of such sounds. He can hear the echoes or reflections, and as he flies, his perception of the intensity or strength of the echoes is employed by him in the avoidance of obstacles. Scientists have strung wires in rooms that were kept in total darkness, yet bats fly in such rooms and were able to avoid the wire obstacles.

Either by sealing the bat's mouth (cutting off his transmitter) or by stuffing the bat's ears (shutting off his receiver), he is rendered helpless and is unable to avoid obstacles. The engineer who constructs a radar employs principles not unlike those instinctively used by a bat.

1.3. The antenna determines sharpness of beam

The time interval between the pulse and the echo shows the distance to the object. How shall we find the direction of the target (object)? The antenna from which the pulses are radiated into space is made highly directional and sends out narrow beams like a searchlight. In fact, in one type of radar antenna, a reflector of parabolic cross-section is employed, very similar to the reflector in the large Army searchlights whose penetrating beams swept the night skies during the war. The antenna can be rotated completely around a horizontal plane (in azimuth, to be technical) and can be swung through a large vertical angle. When the antenna points directly at the target, a "pip" (radar slang) or indication appears on the viewing screen of the radar indicator.

The sharpness of vision of a radar set, its ability to "see" separately two objects that are close together, depends upon the sharpness of the beam sent out by the transmitter. For a given antenna, the beam will be sharper as the wave length of the pulse is decreased. If a wave length is halved, the sharpness of the beam width is doubled. Thus, we can see how important it is to employ the smallest possible wave lengths. Near the end of the war, we were building large quantities of radar sets that employed microwaves of about three centimeters ($2\frac{1}{2}$ centimeters equal one inch, approximately) in length. These correspond to a frequency of 10,000 megacycles. The beam width was narrowed down to fourth-tenths of a degree—the angle over which the beam spread when leaving the antenna was less than a half degree.

1.4. *Radar and the magnetron*

The greatest obstacle to employing microwaves for radar was the inability to generate large power at such tiny wave lengths. It was not until the English scientists invented a vacuum tube known as the *cavity magnetron* that radar as we know it today became possible. Some time in 1940, the British sent to us a specimen magnetron tube which could develop many times as much power as our most advanced vacuum tube triodes and at much higher frequencies. This was tested on October 6, 1940, in the Whippany branch of the Bell Telephone Laboratories and the results made us rejoice that we and not the Nazis had this tube. Since the year 1940, we have been able to concentrate thousands of kilowatts in transmitting pulses, thus increasing the range of our radars, and, because of the small waves (high frequencies), their accuracy.

1.5. *Curvature of earth limits radar distance*

The distance for which radar can be employed is limited only by the curvature of the earth. If one stands on the shore and watches a ship going out to see, the vessel will be visible for about twenty miles and then it will disappear below the horizon. This simply means that the hump or curve of the earth has blocked out visibility. The higher the tower on which we stand, the farther away is the horizon. In an airplane 30,000 feet up, the horizon can be seen for two hundred miles. Radar—the short-wave, high-frequency type now used—behaves like light, and the limitation in distance is the same; that is, a maximum of two hundred miles.

1.6. *Radar employed at first defensively*

Originally, radar was employed by the English for defense purposes only. In 1936, they began to install radar chains for long-range detection of hostile craft. At that time, huge towers were erected at each radar site. Had the Germans possessed sufficient foresight, they would have bombed the radar installations at the outset, thus blinding their enemy. Through their radar detectors, however, the British were given ample warning of approaching attacks. As they had a mere handful of planes compared to the Germans, it was imperative for them to concentrate their planes only where danger existed. Instead of patrolling the entire English coast and thus thinning out their numbers dangerously, the British were spared the need for patrolling. As the radar revealed the Nazis and their formations when they were hundreds of miles away from the English coast, it was a relatively simple matter for the British to send up their own fighters to meet the approaching hostile craft. In the battle of September 15, 1940, the Nazis attacked with five hundred planes, and the British, thanks to their radars, brought down 185 of them. This was enough for the supermen. Thereafter, the Nazis attacked only at night.

1.7. Radar in night use

The method of meeting night attacks placed a still greater burden upon radar and it rose magnificently to the occasion. In night fighting, the British employed "controllers". Seated before a radar indicator the controller selected a German Plane as a target. How could the controller tell which were German and which were English planes? An extremely valuable characteristic of radar in war is what is known as IFF. Just as different craft bore visual insignia for purposes of identification, so the radar enabled an electronic indicator to function. This was called IFF, an abbreviation for "identification of friend or foe". When a moving vessel was detected by radar and there was no IFF response, the radar operator knew the ship belonged to the enemy. The controller was in radio contact with a British plane which was guided (all this in the pitch blackness of a dark night) to the enemy craft by instructions from the controller on the ground. The latter was able to follow the paths of both planes visually on his radar screen. When the British pilot came sufficiently close to the Nazi, he (the British pilot) was told to "flash his weapon"—meaning that he was to turn on his own radar set on board his plane. One controller on the ground could, and often did, bring down as many as six Nazis in a single night.

1.8. Radar and the buzz bombs

The most magnificent job of defense was done by radar against the buzz bombs. Here, it was necessary to employ radar-controlled antiaircraft missiles. On a certain Sunday in the latter part of August 1944, out of 105 buzz bombs that crossed the British coast, 102 were shot down. Only three bombs got through. Considering the enormous cost, effort, and valuable materials that the Nazis were putting into the buzz bombs, they were duds, militarily. So accurate was the radar gunfire that ground crews relied upon this even when visibility was good.

1.9. Radar and the U-boats

Had we not succeeded in driving the U-boats from the seas, we would have lost the war. Only so long as we could get our men and

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