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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

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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 waveguides). 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.

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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

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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

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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.

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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

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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.

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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

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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 anti-aircraft 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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supplies across to Europe could we hope to succeed. At one time, the Nazis were sinking ships at the rate of five million tons a year.

At the beginning of the war, the British offensive against U-boats was successful because the English were able to locate the submarines through radar indications. Not while they were submerged, mind you, but when the undersea craft came to the surface. The submarines remained submerged during the day, and, relying upon the cover of darkness, emerged at night for fresh air and the charging of their storage batteries. Radar spotted them on the surface and the Germans soon realized that lack of visibility was no protection to their U-boats.

Learning what radar was doing to their submarines, the Germans tried a countermeasure. In the course of our operations, the Germans had captured one of our radar devices intact. From this they were able (no great feat) to build a receiver that could receive signals from such a radar transmitter. They then installed radar receivers on board all the U-boats which gave an indication when radar pulses of the same wave length sent out by the British transmitter struck them. Thus, before a plane could reach the submarine detected by the radar, the U-boat, warned by the receiver on board, had submerged and was under cover. For a while these tactics were effective and the number of U-boats sunk by means of radar fell off appreciably.

Responding to the increased menace, the allies designed and built a radar transmitter of much smaller wave length—microwave size. Not being able to detect microwave pulses with their receivers designed for long wave lengths, the Germans once more began to feel the effects of manifold sinkings of U-boats. During May, June, and July of 1943, we sank more than a hundred U-boats. So desperate did the Nazis become that they organised two scientific U-boat expeditions to gather materials that could cope with the latest radar menace.

The first U-boat expedition went to sea from St. Nazaire on February 5, 1944 and was sunk on February 18th. The second U-boat departed from Lorient on April 27, 1944, and was sunk on May 6th. Finally, the Nazis were compelled to resort to new measures: they invented the "Schnorkel" tube by which a submarine could not only obtain fresh air even though submerged, but also run its Diesel engines while below the surface. We countered with new measures, but before we could test our latest devices, the Nazis succumbed.

It is conceded by all that are familiar with the facts that the convoy system of transportation was pre-eminently successful against the

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U-boats. The loss of all types of ships in convoy was one in a thousand, or 1/10 of 1 per cent, thanks to radar. Before the days of radar, a submarine would emerge under cover of darkness or fog, attack a convenient vessel at high surface speed, and submerge again before she was detected by the destroyer escort. This stopped as soon as all escort vessels were equipped with radar, for the submarine was spotted and attacked at night, or in fog, with the same accuracy as in broad clear daylight. Again, before the days of radar, if a ship in a convoy strayed away for any reason whatsoever, she became an easy and almost certain victim of a U-boat. When radar was introduced, every vessel became "visible" to the convoy commander. Should a ship fall out of the convoy, the commander could follow her course, assign a destroyer escort for protection, and then lead her back to the convoy.

Another advantage to the convoys resulting from the presence of radar was the prevention of collisions between sister vessels. Before the introduction of radar, collisions between vessels of a convoy were frequent. Such collisions ceased with the installation of radar. When two vessels approached too closely in darkness or in fog, the convoy commander issued orders to the ships to alter their courses and speed.

1.10. Radar in naval battles

Just how radar works in naval warfare may be indicated by the following account.

The theatre of operations is the South Pacific near the Solomon Islands. It is late in the evening of November 4, 1942. Prowling through the hostile waters, a United States warship of the latest design, through its radar, discovers an enemy ship about eight miles distant. Visually, the night is pitch black and ordinary visibility is limited to a few hundred yards. The large guns of the battleship are aimed by the radar director. At the second salvo, the "pip" on the radar screen disappears; this means the enemy vessel has been sunk. Remember that neither the enemy nor our vessel has "seen" each other.

This is not a hypothetical illustration but an actual occurrence, the general pattern of which was repeated time and again during the war. The radar is so delicate that it is possible for the operator to see the path of the shells moving across the radar screen. Should they fall short of the target, he can see the splashes on the screen and tell by how much the shell has fallen short.

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When the radar operator has become accustomed to interpreting the pips and echoes on the radar system screen, the effect is as though he were actually and visually examining the scene. In the battle of Suriago Strait, the captain of the leader of a column of destroyers was impressed with the spectacular effects of our attack upon the enemy. Flames were spouting in fountains from the Japanese vessels whose magazines were exploding. The ships became floating rockets. Though a battle-scarred veteran, the captain was stirred to his depths. He called from above to the commodore of the fleet down below,

"Come up here for the sight of your life!"

The commodore was in front of a radar indicator. His answer was, "No, thanks, I can see it better from here."

Just as the radar will show hostile craft and planes and enemies, it will show reefs, shore lies, channels, and other landmarks. By use of it, a vessel can navigate safely through uncharted waters in the blackest night and the thickest fog. At the outset of the war, a group of cruisers was ordered to attack enemy shore installations in the Solomon Archipelago. With deliberation, the time selected was at night, during an inky all-pervading pall. Guided by radar, our cruisers proceeded in formation at twenty-five knots (about thirty miles) an hour through uncharted waters to the point indicated. There they bombarded the shore installations, and returned in formation at twenty-five knots an hour to their base. All this was done under cover of darkness, in strange waters, through a maze of reefs, and in zero visibility.

1.11. *Radar in D-day invasion of France*

In the D-day invasion of France, radar played a stellar role. The whole area between Britain and the invasion coast was blanketed by heavy clouds. As visual bombing by our planes in advance of our troop landings was out of the question, we had to rely on radar bombings. This was done so well that not a single man in our forces was killed or wounded by the bombing, despite a barrage that saturated the invasion beaches just ahead of our advancing men.

1.12. *General characteristics and requirements of radar*

If we examine a radar set, we find, in general, it is made up of the following components:

An *antenna*, which is the means by which the radar pulses are sent out and the echoes are received; that is, the same device is used for both transmitting and receiving. What characteristics should such an

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antenna have? It should be able to send out a very narrow beam, mobile, light in weight, and easily rotated in any desired direction. It should be very efficient, so that the energy that goes out will be concentrated in the useful beam, not lost around the antenna system.

Where does the antenna get its energy from when it is transmitting? From the *oscillator.* The pulses of power of extremely high energy (sometimes more than a thousand kilowatts) are generated in the oscillator at the frequency desired. The vacuum tube usually employed as a generator of high-powered very high frequency pulses is the *cavity magnetron.* As the power is employed in pulses or peaks of extremely short duration the average power is quite small.

The timing of the pulses in the oscillator is controlled from a central source known as the *modulator.* This supplies the voltage pulses to the oscillator and also takes the primary power from a battery, a dynamo, or a motor-generator. The modulator serves as a switch or relay for turning on the radio-frequency oscillator; this, in turn, will oscillate for a millionth of a second or so before it is shut off by the modulator.

For reception, the radar echoes are conveyed to the *receiver.* This is nothing more nor less than a sensitive superheterodyne radio receiver. Oddly enough, the simple crystal, originally employed when radio was in its infancy, has turned out to be very effective as a detector and mixer in the very high frequencies used in radar. An ingenious device known as the *T-R box* (transmitter-receiver) is employed to shut off the receiver when the transmitter is operating, and to block the path to the transmitter when the receiver is functioning. Without some such device, the huge power in the transmitter would paralyze and destroy the sensitive receiver. This switching is done automatically and in millionths of a second.

The radar operator watches the screen of a cathode ray tube. This is identical with the tubes used in television, except that radar tubes are usually of long persistence. This viewing portion of the radar is known as the indicator. In one type of indicator, a bright line appears across the screen of the cathode ray tube when the radar is operating. If an echo comes back from some object, it produces a peak on the horizontal line like an inverted "v". The distance of the "pip" from the beginning of the line or reference point is a measure of the remoteness of the object (target) that causes the echo.

Most laymen who have been introduced briefly to radar are puzzled by the term, "plumbing". The various components just discussed, such as the antenna, the oscillator, the modulator, the receiver, and

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the indicator, must all be connected. By wires? No, by hollow wave guides. As the frequency of an oscillator or circuit increases, the energy radiated increases as the fourth power.

Let me illustrate this with a simple example. Suppose there are two circuits with alternating power flowing through them, one at one cycle a second, the other at two cycles a second. The latter will radiate, not twice the power of the first but 2^4 times as much; that is, $2 \times 2 \times 2 \times 2$ or 16 times as much. In the ordinary house current in the United States, 60-cycle alternating power is employed. In a radar set, operating on a wave length of three centimeters, the frequency is 10,000 megacycles. A megacycle is one million cycles, so 10,000 megacycles means 10,000 million cycles. To ascertain the power radiated, raise this huge number to the fourth power.

In the foregoing paragraph, we have shown one of the reasons for the employment of very high frequencies: because the power radiated is very high. If we connected the parts of a radar set with ordinary wire, each piece of such connecting wire would be radiating power into space indiscriminately because of the extremely high frequency employed. As only the antenna should radiate power, we must shield the rest of the set against radiation. For this reason we employ hollow tubes instead of wires. These convey power effectively from one component of the radar to the other and yet they radiate nothing into space, for the shielding is perfect.

In the following pages, we shall explain and develop the components of radar to which we have just made a casual and general reference.

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Chapter 2

RADAR DISTINGUISHED FROM RADIO

2.1. Relation among frequency, wave length, and velocity

How does radar differ from ordinary radio? In radio we have a transmitter (the broadcasting station) that sends out the radio (electromagnetic) waves and a receiver that intercepts them. The frequency of transmission is relatively low and the wave length, long. As the frequency is the number of waves passing a point in a second, it is evident that the longer the waves are, the smaller will be the number passing any given point for the same period of time. The speed of waves in free space is the same as the speed of light. As Figure 2 : 1

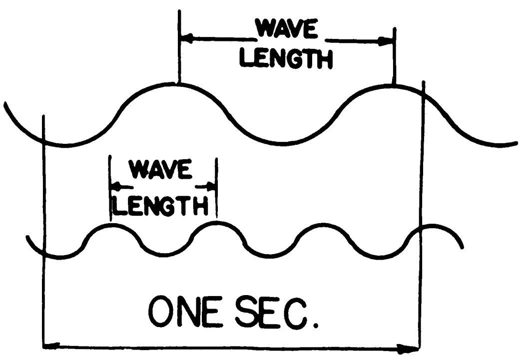

FIG. 2 : 1. RELATIONS AMONG WAVE LENGTHS, FREQUENCY AND TIME

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shows, the wave length is directly related to the frequency. If λ (lambda) is the wave length, v is the speed of light, and f is the frequency, then

$$\lambda = v/f \text{ and } f = v/\lambda$$

Borrowing an example from the physics of sound, if a tuning fork is vibrating 1100 times a second, it sends out (radiates) 1100 waves a second. As the speed of sound through air is 1100 feet (approximately) a second, the wave length of the sound waves will be 1100/1100 or one foot.

2.2. Comparison of power transmitted and power received

In Figure 2 : 2, T is a radio transmitter and R is a radio receiver; the distance from one to the other is one hundred miles. We will assume that the transmitter sends out waves equally well in all directions.

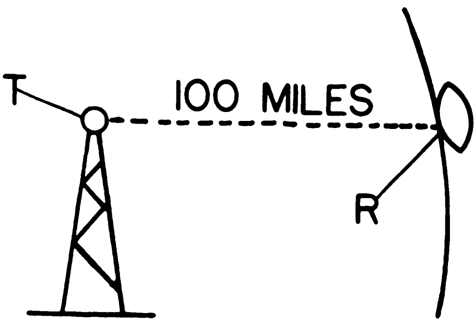

FIG. 2 . 2. SPREAD OF ENERGY: T, TRANSMITTER; R, RECEIVER

The energy of the waves one hundred miles away will be spread out over a sphere whose center is at the transmitter and whose radius is one hundred miles. Remembering that the area of the surface of a sphere is $4\pi r^2$, wherein r is the radius, and π is 3.14, the area of our sphere will be $4 \times 3.14 = (100)^2$ or 12.56×10^4, which is 125,600 square miles.

Let us assume that the transmitter is a moderately powerful one—a hundred kilowatts. This is 100,000 watts. If we divide the surface —125,600—by 100,000, we obtain 1.256 watts per square mile. Let us further assume that the receiving antenna is a square sheet of copper 100 feet on a side; then its area will be 100×100 or 10,000 square feet. In a square mile, we have 5280×5280 or 27,878,400

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square feet. Dividing the area of our antenna—10,000—by 27,878,400, we obtain 0.0003 of a square mile; that is, our receiving antenna covers a surface 0.0003 of a square mile. We have shown that the power received is 1.256 watts per square mile. Thus, the receiving antenna intercepts 0.0003 × 1.256 or 0.0003768 watt. In other words, from a transmitter sending out power of 100,000 watts, a receiving set one hundred miles away, if it employs an antenna of 10,000 square feet of surface, will receive slightly more than 3/10,000 of a watt. If we divide the power at the receiver—0.0003768—by the power of the transmitter—100,000—we obtain, 0.000000003768; that is, 3-billionths of the power[1] of the transmitter is received. Though this is small, it is more than sufficient to operate a modern radio receiver like the superheterodyne.

2.3. *Power received by a radar receiver*

A radio transmitter that sends out power equally well in all directions is very wasteful. In practice, all radio transmitters are directional, so that the power is beamed into useful channels, thus effecting greater economy. An ordinary lamp may scatter its rays in all directions. By placing it in a suitable container with a reflector behind it, we concentrate the light in a given direction as in a searchlight, greatly increasing the intensity where it is needed, without increasing the power expended by the lamp. We shall see later how this is accomplished with radio waves.

In the example given in 2.2, the transmitter and the receiver were one hundred miles apart. If the distance is increased to two hundred miles, that is, doubled, the power received will be one-quarter as large, for the surface of the sphere at two hundred miles is four times as large. In other words, the power received varies inversely as the square of the distance.

In a search radar, the purpose is to locate objects in the path of the beam. We desire to ascertain how far the object is and in which direction it is located. In radar, the transmitter and the receiver (frequently) are located in the same place. The transmitter sends out a beam of electric waves; these strike the object in its path and some are reflected back to the receiver where they are detected. Observe that the receiver is operated by the *echo* reflected from the object. Let us inquire as to the amount of power required to operate the receiver.

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[1] Gain and loss in power are often expressed in a short form known as decibel notation; for full explanation, see Appendix.

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We shall employ the same power and antenna as in the previous illustration where the transmitter and the receiver were one hundred miles apart. In place of the receiver, we shall set up just the reflecting antenna which measures 100×100 or 10,000 square feet. You will recall that the amount of power intercepted by the receiving antenna was 0.0003768 watt. This small amount of power will be more or less reflected in all directions and some of it will find its way back to where the transmitter is.

Let us see how much. As the distance is one hundred miles, the echo power, when it reaches the transmitter where the radar receiver is also located, will be spread over a sphere whose surface is $4\pi r^2$ or $4 \times 3.14 \times (100)^2$, which equals 125,600 square miles. The power is now, not 100,000 watts, but the echo power, 0.0003768 watt. The power received will thus be $0.0003768/125{,}600 \times 10{,}000/27{,}878{,}400$ or 1/1,000,000,000,000 watt, approximately. That is, with 100,000 watts at the radar transmitter and with an object presenting a surface of 10,000 square feet located one hundred miles away, the power received by the radar receiver will be of the order of one millionth of a millionth of a watt. To detect this power, our receiver will have to be much more sensitive than the radio receiver we employed previously. One of the requirements of a radar receiver, therefore, is very high sensitiveness.

2.4. *The advantage of microwaves*

We mentioned the echo reflected by the object. Will ordinary broadcast waves, say of the order of three hundred meters, used in commercial radio, reflect an echo? The answer is, no. To be reflected, the waves must be very much smaller than the reflecting object. This means that the frequency must be very high, for we saw that the relation between the wave length, the frequency, and the speed of the waves was given by the formula, $\lambda = v/f$ (2.1). For very small waves, known as microwaves (near the end of World War II, we were employing waves three centimeters in length), the frequency is several thousand megacycles (a megacycle is a million cycles). As we must determine not only distance but also direction with our radar, the beam must be directive. This serves another purpose; it enables us to concentrate or focus the power in a given direction.

To detect an object, we must observe the echo from it. The transmitter must be shut off while the echo is being observed; that is, the energy must be sent out in very short pulses with relatively long intervals between pulses. Also, to prevent the receiver from being

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paralyzed by the huge power of the transmitter, some automatic means must be devised to protect the receiver while the transmitter is sending out its bursts of energy.

In brief, then, a radar should employ a transmitter of very high frequency and a highly directional antenna, and it should concentrate its power in extremely short powerful bursts of energy. In addition, it should incorporate some means of protecting the receiver during the transmission, and it should include an indicator for visual observations.

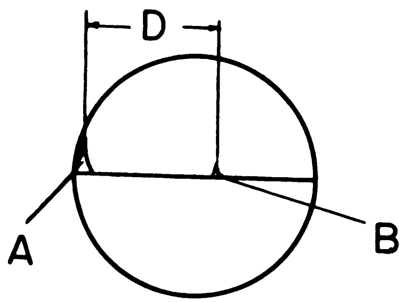

FIG. 2 : 3. APPEARANCE OF RADAR SCREEN
A, transmitting pip; B, echo; D, distance between pips

In most radar receivers, the indications are visual effects, not sound. On the screen of a specially built tube known as a cathode ray tube, a burst from the transmitter produces a pip of light; the returning echo also produces a pip, and the distance between the pips is a measure of the distance to the object observed (Figure 2 : 3). In another type of indicator, a beam of light travels radially from a center, and, at the same time, rotates about the center like the spoke of a wheel. An echo produces an intensification of the light which persists for several seconds. By coupling the radial beam of the cathode ray tube with the rotating antenna, they can be so synchronized that the radial direction of the light beam will be an accurate indication of the direction of the antenna (Figure 2 : 4).

The power radiated from a given transmitter varies as the fourth power of the frequency; if we double the frequency, the power radiated will be sixteen times as much. This is a potent and controlling reason why extremely high frequencies are employed in radar. Furthermore, as the frequency is increased, the wave length decreases correspondingly, so that the radiator becomes smaller and lighter. Where weight

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and size are limited, as on board an airplane, extremely high frequencies (microwaves) are absolutely essential.

In ordinary radio transmission, the power varies as the square of the distance. In radar, the transmitted beam must cover the distance to the reflecting object and back from the object to the receiver, that is, the energy must cover a path twice as long. Therefore, the range covered by a radar transmitter varies as the fourth power of the distance. To detect an object twice as far requires 2^4 or sixteen times as much power. The foregoing would apply under ideal conditions.

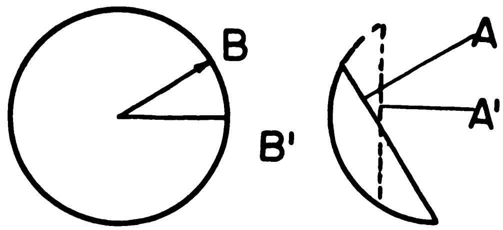

FIG. 2 : 4. CHANGE IN DIRECTION OF BEAM AS ANTENNA ROTATES
Beams B, B′ correspond respectively to antennas A, A′

Actually, because of the curvature of the earth, interference caused by reflections, and absorption by the atmosphere, the power may vary between the fourth and the sixteenth. To illustrate extreme conditions, we may cite transmission between a vessel at sea and a high-angle airplane overhead where the fourth power would apply; in a dense fog, however, from ship to ship, the sixteenth power might well be applicable.

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Chapter 3

TRANSMISSION LINES, WAVE GUIDES AND CAVITIES

3.1. Characteristic impedance of infinite line

Though the principles employed in microwave circuits embodied in radar do not differ from those in radio and in low frequencies, the components and constituents often assume unfamiliar guises.

Let *AB* in Figure 3 : 1 represent the input point of a two-wire trans-

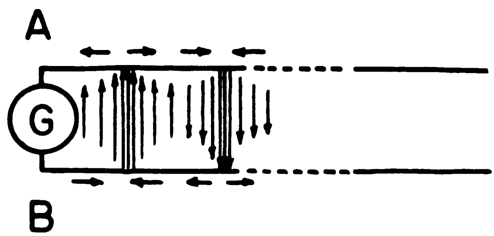

FIG. 3 : 1. FLOW OF CURRENT AND POTENTIAL FIELD IN HIGH-FREQUENCY TRANSMISSION LINE
Horizontal arrows, current; vertical arrows, potential; G, high-frequency oscillator

mission line stretching out to infinity; G is an oscillator of high frequency waves. The line is an open-circuit at its outer end. The two wires, like two plates with an air space between, form a condenser that has capacity. When a condenser is connected to a source of voltage, a current will flow into the condenser until it becomes charged, whereupon the voltage of the condenser will equal the applied voltage and

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no further current will flow. For this reason, current will flow into the transmission line. The vertical arrows represent the direction of the electric field as well as the direction of the flow of current (leakage) from one wire to the other. The wires, like all conductors, offer resistance which reduces the flow of current as we move away from the generator. So because of the resistance and the leakage between conductors, the current is attenuated (diminished), becoming less and less, as we proceed away from the generator.

If we insert an ammeter into the transmission line to measure its current, and apply a voltmeter to measure its voltage, the ratio of the voltage to the current will be constant and equal to the characteristic impedance (total opposition to flow of alternating current). This is true only for a line of infinite length; in such a line, all the energy travels outward.

3.2. *Standing waves in finite lines*

Suppose, now, we set up a line of finite length, as all practical lines are. The waves of voltage and current will travel to the end of the line and then be reflected, whether the end of the line is an open circuit or a short circuit. If we assume an ideal line that has no resistance, then there will be no attenuation. All the energy that passes out will be reflected or returned, and the combined effect of the outgoing and the reflected waves will be to set up *standing waves.*[1] Similarly, if we have a rope of infinite length and set up a wave motion in it at one end by a rapid back-and-forth-motion, a wave can be seen traversing the rope and getting smaller and smaller as it progresses, because of attenuation. On the other hand, if the rope is tied to a firm post at one end, and the other end is given a short violent back-and-forth motion, waves will be seen along the rope as in Figure 3 : 2 (*a*).

These waves which are stationary, are the ones known as standing waves. The existence of standing waves on an electric transmission line of finite length, terminated by either a short-circuit or an open-circuit can be shown by suitable meters. Where the standing wave has the maximum amplitude, the meter will show the maximum reading; where the minimum occurs, the meter will show the minimum reading.

[1] If two sinusoidal waves having the same amplitude and frequency travel through a medium in opposite directions, the medium is supporting a *standing wave.* If the waves are not of equal amplitude, the larger of the two may be deemed composed of two waves, one equal in amplitude and frequency to the smaller opposite wave, and the other a wave of such size as to equal the remainder of the available amplitude. The medium is then supporting a standing wave and a traveling wave.

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The ratio of the maximum intensity to minimum intensity, i.e., the standing wave ratio, will be infinite where the reflection is complete (for either open-circuit or short-circuit terminations). For any other termination of a finite line, the reflection will be partial, and the appearance of the waves will be that shown in Figure 3 : 2 (*b*). Here, the ratio of the maximum to the minimum will be less than infinite but more than unity. For a line of infinite length where no reflections occur, the standing wave ratio is unity, and the appearance of the waves will be that of Figure 3 : 2 (*c*).

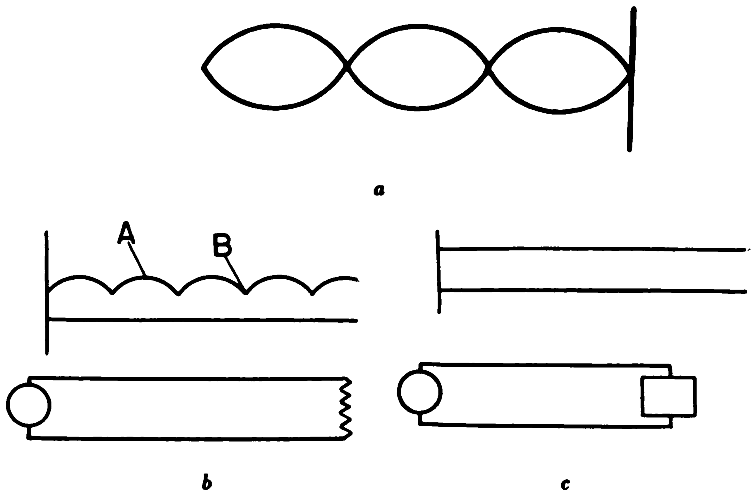

FIG. 3 : 2. APPEARANCE OF STANDING WAVES
(*a*) Nodes and loops in fully reflected waves
(*b*) In transmission line with partial reflections: A, loop; B, node
(*c*) Line with standing wave ratio of unity

3.3. Characteristic impedance of finite line

We shall see soon what the practical effect of standing waves is. As all lines in real life are finite in length, does this mean that every transmission line has standing waves? The answer is, no. Suppose we terminate a transmission line by connecting it to a load whose impedance equals the characteristic impedance of the line. What, then, will be the effect? If we remove a short length of line from an infinite line, the characteristic impedance will not be affected, for the line will still be infinite. It is a mathematical quality of infinity that a finite deduction leaves it unaffected).

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As a result of the foregoing reasoning, if we add a characteristic impedance to a finite line, it is as though the line were made infinite in length. Thus, there will be no reflection on a short line, if we terminate it by its characteristic impedance. To ascertain the characteristic impedance of a short line, we need only measure the impedance of the line at the generator end when the line is open-circuited, and again when it is short-circuited. If these values are respectively, Z_o and Z_s, then the characteristic impedance, Z_c, will be

$$\sqrt{Z_o Z_s}.$$

A line terminated by its characteristic impedance is said to be *matched*. All other lines are *unmatched* or *mismatched*. The degree of mismatch is indicated by the *standing wave ratio*. The ratio of the maximum intensity of the wave to its minimum is a measure of the standing wave ratio. Except in antennas where we want standing waves, they are usually undesirable elsewhere. A line that contains standing waves wastes energy and becomes a radiator. *Any* discontinuity[2] in a transmission line will cause some reflections and set up standing waves.

In an RF transmission line, it is desirable to have a very low standing wave ratio. Ideally, it should be zero; actually, in practice, values ranging between 1.1 and 2 are feasible and satisfactory. Among the reasons why a low ratio is desirable are the higher power capacity (because the breakdown voltage is increased) and the greater efficiency of the line; the fact that the input impedance is not so sensitive to slight variations of frequency and line length; and that the risk (in the case of a magnetron) of pulling the frequency is lessened.

3.4. Radiation from open-wire transmission lines

As the frequency of the oscillations is increased, radiation increases as the fourth power; a two-wire transmission line will radiate farther and farther as the wires are separated. To minimize radiation from a transmission line, we must bring the wires close together. The reason for this becomes clear when we examine the diagrams in Figure 3 : 3.

As the frequency is increased, the wave length decreases, and even a short separation between wires may still be greater than several wave lengths. Open-wire transmission lines or connecting lines are seldom if

[2] Theoretically, at a discontinuity in a wave guide there is an infinity of modes of nonpropagating types in addition to the principal mode of propagation along the wave guide.

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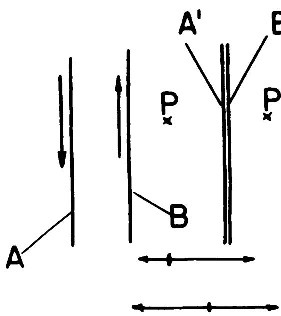
never used in microwave equipment. As the frequency of an alternating current rises, less and less current passes through the interior of the conductor and more of the current is restricted to the outer layers of the conductor. This phenomenon is known as *skin effect.* As the resistance of a conductor depends on its cross-section, skin effect causes an increase in the resistance of the conductor, and the current penetrates the wires less and less. The resistance of wire at extremely high frequencies far exceeds the low frequency or direct current resistance. At a frequency of 3000 megacycles, the depth of penetration of the current into the conductor is a fraction of a thousandth of an inch. This is another reason why open, unshielded wires are not employed for connections in microwave equipment.



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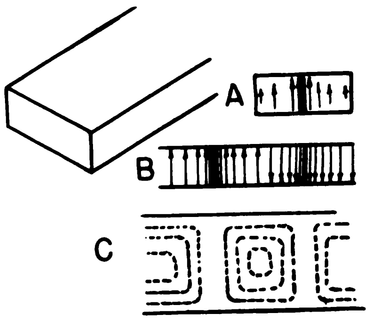

3 : 4

FIG. 3 : 3. RELATIONSHIP BETWEEN RADIATION FROM PARALLEL LINES AND WIDTH OF SEPARATION
AB, wide separation; A′B′, close spacing. Top horizontal vectors represent AB; lower, A′B′

FIG. 3 : 4. ELECTRIC AND MAGNETIC FIELDS IN RECTANGULAR WAVE GUIDE
A, Electric field in cross section; B, in longitudinal section; C, top view, showing magnetic (dotted) field

3.5. Coaxial cables for high frequencies

If wires are unsuitable for transmission lines and connecting links, what shall we employ? Coaxial lines are usable up to frequencies of 3000 megacycles—ten-centimeter waves. The coaxial line consists of a tube containing a wire that runs along its axis and is insulated by spacers or solid insulation from the outside conductor (the tube). As the field between the conductors is entirely enclosed and none appears externally, the coaxial line does not radiate. Furthermore, as the inner

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surface of the external conductor is relatively large, it can carry large currents. By insulating the inner conductor with small beads of polystyrene (or equally effective substances), the losses by insulation can be kept small and the attenuation of the coaxial cable made low.

3.6. Hollow wave guides

You will note that we said that coaxial cables can be used up to 3000 megacycles. This corresponds to a wave length of ten centimeters. What happens when the frequency exceeds 3000 megacycles? As the frequency is increased, the inner surface of the outer conductor carries more and more of the current; the central conductor loses its usefulness and can be made smaller and smaller. When the frequency exceeds 3000 megacycles, we dispense entirely with the inner conductor, and employ only the outer shell. Our coaxial cable has become a simple hollow tube in the limiting condition, known as a *wave guide*. The current is carried entirely by the inner surface of the pipe or wave guide. At a frequency of 3000 megacycles, the depth of penetration of current (*skin depth*)[3] is less than one-tenth of a mil (0.0001 of an inch).

In the ideal wave guide, the walls have no resistance; that is, they have infinite conductivity. In actual wave guides, the material has *some* resistance. As a consequence, the electric field is no longer perpendicular to the bounding walls but has a component that is tangential.[4] This component, in conjunction with the vector of the magnetic field, which is normally tangential at the bounding surfaces, produces a power component, or Poynting vector, directed into the bounding walls.

By plating the inside of the wave guide with silver to a depth of only one-ten thousandth of an inch, the path of the high frequency current is entirely through silver. Furthermore, the electromagnetic field is wholly within the guide, so that none is radiated or lost. Thus,

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[3] By *skin depth* of a conductor is meant the distance (measured in centimeters or inches) in which an electromagnetic wave is attenuated to $1/e$ of the original strength, where e is the Napierian base, 2.718. The fitness of a material to serve as guide walls is gauged by the depth of the skin effect.

[4] If a round wave guide and a coaxial cable of the same outer diameter be compared, the power transmitted is proportional to the square of the applied voltage. For a coaxial cable, the voltage is across the dielectric between the inner and the outer conductors. In a wave guide in the dominant mode, the voltage is across points of a diameter. As the distance between such points is greater than between the conductors, the applied voltage (and hence power) can be larger in the wave guide than in the coaxial cable.

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for connecting purposes and transmission lines at microwave frequencies, the wave guide is most effective. These lines have the lowest losses; that is, they have the least attenuation. Wave guides have one characteristic that sets them apart from open lines and coaxial conductors: they do not transmit frequencies below a certain minimum, known as the cut-off frequency.

3.7. How wave guides transmit power

At first sight, it seems odd that a single conductor can convey power; we have become so accustomed to the double wire of low frequency power transmission that a wave guide appears like a paradox. Actually, we must acquire the viewpoint of contemplating electromagnetic fields passing through the wave guides. If we should take sectional views of a wave guide as it transmits power, we would observe that the electric and magnetic fields appear as in Figure 3 : 4. The arrangement of the fields conforms to a pattern known as a *mode*. It is possible for several modes to exist simultaneously within a wave guide. In a rectangular wave guide, the lowest frequency, or the 0,1 mode, that can exist in the guide has a wave length equal to twice the width of the guide. The height of the guide does not affect the wave length but it does influence the amount of power transmitted, or the attenuation.

If a round wave guide and a coaxial cable of the same outer diameter are compared, the power transmitted is proportional to the square of the applied voltage. For a coaxial cable, the voltage is across the dielectric between the inner and the outer conductors. In a wave guide, in the dominant mode, the voltage is greater across points of a diameter. As the distance between such points is greater than between the conductors, the applied voltage (and hence, the power) can be larger in the wave guide than in the coaxial cable.

Engineers and technicians that work around microwave equipment refer to the wave guide as "plumbing". Commercially and practically, only two shapes are in use, that of round cross-section, and that of rectangular cross-section. Both copper and brass are employed as materials, and where it is desired to keep the attenuation particularly low, the inside of the wave guide is plated with silver or gold; an extremely thin plating (0.0001 inch) is sufficient.

3.8. Electric and magnetic fields in wave guides

In studying wave guides, we must remember a few characteristics of electric and magnetic fields that apply universally. An electric field is always perpendicular to the bounding conductors; a magnetic field

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is always parallel or tangent to the bounding conductors. The electric field is always perpendicular to the magnetic field. The magnetic field always consists of closed loops. In Figure 3 : 5, we show in section, two conductors of a transmission line—one pair round, one pair rectangular. With the round conductors, the electric lines run in curved arcs from one to the other (solid lines); the magnetic loops surround the conductors and cut the electric lines at right angles (broken lines). With the rectangular transmission conductors the electric field is shown in broken perpendicular lines, and the magnetic field is drawn in solid curved lines.

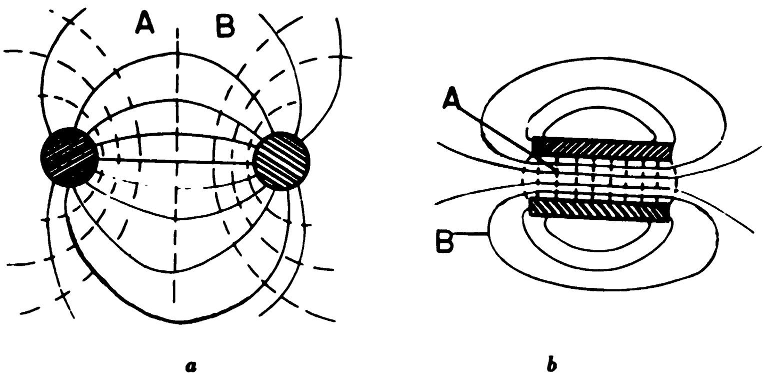

FIG. 3 : 5. ELECTRIC AND MAGNETIC FIELDS ABOUT 2-CONDUCTOR TRANSMISSION LINES OF (*a*) ROUND, (*b*) RECTANGULAR SECTIONS

In Figure 3 : 6 is shown a coaxial cable in cross-section and the fields that exist within it. Note that the cable might be considered as the transmission line in which one of the lines is wrapped around the other, which is, itself, wound tightly into a cylinder. The electric field is now radial, the magnetic field consists of concentric cylinders, and all of both fields lie within the inter-conductor space.

Let us go a step further. Let us add closing walls to the flat transmission line and observe the effect. The electric field runs from top to bottom as before, perpendicular to the conductor. As an electric field cannot be parallel or tangent to the side walls, it must, in the present example, be zero at the side walls. The magnetic field cuts across the electric field at right angles, but it must lie tangent or parallel to the side walls; hence, the magnetic lines are shown curving parallel at the broad ends of the wave guide.

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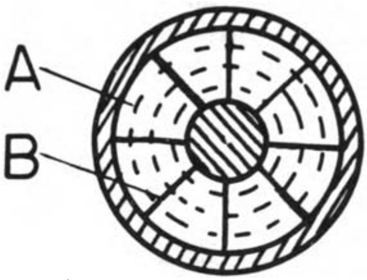
The currents in the walls of a wave guide must be perpendicular to the magnetic fields. How the current flows is important for a number of reasons. The current flows toward M and away from N (Figure 3 : 7). Running through the guide from broad face to broad face, from E to its opposite facc, is the electric field which is minimum at M and N. As power passes down the guide, the entire pattern moves at the velocity of the flow of power.



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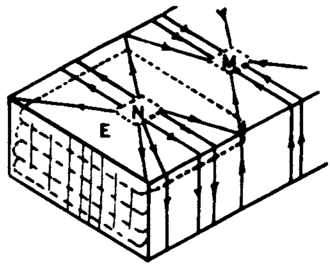

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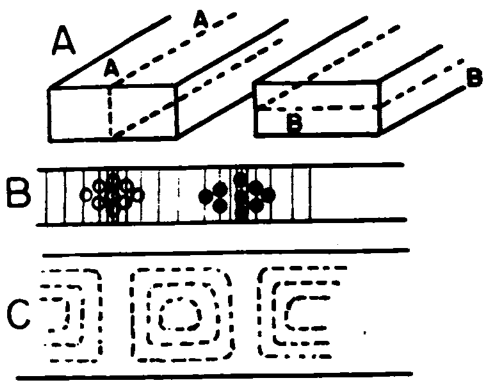

3 : 8

FIG. 3 : 6. APPEARANCE OF (A) MAGNETIC AND (B) ELECTRIC FIELDS WITHIN COAXIAL CABLE

FIG. 3 : 7. FLOW OF CURRENT IN SURFACE OF WAVE GUIDE
Solid lines, electricity; dotted lines, magnetic field

FIG. 3 : 8. APPEARANCE OF MAGNETIC AND ELECTRIC FIELDS SHOWING $TE_{0,1}$ OR $H_{0,1}$ MODE IN RECTANGULAR WAVE GUIDE

3.9. Modes in wave guides

If we were to cut a section through the wave guide, as at A-A in Figure 3 : 8, the appearance of the fields in the guide would be much

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like that shown at B; and for the section through B-B, it would be like that at C. The solid lines represent the electric field and the dotted lines represent the magnetic fields. The views as shown are those at a given moment. As long as power is being transmitted down the wave guide, the entire field moves in the direction of the arrow.

The field arrangement shown in the wave guide is the most fundamental and simple possible. It is known as the $TE_{0,1}$, or the $H_{0,1}$ mode. The expression *TE* stands for transverse electric, or *H*. The letter *H* is used to indicate a magnetic field. In the present instance, the field that moves down the wave guide is the magnetic field, whereas the electric field is transverse or across the guide. Only one field—either the electric or the magnetic—can progress down a wave guide, but not both. If the electric field moves down the guide, then the magnetic field would be transverse, and the mode would be called *TM* (transverse magnetic), or the *E* mode. The letter *E*, is used to indicate an electric field.

Wire conductors or flat parallel conductors can carry or transmit transverse electromagnetic waves (*TEM*). The flat parallel conductors may be considered as coaxial cables in which the radius of curvature is infinity. The coaxial cable can transmit *TEM* modes, which is logical, for the plane parallel type of conductors is only one form of coaxial.

There are many types or modes possible; for instance, in Figure 3 : 9 (*a*), A, shows the end view of a mode, $TE_{0,2}$, or $H_{0,2}$; B is a top view. This is the *transverse electric*, ($TE_{0,2}$), or *magnetic* ($H_{0,2}$) mode. Observe that in going from top to bottom, parallel to the vertical direction (y)[5], there is no change in intensity; the electric field, indicated by the solid lines, is uniform from top to bottom. On the other hand, as we proceed parallel to the horizontal direction (x), there are two complete changes or cycles. The subscript, 0,2, is a shorthand method of describing this fact. Thus, $TE_{0,2}$ ($H_{0,2}$) tells us that the field is a transverse electric and that there are no variation from top to bottom; that there are two changes across the width of the guide. Because the field is a transverse electric, only the magnetic field progresses down the guide.

Using this notation to describe the mode of a field, we can see why the field shown in Figure 3 : 8 is a $TE_{0,1}$ or $H_{0,1}$ mode. In radar that

[5] The notation of x direction and y direction is borrowed from the rectangular coordinate system used in graphic analysis.

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employs wave guides of rectangular cross-section, only the $TE_{0,1}$, or $H_{0,1}$ is in wide use.

In Figure 3 : 9 (*b*), are shown two views of a wave guide carrying a $TM_{1,1}$ or $E_{1,1}$ mode. This is the transverse magnetic or the electric mode. As the name suggests, the maguetic field lines in planes at right angles to the axis or length; and the electric field progresses down the guide. Viewed in cross-section, it can be seen that there is a single variation of the field from top to bottom and from side to side; hence, the mode is the 1,1 type. Observe that the electric loops shown in *A* terminate, as they must, at right angles to the surface of the guide.

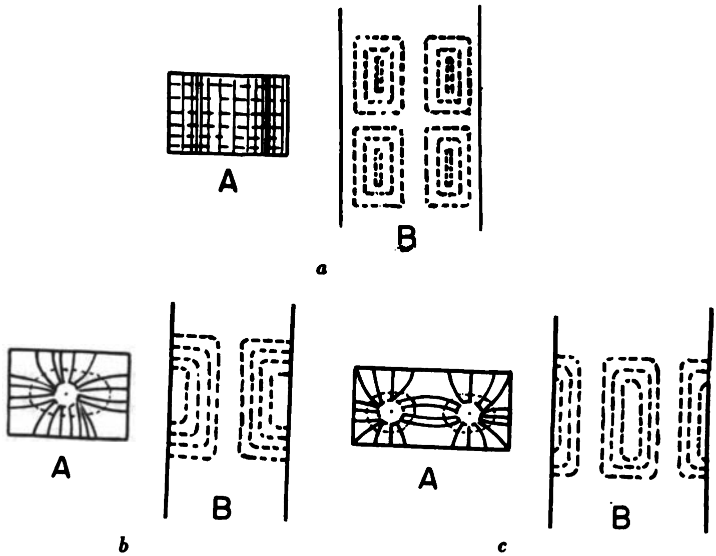

FIG. 3 : 9. APPEARANCE OF MODES IN RECTANGULAR WAVE GUIDES
(*a*) $TE_{0,2}$ or $H_{0,2}$; (*b*) $TM_{1,1}$ or $E_{1,1}$; (*c*) $TM_{2,2}$ or $E_{2,2}$

Figure 3 : 9 (*e*) shows another *E* wave of a higher mode; this is the $TM_{2,2}$ or the $E_{2,2}$ mode.

In radar, two wave guides are in wide use: the rectangular and the circular (referring to the cross-section). In Figure 3 : 10 (*a*) is shown a circular wave guide[6] carrying an $E_{0,1}$ wave, or $TM_{0,1}$. As the mode

[6] Actually, there are no perfectly round wave guides. In practice, all wave guides of circular cross-section are actually slightly elliptical but the deformation is sufficiently small not to affect calculations materially. In this respect, the effects of warping of a section of a circular wave guide is not greater than the departure from an ideal conductor of the actual material of the wave guide.

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indicates, the magnetic field lies in the transverse plane and consists of circles in the cross-sectional planes. The electric lines are perpendicular to the magnetic lines and terminate at right angles to the outer boundary. As seen from the longitudinal view, the electric lines are semiloops.

The method of describing the modes in a circular guide deserves a few words of explanation. Obviously, there are no x and y axes here. In circular guides, we note the complete changes in passing around the axis or center of the guide; then we note the changes in passing from the center to the circumference. Thus, in the mode just shown, there

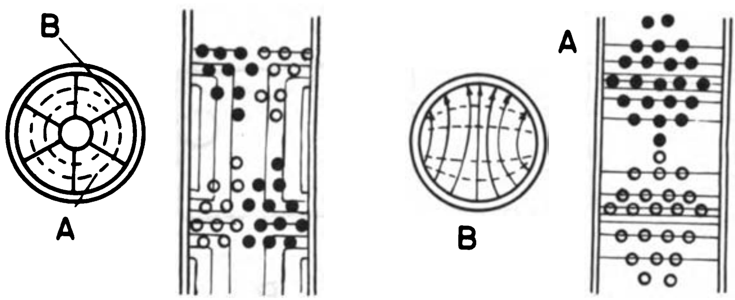

FIG. 3 : 10. APPEARANCE OF MODES IN CIRCULAR WAVE GUIDES
(a) $TM_{0,1}$ or $E_{0,1}$; (b) $TE_{1,1}$ or $H_{1,1}$

is no change in the field as we pass around the axis, but there is a complete change in passing from the center to the circumference; hence the mode is 0,1.[7]

In Figure 3 : 10 (b), we present two views of another mode in a circular guide. From the cross-section at B, we see that the electric lines terminate in the circumference (always perpendicularly) and the magnetic lines run down the length of the guide in loops. In the longitudinal view at A, the solid "dots" and the hollow "dots" represent the magnetic lines viewed in section. Observe that in going around the axis of the guide, it will be seen there is one complete change; also, in

[7] Even though the mode known as $TE_{0,1}$ has the remarkable property that its attenuation decreases as the frequency rises, it has not been put to any practical use. It has been found that this mode is very unstable and the slightest departure from circularity of a round wave guide causes the mode to be transformed into other and more stable forms.

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going from center to circumference, there is one complete change; hence, this is a "1,1" mode.[8]

3.10. How fields are set up in wave guides

How are the fields launched or introduced into guides? By means of either probes or loops. If by a probe, it should be introduced where the electric field is strong and it should be parallel to the field. If the field is launched by a loop, it should be introduced where the magnetic field is strong and it should thread, or be perpendicular to, the field. Figure 3 : 11 shows the launching of a probe, and of a loop. By varying

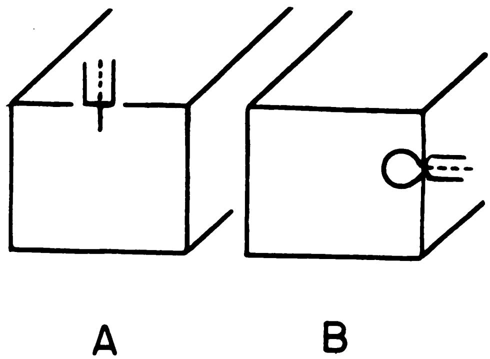

FIG. 3 : 11. LAUNCHING A PROBE (A) AND A LOOP (B) IN RECTANGULAR WAVE GUIDE

the length of insertion of the probe, the coupling effect and the amount of energy introduced can be varied. Similarly, with a loop, by turning it, we vary the coupling between it and the guide. If the loop is turned so that it lies parallel to the maguetic lines, the coupling and the energy will be minimized. Just as loops and probes introduce the energy into wave guides, so they are employed also to abstract energy from wave guides.

3.11. Combining wave guides

Having observed simple forms of wave guides, let us now examine a few combination forms that are encountered in practice with radar.

[8] In the expression, TM_{mn}, the subscript, m, gives the order of the Bessel function, $J_m(kb)$, where k is a constant in the solution of the function. The subscript, n, is numerically equal to the root of the equation when the function is equated to zero, or $J_m(kb) = 0$. The first value or root that would satisfy the equation is obtained when $n = 1$. This characterizes the cyclic changes that occur radially; that is, it denotes the radial periodicity.

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In Figure 3 : 12 (*a*) are shown two T forms; A shows the *Series T*, and B, the *Shunt T*. They are widely used in coupling wave guides. The Series T, is so called because there is a break in the broad face of the guide which interrupts the flow of current along the length of the guide. On the other hand, B does not destroy the continuity of the flow of current, so it is known as the "shunt T". In Figure 3 : 12 (*b*) represents at A a parallel form employed in transmission lines with a

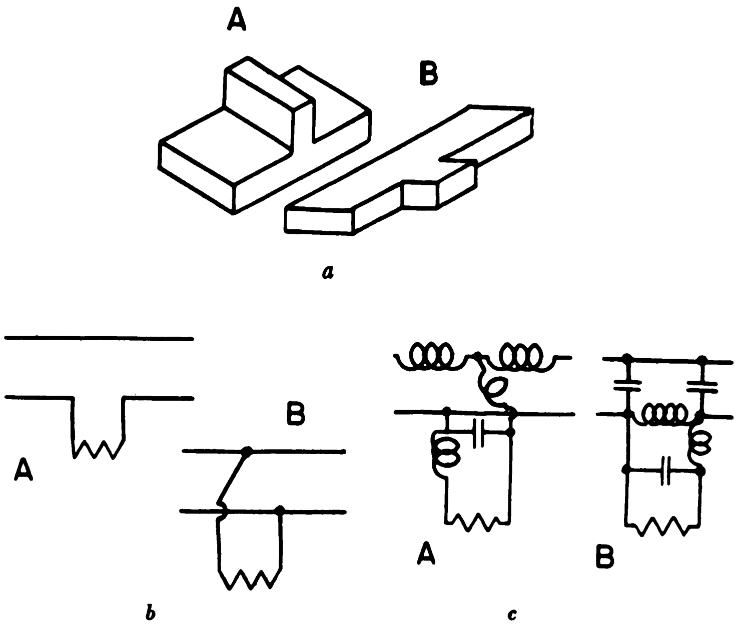

FIG. 3 : 12. COUPLINGS FOR RECTANGULAR WAVE GUIDES
(*a*) Series T (A); shunt T (B)
(*b*) Simple equivalent Wire forms for T-couplings shown in (*a*)
(*c*) Detailed equivalent of (*a*)

series interruption; similarly, B portrays the shunt T form. Strictly speaking, the diagram of wiring shown in Figure 3 : 12 (*b*) for the series and for the shunt T junctions do not truly represent the actual conditions. At the points where the junction occurs, eddies are produced in the fields. The effect of such distortions is like the introduction of reactances or networks across the guide. Actually, the shunt T will appear as at A in Figure 3 : 12 (*c*), and the series T, at B.

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3.12. The magic or hybrid T

A combination of both T's in one form, as shown in Figure 3 : 13 (*a*), has very remarkable properties. If we send or launch a wave into arm 1 and we terminate 2 and 4 so that there is no reflection in the branches, then 3 will carry no power at all; that is, all the power will go into 2 and 4. Again, if we launch a wave in 3, and 1, 2, and 4 are terminated to absorb without reflection, all the power passes into 2 and 4, and none proceeds down 1.

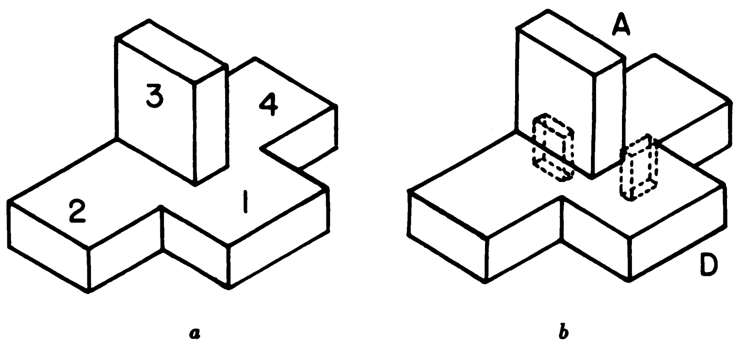

FIG. 3 : 13. EFFECTS WITH MAGIC T
(*a*) Hybrid T for rectangular wave guide
(*b*) Location of matching devices

On the other hand, if 1 and 4 are matched at their terminations and (hence, no reflections) 2 is unmatched, and energy is fed into 3, there will be a reflection in 2. This reflected energy will return to the common junction where it will produce a flow of power in 1, 3, and 4. If 2 and 4 are not matched at their terminations, the energy fed into 3 will pass along 1. This combination T is known as the "Magic T" but a better name for it is the *Hybrid T*.

To understand the operation of the Magic T, let us examine the electric fields set up, as shown in Figure 3 : 14 (*a*). Let us consider the effect of sending a signal down an arm, D. The arrows show the direction of the electric field at one instant. In arm D the field runs from right to left. At the junction with the horizontal arms, B and C, the field fringes and spreads. At equal distances from the center or plane of symmetry, the fields in arms B and C are equal but of opposite phase (directions of arrows are reversed); that is, energy transmitted down arm D spreads equally in arms B and C with odd symmetry.

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Now let us consider Figure 3 : 14 (*b*). A signal is sent into arm A where the arrows indicate the direction of the electric field. At the junction of arms B and C the field fringes and spreads. Note that all the arrows point in the same direction. At equal distances from the plane of symmetry, the fields in arms B and C are not only equal but they also have the same phase. We can now see the reason why energy in arm A or D can spread in B and C but A and D cannot send into each other. The field in D has odd symmetry whereas that of A has even symmetry.

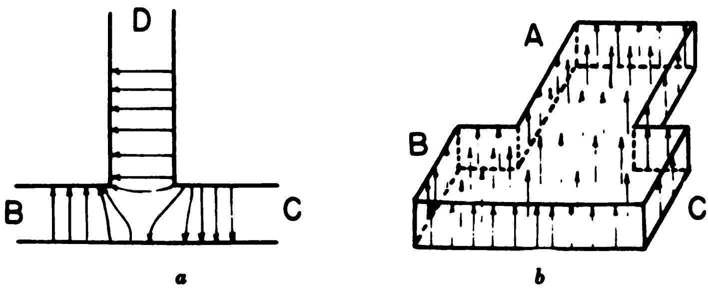

FIG. 3 : 14. ELECTRIC FIELDS IN MAGIC T
(*a*) Series part; (*b*) shunt part

By transmitting energy into A and D simultaneously and regulating the amount, it is possible to cancel the energy in arm C (if the opposite fields just cancel) and send all the energy into arm B. By reversing one of the fields, we can cancel the energy in arm B and transmit all into arm C.

The foregoing assumes that arms B and C are matched at their terminations so that there are no reflections. If they are unmatched, energy will be reflected into arms D and A; the amount of this energy is a measure of the mismatch.

In the ordinary Magic T, a signal sent into arm A or arm D will be partly reflected along A or D because of the mismatch at the junction. As a result, it is customary to interpose a matching device at the junction of each arm, A and D as shown in Figure 3 : 13 (*b*).

3.13. Coupling wave guides through slots

A simple and common method of coupling wave guides together is by means of slots. If a slot in a wave guide runs across the width of the guide so as to interrupt the current in its face, as at A in Figure 3 : 15

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(*a*), it is a ***series slot***. If it runs parallel to its long axis, as at B in the drawing, it is a ***shunt slot***. Figure 3 : 15 (*b*) shows, at A, two wave guides coupled by series slots, at B, two wave guides coupled by shunt slots, and at C, two coupled by a combination of shunt-series.

Figure 3 : 15 (*c*) shows three wire arrangements, A, B, and C, equivalent to the couplings; similarly designated in Figure 3 : 15 (*b*).

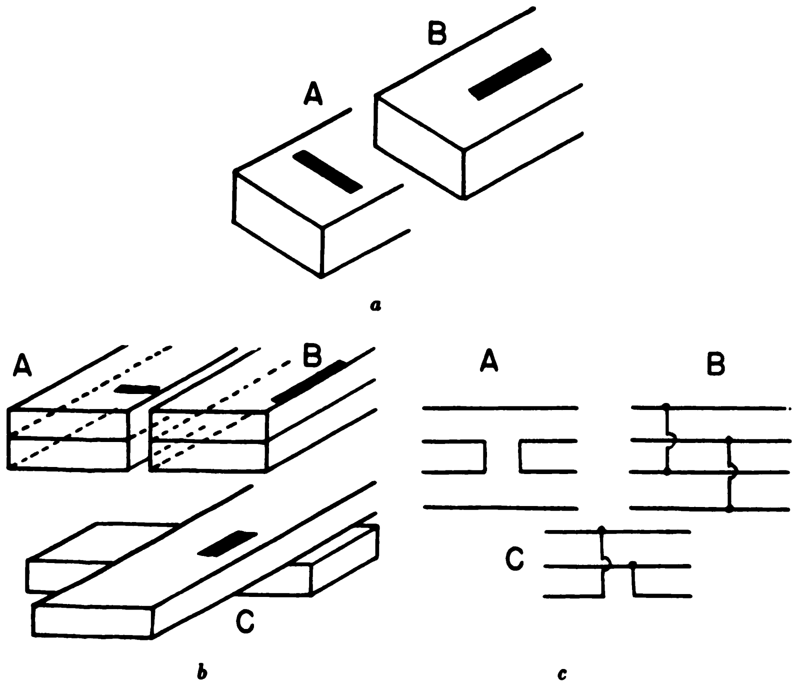

FIG. 3 : 15. COUPLING OF WAVE GUIDES
(*a*) Series slot (A); shunt slot (B);
(*b*) By series slots (A); by shunt slots (B); by combination of series-shunt (C);
(*c*) Schematic Wire Equivalents of combinations in (*b*)

3.14. Coupling circular and rectangular wave guides

With certain modes or fields, it is possible to couple circular and rectangular wave guides. This is highly important, for it enables us to couple an antenna dish to a guide, thus permitting a complete rotation of the antenna without interrupting its power supply. Figure 3 : 16 (*a*)

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will make this clear. The field in the circular guide should be symmetrical about its center so that, regardless of its rotation, its mode remains constant. The $E_{0,1}$ wave form (see Figure 3 : 10 (*a*)) satisfies this condition. B shows how the fields are transferred to and from the rectangular guide.

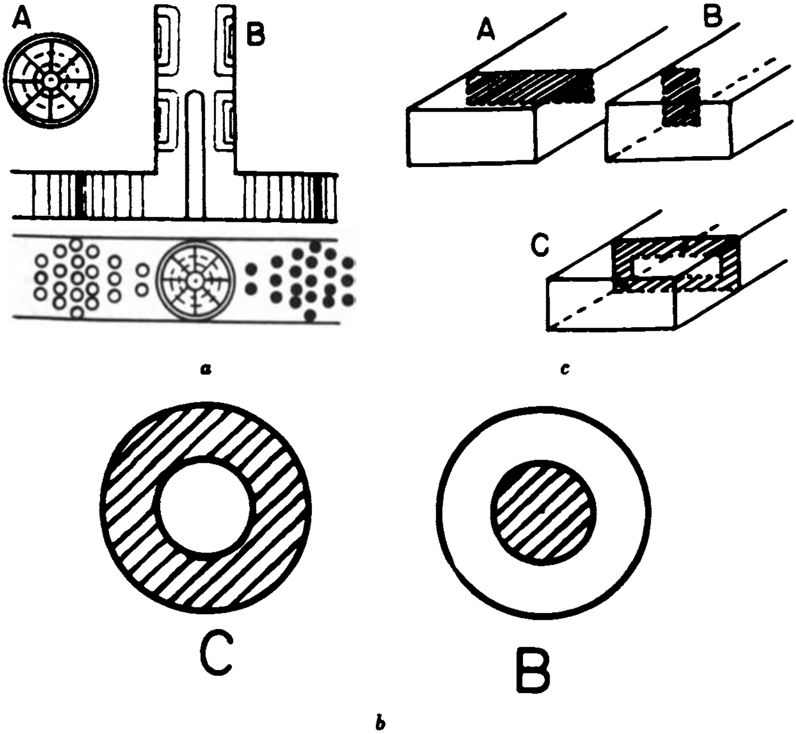

FIG. 3 : 16. FIELDS AT COUPLING JUNCTION
(*a*) Effects in circular and rectangular guides
(*b*) Inductive (C) and capacity (B) effects produced by diaphragms
(*c*) Capacitive (A), inductive (B), and combination (C) effects of diaphragms

3.15. Producing inductive and capacitive effects in guides

A circular disc across a circular guide is shown in Figure 3 : 16 (*b*) B; this produces a capacitive effect. A ring-shaped partition is shown in C; this produces an inductive effect. As in low-frequency and wire circuits, the effect of resonance is the same. A combination of capacitance and inductance in parallel acts as an enormous impedance across

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the wave guide and permits free passage through it; a combination in series at resonance, across the wave guide, behaves as though the guide were short-circuited.

We have observed that a short-circuit across a wave guide, such as a solid sheet of metal, causes a total reflection (complete mismatch). Equally effective, a wave guide ending in a complete open circuit causes a total reflection. Any partial obstruction,[9] whether metallic (perfect conductor) or dielectric, will cause partial reflection (mismatch), except at resonance. If a conductor is perfect, no losses should occur, and the obstruction will produce reactive effects; that is, it will behave as a pure inductance or a pure capacitance.

3.16. Resonance effects in wave guides

We have seen that a partition placed across a wave guide, as in A, in Figure 3 : 16 (*c*) behaves as a condenser; if placed as in B, it acts as an inductance; if as in C, it becomes a combination of both in parallel, placed across the wave guide. By suitably adjusting the dimensions of the slot or opening, the inductance effect can neutralize the capacity effect, and the partition becomes a resonant circuit. When this condition occurs, the waves in the guide proceed along its length without hindrance, just as though the partition were absent. At resonance, the parallel combination of inductance and capacitance has infinite impedance.

It has been proved that when the corners of the *iris*,[10] MNOP, QRST, fall on the branches of a hyperbola, the iris will be resonant (Figure 3 : 17 (*a*)).

In circular wave guides, the type of iris shown at A in Figure 3 : 17 (*b*), where the opening is a thin annular space whose circumference is slightly less than a wave length, will act as a parallel resonant circuit shunted across the guide. On the other hand, an iris that is completely open, except for a thin annular metal barrier slightly greater than a wave length in circumference, as in B, serves as a perfect reflector. In other words, the iris becomes a series-resonant circuit across the wave guide. The circular opening thus behaves as a completely open wave

[9] Though a single post jutting out into a wave guide may have the properties of an inductance (see 3.28) or a capacitance, depending on its length, in the form of a movable screw it can be made to produce a match for a minimum standing wave ratio. Even so, the spacing between post and wave guide termination is extremely critical for a minimum standing wave ratio. By employing three turning screws with a spacing of a quarter-wave length between pairs, the adjustment is not too critical.

[10] The opening into the wave guide, indicated by the dotted rectangles.

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guide; the circular ring produces the effect of a completely closed wave guide.

In Figure 3 : 17 (*c*), A is a rod slightly longer than a half-wave placed across a circular wave guide which behaves as a series-resonant circuit; thus it acts as a short-circuit and becomes a perfect reflector. B is an iris with a bar-shaped opening slightly shorter than a half-wave length which behaves as a shunt resonant circuit; thus it acts as a perfectly transparent object, permitting free transmission of energy.

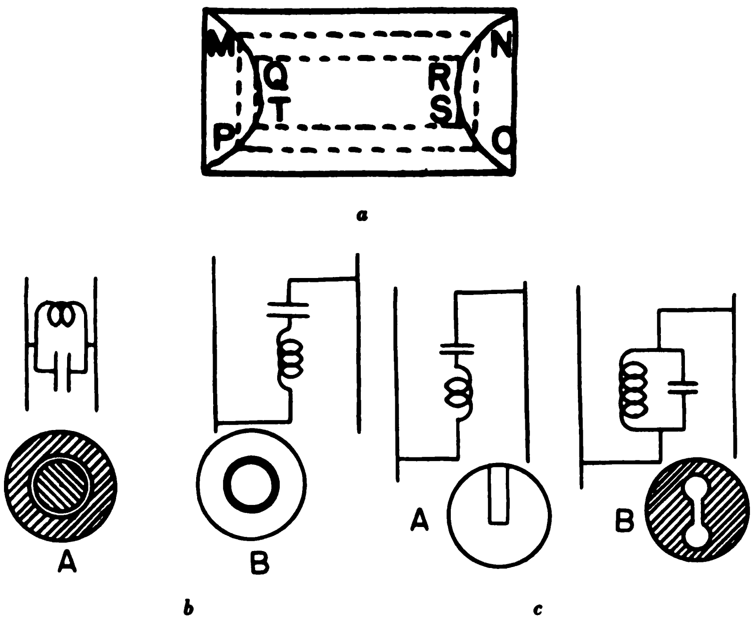

FIG. 3 : 17. RESONANCE EFFECTS IN IRIS
(*a*) Corners fall on hyperbola
(*b*) Iris and wire equivalents: (A) parallel-resonant circuit; (B) series-resonant circuit
(*c*) Series-resonant equivalent of rod (A), shunt-resonant equivalent of iris (B)

3.17. Effects of slots in wave guides

The effect of a slot in a wave guide will depend on the location of it with reference to the axis of the guide, and whether it interrupts the current. To be resonant, a slot should be half a wave length. Thus, for an $H_{1,0}$ wave, a slot (Figure 3 : 18 (*a*)) running crosswise (A) will interrupt the path of current; therefore, it will radiate energy. Slot B,

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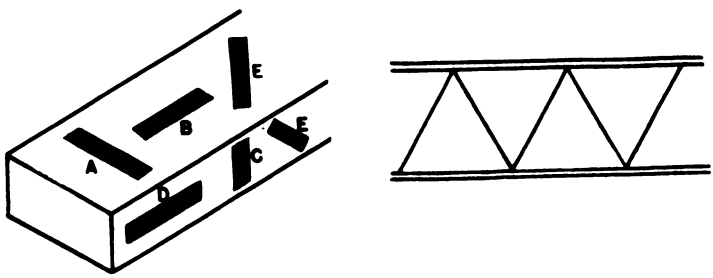
running parallel to the length of the wave guide, will not interrupt the current, and will not radiate; nor will slot C, placed along the narrow dimension. Slot D will radiate; slot E, placed at an angle, has a component that will radiate. A slot that radiates may be employed for coupling purposes.

3.18. Flexible wave guides

Wave guides can be built in flexible form. In one kind, the guide is built on a square mandrel of the required cross-section. A flat metal ribbon with upturned edges is wound over the mandrel; then a similar ribbon with edges turned down is wound over the first ribbon, thus causing the edges to interlock and providing considerable flexibility. By encasing the whole in a rubber sheath, the flexibility is preserved, yet the wave guide is made airtight.



a *b*

FIG. 3 : 18. RADIATION IN WAVE GUIDES
(*a*) Slots A, D, E radiate; B and C do not
(*b*) Zigzag path of waves in rectangular wave guides

3.19. Velocity of transmission in a wave guide

In wave guides, we must consider two kinds of velocity: group velocity and phase velocity. The individual waves or cycles of the carrier move with a phase velocity; the wave form impressed on the carrier by the modulation of the signal moves with the group velocity. Phase velocity *always* exceeds the speed of light; group velocity *never* exceeds the speed of light.[11]

In a rectangular wave guide the waves travel in a zig-zag path, as shown in Figure 3 : 18 (*b*). Thus, the effect of such a path is to slow down the transmission of the waves along the length of the wave guide.

[11] For details, see Appendix.

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In free space,[12] they travel with the speed of light, 186,000 miles a second; in the wave guide, their speed is less.

3.20. *Cause of attenuation in wave guides*

In a rectangular wave guide, the dimension from side to side should be appreciably more than twice the wave length, and the height of the wave guide, the dimension from top to bottom should not exceed a half wave length. On the other hand, the height should not be made too small, for the electric field (the voltage) running from top to bottom may cause sparking.[13]

With a given wave guide, as the wave length is increased, the reflections from the guide walls become more frequent, and the speed down the wave guide decreases. When the wave length reaches a maximum length known as the cut-off wave length (or cut-off frequency), the wave bounces back and forth between the walls of the guide and there is no passage of power down the guide. As the wave length approaches cut-off, the losses in the wave guide increase. These losses in an air-filled wave guide occur almost entirely in the walls of the guide. It follows that the resistance of the metal walls is important and the higher the resistance of the metal, the greater will be the resistance losses. On the other hand, in attenuators, where the amount of energy passing through the wave guide is to be cut down, resistors may be inserted into the wave guide.

In other words, as the critical wave length of the wave guide is approached,[14] less and less power is transmitted, more and more power is wasted in the walls of the guide, and we say the attenuation of the guide is increasing. As one of the primary reasons for employing wave guides is to minimize the losses of transmission at high frequencies, it becomes necessary to employ wave guides whose wall-to-wall dimensions appreciably exceed the wave length to be transmitted.

3.21. *Evolution of the cavity resonator*

Inductances, capacitors, and resistors are the building blocks of ordinary low frequency radio as well as of radar. When we tune a radio, we vary the inductance or the capacitance of the circuits until resonance is established for a given frequency (wave length). At

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[12] Space itself may be considered as a wave guide with infinite dimensions (cross section unlimited). A plane wave propagated through space has an attenuation constant which is determined entirely by dielectric losses occurring in the space.

[13] For details, see Appendix.

[14] For details, see Appendix.

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resonance, the following relationship exists between the inductance, L, the capacitance, C, and the frequency, f:

$$f = 1/2\sqrt{LC}$$

In this simple equation, the expression LC occurs in the denominator of the fraction; we can therefore increase the resonant frequency by

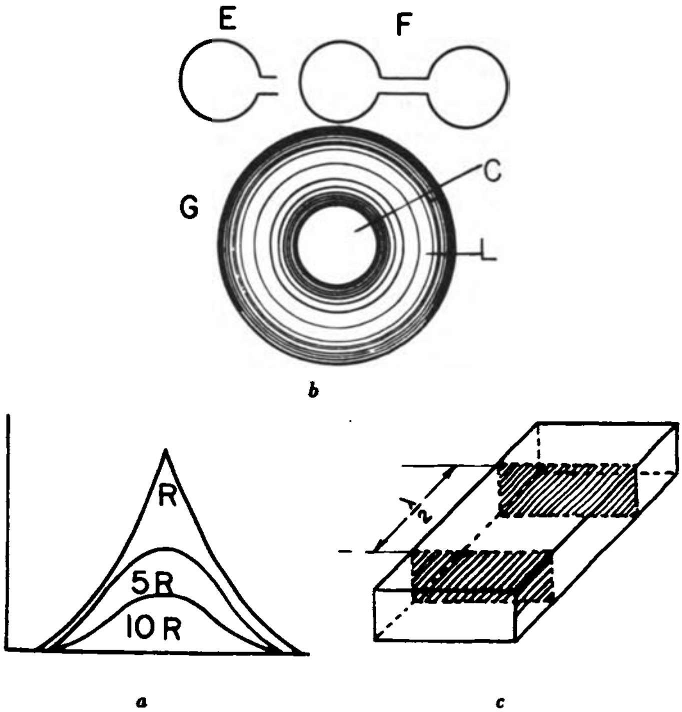

FIG. 3 : 19. RESONANCE EFFECTS
(*a*) Increased sharpness of resonance with decreased resistance
(*b*) Evolution of resonant chamber and successive decreases of resistance;
(*c*) Resonant chamber formed by metal partitions

decreasing either L or C, or both. Resistance in a circuit affects the sharpness of resonance but not the frequency, as shown in Figure 3 : 19 (*a*). The higher the resistance, the broader is the tuning.

Figure 3 : 19 (*b*) shows several resonant circuits whose resonant frequency is progressively higher as we travel from left to right. At E, we have a single turn inductance, and two plates for the condenser.

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The only way to decrease the inductance is to add a turn in multiple, as shown at *F*. By adding more turns in multiple, we can decrease the inductance and increase the resonant frequency. If we add enough turns, we will enclose the entire space and produce a *cavity resonator* (top view). Any closed chamber with conducting walls can be used as a cavity resonator. For microwaves or extremely high frequencies, such resonators are commonly used. The resonant frequency of a closed cavity is entirely a matter of geometry—the size and shape alone determine the resonant frequency.

If we place a metal partition across a wave guide at a node (where the amplitude of the wave is zero), the standing wave is not affected. If we place metal partitions across two different nodes, they will have no effect upon the standing waves. The partitions and the four bounding walls of the wave guide form a closed metal chamber, as shown in Figure 3 : 19 (*c*). So long as the length of this chamber is half a wave length or a multiple of half a wave length, standing waves can be sustained within it.

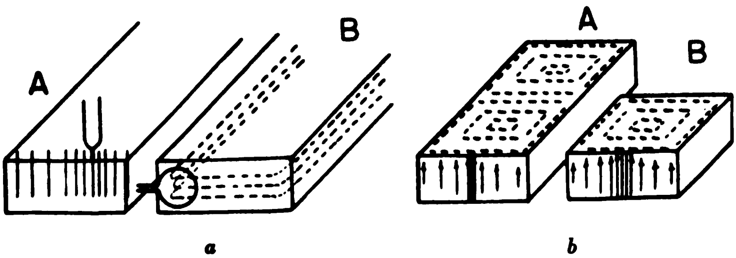

FIG. 3 : 20. FIELDS IN WAVE GUIDES
(*a*) Method of launching by (A) probe; (B) loop
(*b*) Appearance of fields in rectangular cavities: (A) $TE_{0,1,2}$ or $H_{0,1,2}$; (B) $TE_{0,1,1}$ or $H_{0,1,1}$

3.22. Modes in resonant cavities

To set up waves in a resonant cavity, an electric or magnetic field must be established in the chamber. Such a field may be injected by means of a probe or a loop as seen in Figure 3 : 20 (*a*). If a probe is employed (A), it acts as a small antenna from which the electrical field radiates. Around the loop (B) a magnetic field will be set up.

Just as in wave guides, a cavity resonator will oscillate in modes. The notation employed to describe the modes is quite similar to that of a wave guide, with the exception of an additional number or subscript to indicate the cyclic variations along the length of the cavity.

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Thus, in Figure 3 : 20 (*b*), A, the dotted lines represent the magnetic fields and the solid lines, the electric fields. Parallel to the vertical (y) direction, there is no variation of the field. Parallel to the (x) direction, or width of the cavity, there is one cyclic change (zero at the guide walls, maximum at the center); and parallel to the major axis or length of the wave guide, there are two cyclic changes. Thus, the mode in the cavity resonator would be described as $TE_{0,1,2}$ or $H_{0,1,2}$. For the same reason, the mode of B in Figure 3 : 20 (*b*) would be described as $TE_{0,1,1}$ or $H_{0,1,1}$.

3.23. *Resonant wave length of cavities*

Any enclosed chamber made of metal may be used as a cavity resonator, provided the distance from wall to wall is equal to a half-wave

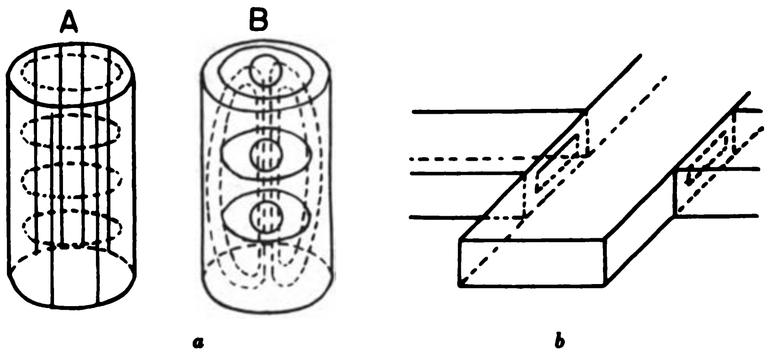

FIG. 3 : 21. EFFECTS IN RESONATORS
(*a*) Appearance of electric fields in cylindrical resonators: (A) vertical; (B) circular
(*b*) Cavity resonator coupled to wave guides by irises

or a multiple of a half-wave. In any event, the wave length is always set by those dimensions of the hollow chamber at right angles to the direction of the electric field. In a cylindrical chamber, with the electric field running from one flat boundary to the other (top and bottom), as at A in Figure 3 : 21 (*a*), the dimensions at right angles to the electric lines can vary only as the radius of the cylinder; hence, this is the only dimension that affects the resonant wave length. At B in the same figure the electric field lines are circular and in planes parallel to the flat boundary surfaces; hence, the resonant wave length, which is determined by the length of the cylinder, varies as the distance from flat surface to flat surface. As the resonant cavity often occurs in radar

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circuits where it is joined by wave guides or coaxial cables, it is important to match the chamber with its guides or cables. The character of the match is determined by the impedance presented by the chamber to the sources of input and output.

3.24. Matching coupling loops to cavities

Figure 3 : 22 (*a*) shows a resonant chamber coupled to a loop at its input and also at its output, being respectively fed by a coaxial cable and tapped by a coaxial cable. The purpose of a loop is to engage the magnetic lines of flux. If we turn the loop completely through an angle of 360°, it will engage the maximum and the minimum number of magnetic lines at intervals of 90°. For instance, if the loop shown in Figure 3 : 22 (*b*) is perpendicular to the magnetic lines, it will link the maximum number of lines of magnetic force. If the loop is turned 90°

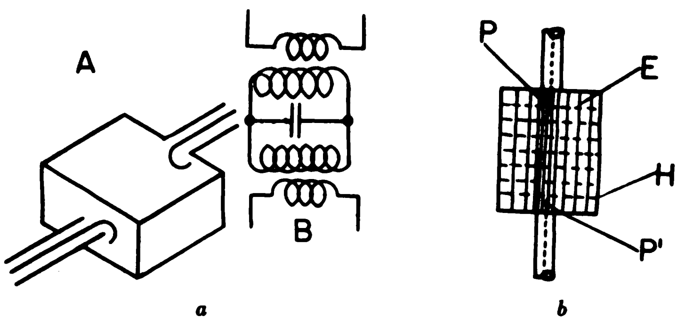

FIG. 3 : 22. COUPLINGS OF COAXIAL CABLES
(*a*) To rectangular cavity resonator (A); equivalent wire circuit (B)
(*b*) To cavity resonator: P, P^1, probes; E, electric, H, magnetic fields

from this position, it will lie parallel to the magnetic field and engage the minimum number of lines.

Another property of a resonator is its shunt resistance. A resonator may be considered as a circuit composed of a pure inductance and a pure capacitance, and a shunt resistance connected across the terminals of the resonator. The loss of energy in the resistor is the energy dissipated in the resonator. The impedance presented by the resonant cavity to either of the coaxial cables will depend, then, on the magnetic lines of force threading the loop. Obviously, this will depend on the size or area of the loop, the strength of the magnetic field in which it lies, and the angle the loop presents to the magnetic lines. If we desire,

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then, to match a coaxial cable terminating in a loop to a resonant cavity, we should rotate the loop until no standing waves appear.

The arrangement of input and output loops coupled to a resonant cavity, as at A in Figure 3 : 22 (*a*), has for its equivalent the series resonant circuit to which are coupled two coils, as shown in B. Each small coil corresponds to a loop. Rotating the loops alters the coupling to the resonant chamber. Rotating the coils alters the coupling to the resonant circuit.

3.25. *Matching probes and apertures to cavities*

When probes are employed instead of loops, as shown in Figure 3 : 22 (*b*), the variation in coupling is made by changing the length of the inserted probe. This will change the matching impedance; a very slight change of length will bring about a great change in impedance or coupling.

It is comparatively common to couple a cavity resonator to a wave guide by means of apertures or openings, as seen in Figure 3 : 21 (*b*). If the openings occur in similar parts of the resonant chamber, that is, where the fields or intensities are equal, then the size of the aperture will determine the amount of coupling. To state it otherwise, the impedance is matched by changing the area of the connecting aperture.

3.26. *Q of resonant cavities*

In low frequency circuits, the quality of a coil (Q) is expressed by a ratio, $L\omega/R$, where L is the inductance of the coil, ω is 2π times the frequency, and R is the resistance of the coil. At microwave frequencies, the Q of a resonant chamber is better expressed as the ratio of the energy that is stored to the energy that is wasted. In a hollow chamber, the energy is stored in the space or volume, that is, in the electromagnetic field, and the energy wasted is what is lost because of the resistance in the walls of the chamber. The Q of a resonant cavity therefore, is the ratio of the volume to the area of its bounding surfaces multiplied by a constant. $Q = KV/A$. The greater the ratio of the volume to the area, the larger is the Q. The geometrical figure with the maximum ratio is the sphere, for it has the least area of surface for a given volume. A sphere, therefore, should have a very large Q.[15]

[15] In actual practice, the Q's encountered for cavities of various shapes do not follow the theoretical conclusions too closely. The reason is that the theoretical basis assumes a uniform magnetic field throughout the volume of the resonator. Actually, the magnetic field near the bounding walls is always more intense than at points nearer the center of the resonator.

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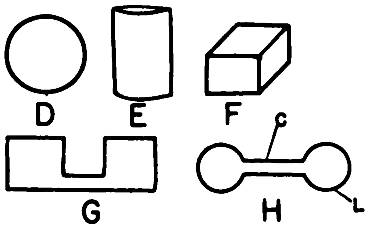
In Figure 3 : 23 are shown several geometrical figures whose Q's are easily calculated. Both G and H are re-entrant cavities which find special use and whose Q's are not easily calculated. In examining G and comparing it with G in Figure 3 : 19 (*b*), we note that the capacity of the resonator is largely concentrated at C and the inductance of the cavity at L. Such re-entrant cavities find use in klystrons, or velocity-modulated tubes (4.18).



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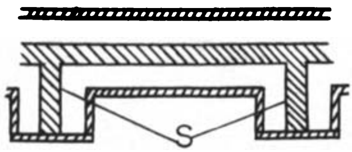

3 : 24

FIG. 3 : 23. Q's OF GEOMETRICAL FIGURES
D, E, F, curves readily calculated; G, H, reentrant, more difficult to calculate
FIG. 3 : 24. QUARTER-WAVE SUPPORTING STUBS (S) USED AS INSULATORS IN COAXIAL LINES

3.27. *Quarter-wave stubs as perfect insulators*

We mentioned that coaxial cables (3.5) employ center conductors insulated from the metallic tubes through which they run by means of insulating beads. Though such cables are very efficient they do have some slight losses because the insulating beads are not perfect insulators. When the highest efficiency of transmission is required, the central conductor is supported by solid metal supports known as *quarter-wave stubs*, as shown in Figure 3 : 24. In other words, the best of all insulators (lowest losses) may be pure copper supports.

To understand this, let us examine B in Figure 3 : 25 (*a*). This is a quater-wave-length piece of coaxial cable, short-circuited at one end (on the right) and open at the other. The solid curve below it shows the magnitude of the voltage, which will be zero at the short-circuit end and the maximum at the open end; the dotted curve shows the current similarly, which is the maximum at the shorted end and zero at the other end. The impedance of a device is the ratio of the voltage to the current; at the open end, therefore, the impedance of the quarter-wave stub, E/I, is infinity. If the central conductor is supported directly by the open end of the stub, it will present an infinite impedance to the central conductor; that is, the quarter-wave stub will be a perfect insulator. Attention should be called to the fact that the stub has infinite impedance only at resonant frequency.

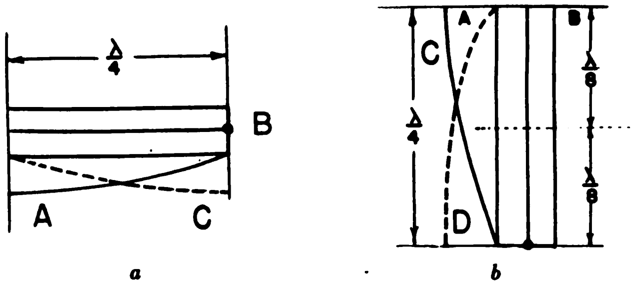

FIG. 3 : 25. EFFECTS WITH QUARTER-WAVE STUBS
(*a*) Curves showing current (C) and voltage (A) on quarter-wave stub shorted at one end
(*b*) Stub-like parallel combination of coil and condenser: condenser above dotted line; inductance below

3.28. Segments of transmission lines; inductances, capacitors

As we observed previously, it is no longer feasible to employ ordinary condensers and coils (**3.21**) in equipment of very high frequencies (microwave circuits). For such purposes, we can use parts or lengths of wave guides and transmission lines. Thus, in Figure 3 : 25 (*b*) the quarter-wave transmission line shorted at the bottom presents an infinite impedance at AB. In other words, it behaves like a parallel combination of coil and condenser at resonant frequency. The eighth-wave-length above the light dotted line behaves like the condenser, and the length below (shorted), like the coil. So a length of line less than a quarter-wave and open at both ends behaves like a condenser, whereas a length shorted at one end behaves like a coil.

Figure 3 : 26 (*a*) shows a half-wave transmission line shorted at the lower end. The curved solid line shows the distribution of voltage, and the dotted line indicates the current. The impedance at any point is the ratio of the voltage to the current, shown by the dashed curve. Observe that the impedance of this half-wave section at the open end is extremely low. That is, a half-wave transmission line shorted at one end behaves at the open end like a resonant series circuit (see diagram at right in Figure 3 : 26 (*a*)).

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On the other hand, a half-wave transmission line open at both ends behaves like a very high impedance. It is similar to a parallel resonant circuit, as shown in Figure 3 : 26 (*b*).

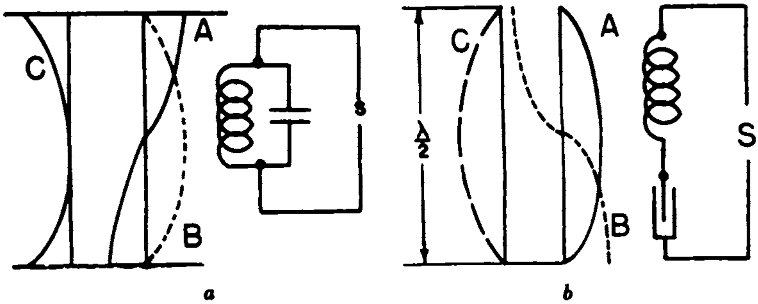

FIG. 3 : 26. VOLTAGE (A), CURRENT (B), IMPEDANCE (C) ON HALF-WAVE TRANSMISSION LINES
(*a*) Short-circuited at one end
(*b*) Open at both ends
(Equivalent wire circuit at right in each diagram)

We saw (3.3) that the characteristic impedance of a transmission line is

$$Z_c = \sqrt{Z_s Z_l},$$

where in Z_s is the impedance of the sending end; and Z_l, the impedance at the load. Thus

$$Z_c^2 = Z_s Z_l \qquad \text{and} \qquad Z_l = Z_c^2/Z_s$$

We can avail ourselves of the property of a quarter-wave open transmission line for matching purposes.[16] Suppose we desire to match a 1000-ohm line to a 10-ohm line, as shown in Figure 3 : 27.

$$Z_x \text{ (matching section)} = \sqrt{Z_s Z_l} = \sqrt{1000 \times 10} = 100 \text{ ohms}$$

for the value of the quarter-wave impedance. The quarter-wave section will have a characteristic impedance of 100 ohms in order to effect a match. Let us check this:

$$Z_s = Z_x^2/Z_l = (100)^2/10 = 1000 \text{ ohms}$$

$$Z_l = Z_x^2/Z_s = (100)^2/1000 = 10 \text{ ohms}$$

[16] For details, see Appendix.

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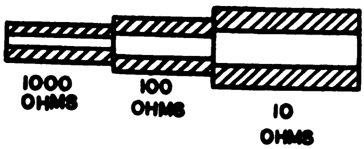
Just what characteristic a segment of a transmission line exhibits will depend upon its length and termination. If it is less than a quarter-wave length and open at each end, it will behave like a capacity; if between a quarter-wave and a half-wave length, it will show the characteristic of an inductance. On the other hand, if it is less than a quarter-wave length but short-circuited at one end, it will behave like an inductance (coil); if more than a quarter-wave length but less than a half-wave length, it will act like a capacity (condenser).

We saw that a quarter-wave section of coaxial cable or of a transmission line can be used as an insulator, It can also be employed as a transformer. This obviously follows from its resemblance to a coil and condenser in a parallel resonant system. Thus, in Figure 3 : 28, at A,



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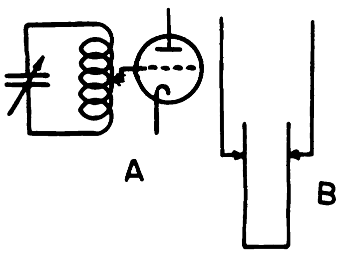

3 : 28

FIG. 3 : 27. MATCHING 1000-OHM AND 10-OHM LINES WITH 100-OHM LINK
FIG. 3 : 28. WIRE EQUIVALENT (A) OF QUARTER-WAVE SECTION (B) USED AS TRANSFORMER

the tap on the coil is connected to the grid of the tube, providing a means by which the voltage of the grid may be varied. Similarly, B shows the use of a quarter-wave short-circuited transmission line as a resonant transformer.

A half-wave length section behaves like a one-to-one transformer. If it is short-circuited at one end, the other end appears as a short-circuit; if it is open at one end, the other end appears open. In general, the ends of a half-wave length repeat each other's characteristics.

3.29. Standing wave indicators

We have mentioned standing waves (3.2) caused by reflection of unmatched terminations. Several simple types of indicators of such waves are in use. A small neon lamp may be run along a transmission line with which its terminals make contact, as shown in Figure 3 : 29.

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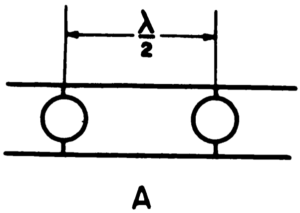
If there are standing waves present, the lamp light will pass from the minimum to the maximum as it is moved along the transmission line. The distance between two minima or two maxima marks a wave-length. More accurately, a crystal in series with a microammeter may be substituted for the lamp. The readings of the meter will vary as the detector is moved along; as with the lamp, the distance between successive maxima or minima will indicate a wave-length.

3.30. Speed of transmission of radio waves

In a perfect vacuum, and substantially so through air, the speed of electromagnetic (radio) waves is that of light, or approximately 3×10^{10} (30,000,000,000) cm per second. Through coaxial cables with solid insulation, the velocity may fall off by a third; it is not unusual



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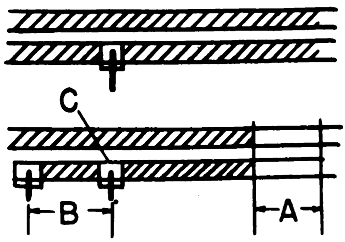

3 : 30

FIG. 3 : 29. USE OF NEON LAMP FOR DETECTING STANDING WAVES
FIG. 3 : 30. MEASURING SPEED OF ELECTROMAGNETIC WAVES IN CABLES WITH SLOTTED CONDUCTOR

for the speed in telephone circuits to fall off to a tenth that of light.

We have seen that velocity, wave length, and frequency are related by a simple formula, $\lambda = v/f$ (2.1).

If the frequency, f, is kept constant and the velocity, v, is decreased, then the wave length, λ, must decrease. Stated otherwise, the wave length in air is decreased as it passes through a cable with solid insulation. Figure 3 : 30 shows a composite coaxial line consisting of an air-insulated line in series with a rubber-insulated line. The air line is slotted for the insertion of a probe. For a frequency of 3000 megacycles in air, the wave length is ten cm; through the rubber-insulated part, if the speed falls off to seventy per cent, the wave length will be seven cm. By using a slotted line, it becomes simple to measure the decreased speed through the solid cable.

In order to set up standing waves, the termination of the cable is

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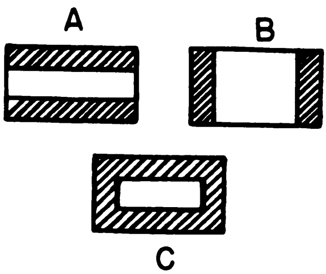
left open. Now, insert a probe (it may be connected to a neon lamp, or a crystal) and slide it toward C until the minimum is indicated. Then, cut off a piece of cable and slide the probe to the left until the minimum is detected again. The ratio of the shift in the slotted conductor to the length of the cable that is cut off yields the information we seek. Suppose the piece of cable cut off is 3.5 cm and the slide is moved five cm between minima. Then, 3.5 divided by five gives 0.7, or seventy per cent; that is, the speed of transmission through the solid cable is seventy per cent of that through air.

3.31. Diaphragms for matching

In A, Figure 3 : 31, the effect of the diaphragm across the top and bottom of the wave guide is to increase the capacitance; in B, the vertical diaphragms cause the inductance to be increased; in C, the



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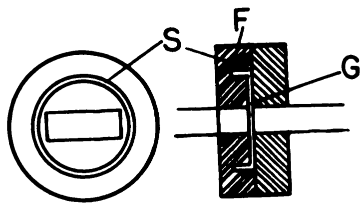

3 : 32

FIG. 3 : 31. WAVE GUIDE DIAGRAMS FOR MATCHING PURPOSES
A, Capacity increased; B, inductance increased; C, both increased
FIG. 3 : 32. CHOKE COUPLING FOR WAVE GUIDE
S, Circular groove; F, short-circuited termination; G, termination a half-wave from F

impedance is increased. Thus, we can match the impedance of wave guides of different characteristics by the use of these shutters or diaphragms.

3.32. Choke flanges for coupling wave guides

Wave guides are usually coupled together by means of flanges at their extremities. If we used simple flanges, there would be a leakage of energy at the coupling, which, as a discontinuity would cause a mismatch (**3.3**) and set up standing waves. Instead, the flanges are slotted or depressed as shown in Figure 3 : 32. S is a slot cut in the form of a ring completely girding the rectangular guide. In depth, S is exactly

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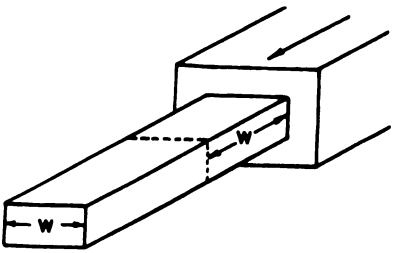
a quarter-wave length; thus, S is itself a wave guide a quarter-wave in length and short-circuited at F. At G, therefore, a half-wave length removed, it will present zero impedance (a short-circuit) and prevent any energy from leaking out of the wave guide. This coupling arrangement is known as a *choke coupling*.

3.33. Attenuator in wave guide

A movable metal vane inserted in a slotted wave guide can serve as an attenuator, diminishing the energy transmitted without affecting the frequency or wave length.

What causes the energy in a wave guide to be attenuated? The losses in the walls of the wave guide and the losses in the dielectric of the wave guide are obvious from the fact that neither a perfect conductor nor a perfect dielectric exists. What is not so evident as a source



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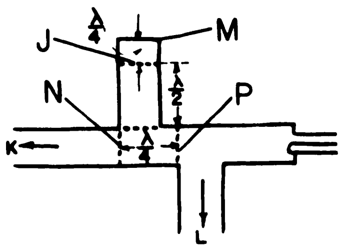

3 : 34

FIG. 3 : 33. WAVE GUIDE ATTENUATOR MUCH BELOW CUT-OFF
FIG. 3 : 34. ARRANGEMENT OF WAVE GUIDE STUBS FOR SWITCHING AND BLOCKING

of attenuation occurs when the impressed wave length exceeds the cut-off wave length. In fact, where this occurs, the attenuation (Figure 3 : 33) is equal to 27.3 decibels for a distance equal to the width of the wave guide, provided such width is very much less than a half-wave in length. Thus, if the wave impressed is ten centimeters and the width of the wave guide is one centimeter, the wave will be diminished or attenuated 27.3 decibels. That is, in traveling one centimeter down the narrow wave guide, it will be attenuated to 0.0018 of its value.

3.34. Wave guide sections as elements in circuits

Any closed metal chamber, as we have already noted (**3.21**) may be used as a resonant chamber. If we close a wave guide with partitions of metal spaced a half-wave apart, it will become a resonant cavity.

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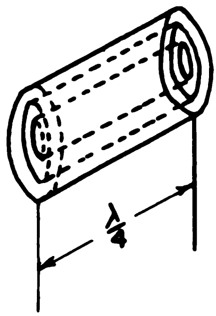
Just as parts of transmission lines and coaxial guides may be employed as transformers, capacities, and inductances, so wave guides in sections find equally effective uses.

Let us consider the arrangement of wave guide stubs shown in Figure 3 : 34. If at point J we short-circuit the guide, then the effect is the same as though we have closed N and the energy supplied by the coaxial cable will feed into K and L. Now let us remove the short at J.



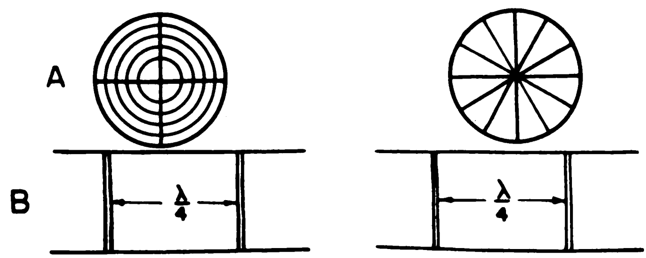


FIG. 3 : 35. WAVE GUIDE FILTERS
(*a*) Grating for $TE_{0,m}$ mode;
(*b*) Concentric cylinders for $TE_{0,m}$ mode;
(*c*) Grating for $TE_{0,m}$ mode

From M to the point P, is a whole wave length; therefore, the short-circuit at M will appear at P, a whole wave length away, and the path to K will be blocked, thus permitting energy to feed into L only.

3.35. Wave guide filters

It is possible to filter out or separate the various frequencies and modes that are transmitted through a wave guide by means of gratings.

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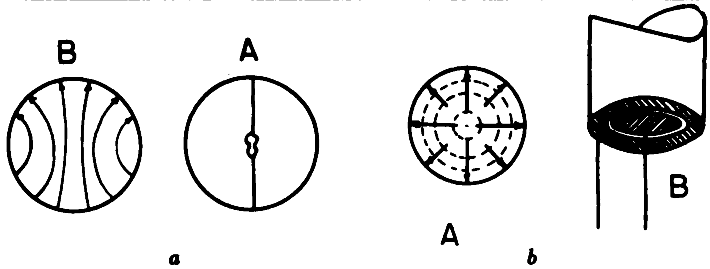

FIG. 3 : 36. FILTERS IN CIRCULAR WAVE GUIDES
(*a*) For $TE_{1,1}$ mode; (*b*) for $TM_{0,ml}$ mode

We must remember that several modes and several frequencies can exist simultaneously in a wave guide if certain conditions are satisfied.

Figure 3 : 35 (*a*) shows a grating consisting of a series of concentric metal rings supported on insulators. Recalling that this resembles the $TE_{0,m}$ mode in a circular wave guide, we interpose a grating in order to filter out this mode from the wave guide. If the material of the screen has high conductivity, this form will reflect most of the energy in the mode. If the conductivity of the material is low much of the energy will be absorbed. To ensure that little if any energy is transmitted past the barrier, it is common practice to set up a similar screen a quarter-wave length away. Better than this, however, is a screen composed of concentric cylinders, as shown in Figure 3 : 35 (*b*)

In Figure 3 : 35 (*c*), is presented a screen for reflecting the $TM_{0,1}$ mode; it is a form that effectively screens off this mode from the wave guide beyond.

Suppose that we desire to abstract or detect waves of a given mode, leaving other modes that are at present unaffected. Thus, the $TE_{1,1}$

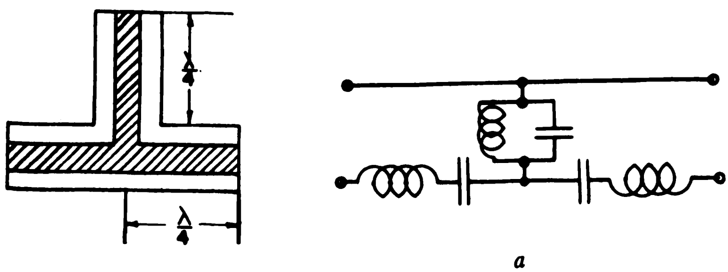

FIG. 3 : 37. COAXIAL T-JUNCTION WITH EQUAL ARMS OF QUARTER-WAVE LENGTH
(*a*) Lumped circuit equivalent of same junction

mode in a circular guide appears as in B in Figure 3 : 36 (*a*). A crystal in a circuit, spanning the diameter of the wave guide as in A, will suffice to remove this mode. Similarly, to remove the energy of a $TM_{0,1}$ mode, as shown in A in Figure 3 : 36 (*b*), an arrangement such as that of B will suffice.

In Figure 3 : 37 is shown a coaxial T junction in which all the arms are a quarter-wave in length. This is equivalent to the statement that each arm is a resonant circuit. In the same figure (*a*) shows the equivalent of the lumped circuit; this is the familiar *band-pass* filter. Another type, shown in Figure 3 : 38, consists of two cavities adjusted to resonance by means of the movable central conductors. Both resonant cavities are connected by a quarter-wave coaxial line. This is a band-pass filter whose lumped constant equivalent is presented in the same figure (*a*).

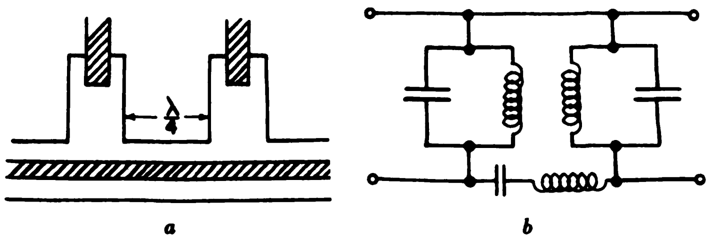

FIG. 3 : 38. CAVITY BAND PASS FILTER WITH MOVABLE CENTRAL CONDUCTORS
(*a*) Lumped circuit equivalent of same filter

3.36. *Wave guide transducer*

In Figure 3 : 39, we present a wire screen known as a *transducer*. Observe that the wire contours partake of two modes, the $TM_{0,1}$ and the $TE_{0,1}$. Hence, by interposing such a screen in a circular wave guide that carries a $TM_{0,1}$ mode, we may convert the form beyond the screen into a $TE_{0,1}$ mode. Similarly, if we transmit a $TE_{0,1}$ mode, then we may abstract energy from a $TM_{0,1}$ mode beyond the screen.

An interesting arrangement is shown in Figure 3 : 40, where a $TM_{0,1}$ mode is abstracted at A, and reflected at B, and a $TE_{0,1}$ mode is abstracted at C.

Figure 3 : 41 shows a wave guide carrying power at several frequencies simultaneously. By means of several chambers, each resonant to a different frequency, the energy can be filtered off by the use of irises.

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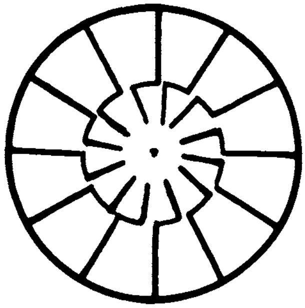
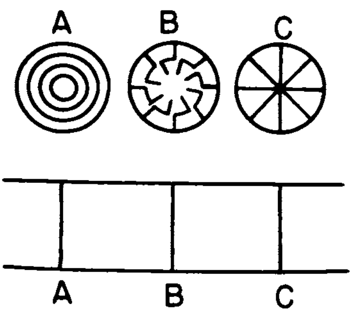


FIG. 3 : 39. WIRE SCREEN TRANSDUCER FOR CONVERTING $TM_{0,1}$ MODE INTO $TE_{0,1}$ AND VICE VERSA

3.37. Dielectrics as wave guides

It has been observed that the power in a hollow wave guide is conveyed through the dielectric (ordinarily air) in the wave guide. The power dissipated or wasted is confined to the inner surface of the metal guide. The question arises, can we remove the outer metal shield and still transmit power? Reasoning strictly from the foregoing, the answer should be "yes". If the dielectric were perfect, there should be no losses and no attenuation.

Using a substance with a high dielectric constant (such as distilled water) and frequencies far beyond the critical or cut-off frequency



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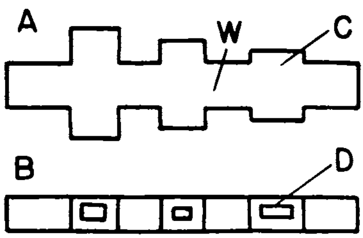

3 : 41

FIG. 3 : 40. ARRANGEMENT FOR ABSTRACTING VARIOUS MODES $TM_{0,1}$ filtered out at A, reflected at B; $TE_{0,1}$ filtered out at C

FIG. 3 : 41. FILTERING DIFFERENT FREQUENCIES BY IRISES FROM RECTANGULAR WAVE GUIDE

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(3.33), experiments show that the power is confined largely to the interior of the guide. If the frequency is lowered (approaches the cut-off) and the dielectric constant of the material is also low (glass or polystyrene, for instance), the power is no longer restricted entirely to the guide, but a considerable part travels in the region outside of the guide.

Because no dielectric is perfect, and hence losses occur in the material, dielectric wave guides have found no practical field, except in certain types of directional antennas known as *polyrods* (10.14).

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Chapter 4

TUBES FOR RADAR OSCILLATORS

4.1. Ineffectiveness of ordinary vacuum tubes

Not until we were able to produce an efficient source of microwaves could we devise workable radar transmitters. To build low-frequency oscillators is not difficult; in fact, practically all radio vacuum tubes such as triodes, tetrodes, and pentodes can be used to produce low-frequency waves. Receiving tubes, being small, are limited in the power they generate. In principle, transmitter tubes for low frequencies are identical with receiving tubes but they employ larger elements to dissipate the greater amount of heat evolved.

As the waves produced by an oscillator decrease in size, and the connecting wires and tube leads approach the waves in length, more and more energy is radiated away by the connecting leads and wires, and the tubes become inefficient. Another quality asserts itself as the frequency rises. As the transit time of the electrons passing between the elements of a tube approaches the time of a cycle, the tube becomes less and less efficient. The speed of electrons can not exceed the speed of light—3×10^{10} cm a second. At a frequency of 3000 megacycles (3,000,000,000 cycles), which corresponds to a wave length of ten cm, the duration of one cycle is 1/3,000,000,000 of a second. If the speed of the electrons in a radio tube is 1/10 of the maximum possible,[1] it would be 3×10^9 cm a second (3,000,000,000). Let us assume the distance travelled between the cathode and the plate (anode) of a vacuum tube is one-half a centimeter (much larger than actually encountered). The time of transit would then be one-half the time of a cycle.

[1] For details, see Appendix.

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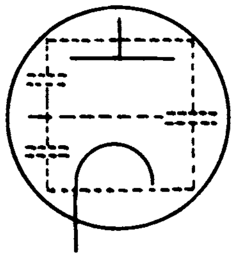
We can decrease transit time by increasing the voltage between cathode and anode (plate). This increases the speed of the electrons and hence the time required to cross from one to the other (transit time). For this reason, the voltage employed in oscillators of extremely high frequency runs into the tens of thousands.

We can also decrease the transit time of the electrons by decreasing the distance travelled; this means that we must bring the elements of



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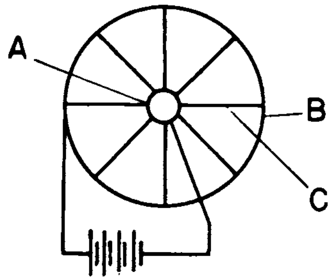
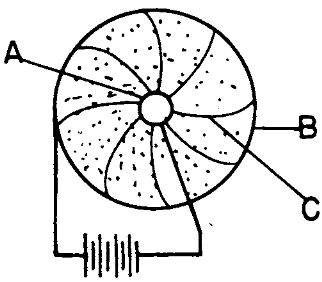
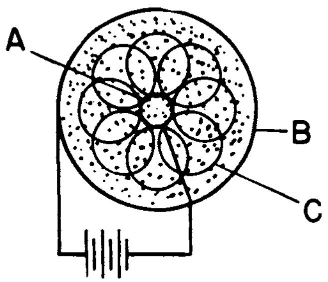


4 : 2 (*a*)



4 : 2 (*b*)



4 : 2 (*c*)

FIG. 4 : 1. CAPACITIES IN TRIODE TUBE BETWEEN ELEMENTS

FIG. 4 : 2. RADIAL PATHS OF ELECTRONS IN MAGNETRONS
(*a*) Without magnetic field: A, cathode; B, anode; C, path of electrons;
(*b*) With weak magnetic field, cycloidal path
(*c*) Strong magnetic field, cycloidal

the vacuum tube closer. By doing so, we also augment the capacity effect which increases the power shunted away from the tube for useful purposes. The plate and grids of a tube behave like the plates of a condenser; and these act as though condensers were connected in parallel with the tube (Figure 4 : 1). By decreasing the size of the elements, we could decrease the capacity effect but we would also lessen

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the ability of the tube to dissipate heat, which means we are diminishing the possible power generated. The design of a radio transmitter tube is thus a compromise, at best. What makes the problem difficult is the production of the huge power required by the radar pulses—as much as several million watts in some of the high-powered transmitters. It is not particularly difficult to generate *minute* quantities of power at any frequency.

4.2. *Electrons affected by magnetic field*

Practically all radar transmitters now employ magnetron tubes. In Figure 4 : 2 (*a*), A is a filament heated to incandescence and giving off electrons; B is an anode connected to a source of high voltage, positive with respect to A. The electrons emitted by A are attracted to B, to which they will travel in straight lines if the voltage is high enough. Now, let us place the filament and its surrounding anode in a strong magnetic field which is perpendicular to the plane of the page. A moderate magnetic field will cause the electrons to move in a curved path, as shown in Figure 4 : 2 (*b*). A moving stream of electrons is a current and a current in a wire will be urged at right angles to a magnetic field. If the magnetic field is increased sufficiently, the path of the electrons leaving the filament A will be curved to such a degree that they will never reach B, as shown in Figure 4 : 2 (*c*). When this occurs, the current between the filament and the anode will be interrupted as shown by the meter on which the reading should drop to zero. The curves described by the electrons are known as *cycloids*.

4.3. *Details of magnetrons*

Ordinary magnetrons produce waves ranging from 0.5 to 50 cm in wave length. At one centimeter, they can easily produce 100 kw; at ten centimeters, 3000 kw. Operating voltages range from 1000–40,000; magnetic fields, from 600 to 15,000 gausses.[2]

The effect of the fields applied to a magnetron is to bunch the electrons in the space of interaction into spokes which sweep past the gaps in the anode and react favorably with the radio-frequency (RF) fields existing in the gaps. The energy is stored in the resonant cavities from which it can be drawn off by means of a loop.

[2] Gauss is the unit of intensity of magnetic field, or one magnetic line of force per square centimeter. Around New York, the intensity of the magnetic field created by the Earth is about 0.2 gauss, which is the force that controls the needle of a compass.

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4.4. *Movement of charge produces current*

For review and proper orientation it may be desirable to discuss a few simple aspects of electric charges. Referring to Figure 4 : 3, if a charged body is brought near an insulated metal cylinder, as shown in A, the opposite charge will form on the end of the cylinder nearer to the charged body and a like charge on the remote end. If the charge is brought between two cylinders, as in B, the charges on the cylinders will be as shown. Now, let us move the positive charge back and forth between the cylinders, as in C, and let us connect the cylinders by a wire in series with a very delicate meter. The meter will show a flow of current, first in one direction, then in the other. The faster the

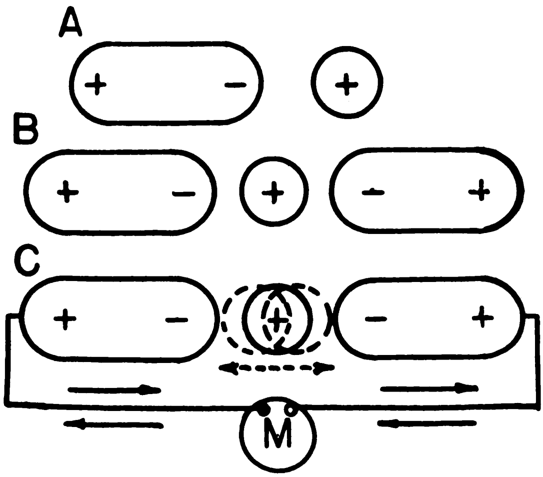

FIG. 4 : 3. CHARGES INDUCED BY MOVING CHARGE

charged body oscillates between the cylinders, the faster will the current in the meter reverse; and the swings or oscillations of the charge will keep in step with the oscillations of current through the meter.

If we could substitute the charged body with an electron, or a group of electrons, their movement back and forth would produce the alternating or oscillating current through the meter. An electron is practically a pure negative charge of electricity and what we call a current in a copper wire is really a movement of electrons. In fact, an electron is so small that approximately 6×10^{18} (6,000,000,000,000,000,000) electrons must pass a given point in a wire in a second for one ampere of current to flow.

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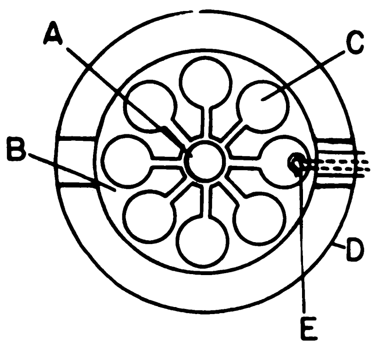
Observe in the illustration given that the charged body (or streams of electrons) does not have to touch either cylinder; just the movement back and forth is sufficient to cause the alternating current by induction.

All bodies in motion have kinetic energy. To put a stationary body in motion, kinetic energy must be imparted to it. This is likewise true of electrons. They must be supplied with kinetic energy from an external source in order to acquire motion. When an electron leaves a surface for any reason whatsoever, it is due to kinetic energy that is applied to it; the faster the electron moves, the more kinetic energy must be supplied to it. If an electron in motion is retarded, it can in any circumstances, be due to only one cause: it has given up some of its kinetic energy.



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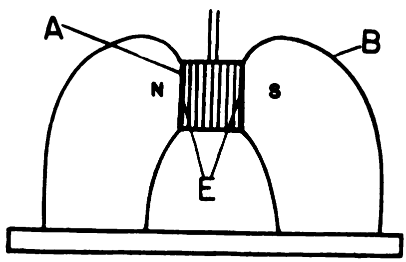

4 : 5

FIG. 4 : 4. CROSS SECTION OF MAGNETRON
A, cathode; B, copper block; C, cavity; D, cooling fin; E, loop

FIG. 4 : 5. EXTERNAL VIEW OF MAGNETRON BETWEEN POLES OF MAGNET
A, Magnetron; B, magnet; E, end covers

In what are known as electric oscillators (they are *not* generators, for they generate nothing), energy is supplied from a D.C. field and transferred to an oscillation field. In effect, all oscillators are converters.

In the magnetron employed in radar for generating waves of a few centimeters in length, the filament heats a cylinder coated with nickel oxide. It is this that emits the electrons. The anode is a massive copper block which is hollowed out for the placement of the cathode and in addition contains a number of cylindrical chambers or cavities surrounding the cathode. The cavities are resonant chambers (Figure 4 : 4) and power is withdrawn by means of a loop tapping one of the resonators or cavities.

Unlike the vacuum tubes employed in ordinary radio, the oscillating

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tubes at microwave frequencies are fixed in wave length. Instead of their wave length characteristics depending on the associated circuit in which they are connected, magnetrons and klystrons (see 4.18), oscillate at fixed periods determined by their inherent geometry and size. It is interesting to learn that a magnetron may be designed by scaling; that is, if it is built for one wave length or frequency, it may be redesigned for another by the simple device of employing other dimensions exactly to scale. Thus, if all the dimensions of a magnetron are reduced by one-half, the wave length will be reduced to one-half and the frequency of operation will be doubled.

The cooling of a magnetron, which is extremely important, is usually effected by radiating fins. It is also essential that the anode be maintained at a constant temperature, otherwise, changes in temperature will cause changes in physical dimensions, as a result of which the wave length and the frequency will vary. To ensure constant frequency the magnetron should be relatively free of the mechanical vibration to which it is especially subject because of its great unsupported length. This tube at least, those built for use at ten cm, is really a long lever supported at one end. Mechanical vibrations cause frequency modulation. Weak spots are of necessity located at the glass seals required for effective vacuum and for insulating purposes.

4.5. Specific magnet for a given magnetron

In the magnetron, the magnetic field serves the same function as a grid in an ordinary triode. Transit time, which limits the operation of the ordinary radio triode, is of little importance in the magnetron because electrons in their passage from cathode to anode deliver energy or power to the electromagnetic field during several oscillations of the RF (radio-frequency) field. It is essential that the orbits of the electrons resonate (vibrate in synchronism) with the RF field as they pass from cathode to anode.

The magnet in a magnetron is so intimately related to the operation of the tube that it may be considered an integral part of it, hence, a change in the magnetron requires a change in the magnet producing the magnetic field. In mounting the magnetron in the magnetic field (Figure 4 : 5), the axis of the tube should be kept parallel to the field. The face of the magnetron that is presented to the poles of the magnet is of little importance, because as a rule, the magnetron is designed symmetrically. The gap from pole to pole of the magnet is slightly larger than the axial length of the magnetron.

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The material of the magnet is Alnico V, an extremely hard (it cannot be machined) alloy of aluminum, nickel, cobalt and iron, or an alloy of similar properties. The tips of the poles are of soft iron, shaped so as to produce the required field in the magnetron where the electrons move. The permanent magnet is covered with a nonmagnetic metallic shield or jacket so that it cannot come directly in contact with magnetic materials. Such contact has often caused some loss of magnetization in the permanent magnet. It is not essential that the magnetic field in the area of interaction (the space between cathode and anode) of the magnetron be strictly uniform; a departure of five per cent from uniformity over the entire volume is permissible. A radial gradient (variation from the center to the circumference) to the field is allowable, if it is not too great, and provided it is symmetrical with respect to the axis.

4.6. *Magnetron adapted for intermittent service*

As magnetrons of the type under discussion (multi-cavity resonant chambered) are designed for high voltage and high current, they can not be employed continuously for any great length of time for two reasons: 1) because of the need for dissipating large amounts of power; 2) because oxide-coated filaments (cathodes) can not supply large currents continuously.

In most applications of radar, the operations are of extremely transitory pulsations, and the power is employed for correspondingly short intervals. Such conditions set the maximum time limit during which the magnetron can be operated, this is measured in microseconds (or a fraction thereof) and is usually adequate for any needs of radar.

As accurate ranging (determination of distance) requires that the pulses be of short duration, it is essential that we employ very large amounts of energy in order that the power concentrated in the short pulse be very great. Where the range or distance over which the radar unit is to operate is extremely long, the pulse must of necessity be of long duration, and the power employed must be very great.

4.7. *Duty cycle of a magnetron*

An important term to be considered in the use of magnetrons is the "duty cycle". This is expressed as a ratio of the time of operating a magnetron to the idle time, where the total period is the interval between corresponding points of successive pulses. The duration of the pulse and multiplied by the frequency of recurrence (the number of pulses per second) gives the duty cycle (Figure 4 : 6). The accuracy of

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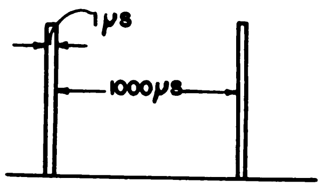
measurement of the duty cycle depends on the accuracy of measurement of the components that make up the ratio. The following illustration may seem involved but it is relatively simple: If the duration of the pulse is one microsecond (10^{-6} or 1/1,000,000 of a second) and the pulse recurs 1000 times a second, the duty cycle will be 1/1,000,000 $\times$ 1000, or 0.001. It is common practice to use the reciprocal of the duty cycle; or in the example just given, $1/0.001 = 1{,}000$.

A possible method of measuring a duty-cycle is to ascertain the ratio of peak power to average power in radio frequency. What makes the method, thus glibly stated, difficult is the fact that it is difficult to measure the peak power of radio frequency with precision.



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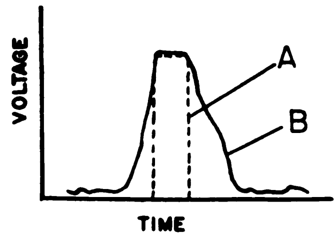

4 : 7

FIG. 4 : 6. COMPONENTS OF DUTY CYCLE (MAGNIFIED)
FIG. 4 : 7. VOLTAGE PULSE IN A MAGNETRON
A, Ideal pulse; B, Actual pulse

The duty cycle is important in determining the life of the magnetron. As the duty cycle is a ratio, we can obtain the same value by varying both quantities of the ratio (numerator and denominator). Thus, we could obtain a duty cycle of 0.002 by employing a pulse of 2000 microseconds duration and a recurrence frequency of one per second; or by any other arrangement which will yield the same resultant, 0.002. But a pulse of such relatively enormous duration (2000 microseconds) would prove destructive to the magnetrons employed in radar at the present time.

4.8 Operation of magnetrons; voltage and current relations

The performance of magnetrons depends on voltage and current. The peak voltage is related to the peak current. A small change of peak voltage will cause an enormous change in peak current. By way of

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illustration, a variation of ten per cent in the peak voltage may cause a change of 100% in current. The resulting RF output of power would be great and the wave length would change slightly. Among other evils, the magnetron might be forced into an unstable region where undesirable modes of operation would occur.

The rate of decay of the voltage pulse (Figure 4 : 7) should be kept sufficiently high so that undesirable modes of oscillation will not be excited. This is the important determining condition for operation of the magnetron. Although the time of decay or fall of a voltage pulse may be greater than the rise, it should, on the whole, be comparable. The voltage pulse may be measured by taking a known fraction of it (obtained by a non-inductive voltage divider through an oscilloscope), and measuring this on the oscilloscope. The shape of the pulse will not be changed if the voltage divider is non-inductive (that is, a pure resistance).

As has been already mentioned, current is closely related to voltage in a magnetron. Current will begin to reach the anode of the magnetron as the voltage first approaches equilibrium at the peak. The current will continue to build up until it reaches its peak value, provided the peak voltage remains constant, and it will begin to decrease as the voltage decays. The rate of decrease of current will then vary as the decrease of voltage, as well as the Q of the magnetron. Variation of the pulse of the voltage will be magnified in the pulse of the current; for this reason, troubles in a system are more easily observed by examining the pulse of the current.

Peak value of current can be measured by passing it through a non-inductive resistance and measuring the drop in voltage. The shape of the current pulse can be observed in an oscilloscope.

4.9. Importance of matching impedance in magnetrons

In some types of systems, the dynamic impedance (the ratio of *change* of voltage to *change* of current) is very important. This will naturally vary throughout the path of the pulse; these pulses may be likened to a transmission line charged and then discharged through an impedance equal to the characteristic impedance of the line (3.28). When the load and the line are matched (3.3), the pulse will have a calculable rise and fall. In the case of the magnetron, the load impedance is infinite during most of the voltage pulse (in other words, during open circuit) and the match of impedance is very bad. It is

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possible for the voltage to rise so fast that it may pass through the operating region of the magnetron before it begins to oscillate. If we assume, however, that the magnetron does oscillate on the rising pulse, the impedance goes from a very high value to a very low value—under a thousand ohms—at the beginning of the pulse. Standing waves will be created as a result of the reflections caused by the failure of impedance to match (3.3) when a line pulser is employed to drive the magnetron.[3]

4.10. *Life of magnetron depends on cathode*

It is a characteristic of the magnetron under discussion that electrons leaving the surface of the cathode during part of the RF cycle should withdraw energy from the electromagnetic field in the interaction space, and return it to the cathode with the increased energy when it is surrendered as heat. During each pulse, several kilowatts of peak power may be wasted at the cathode. This instantaneously raises the cathode to a very high temperature, depending on the peak power, duration, and thermal properties of the surface, and upon the duty cycle. By lowering the duty cycle, the mean operating temperature of the cathode will be lowered, and this in turn, will increase the life of the magnetron. Other factors will control peak temperatures, and what takes place at very high temperatures, even though for short intervals, will be very crucial.

A magnetron depends chiefly upon its cathode for long life. The health of the cathode will depend upon the duty cycle, peak power input, efficiency, pulse duration, power of the cathode heater, and the effect of the load of the magnetron. The average magnetron requires at least a minute or more to reach equilibrium, after the heater is turned on, for the cathode to come to a temperature for uniform operation: the magnetron as a whole, having a much larger mass than the cathode, will require a slightly longer period.

4.11. *Keep temperature constant at anode*

The anode is cut out of a solid cylinder of copper (4.17); the expansion or contraction of this block will alter the frequency which, in turn,

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[3] Modulators employ two kinds of pulse-forming networks. In one kind, an open-end transmission line is employed. Between pulses, this network is charged slowly (a purely relative term) and to form the pulse, it is suddenly discharged. In the other, or closed-end transmission line, a current is built up between pulses. When a pulse is required, the circuit is suddenly opened, whereupon a pulse of voltage will suddenly appear.

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depends upon the physical dimensions of the block. For this reason, there will be a change of frequency before the heater and the high voltage are turned on to the magnetron, and after normal operating conditions are reached. Changes in frequency vary with the change of temperature and with the linear coefficient of expansion of the copper. Hence, constant temperature must be maintained at the anode. (4.10).

4.12. *Magnetrons now fairly uniform*

The resonant frequency of the cold block, when excited externally to the proper mode of oscillation in which it normally should work, is somewhat different from the frequency when the anode is operating as a magnetron. The difference is due to the presence of a space charge during operation. The cold resonance is always at a shorter wave length. This makes duplexing (9.1) feasible and determines the location of the T-R box (9.2). Magnetrons of proper design are sufficiently uniform in cold impedance characteristics (standing wave ratio; 3.2) so that it is generally possible to fix the location of the T-R box. For this reason, all magnetrons of a given type in a given range of wave length will operate satisfactorily without tuning the magnetron during operation. Eliminating the tuning of the magnetron and the T-R box is called *pre-plumbing*.

4.13. *Operating frequency dependent on load*

The exact operating frequency or wave length of a specific magnetron depends on a number of factors that differ from one modulator to another, and also for different loads. The differences may cause cumulative variations amounting to several megacycles. Thus it is possible for a magnetron designed for one wave length to be measured under circumstances different from those of a factory test and found to operate at a considerably different wave length. In all factory tests of magnetrons, the wave length is measured with the N-seeking pole of the permanent magnet adjacent to the face of the magnetron nearest to the cathode.

4.14. *Bandwith and pulse duration inversely related*

If we assume that the magnetron is excited into oscillation by an approximately rectangular voltage pulse[4] one microsecond in duration, a spread in the frequency generated would be expected. This is actually

[4] For details, see Appendix.

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observed in practice, a pulse of one-microsecond giving rise to a spread or bandwith (5.9) close to two megacycles under best conditions. The bandwith of the RF spectrum of a magnetron decreases as the duration of pulse increases, and vice versa, as we would anticipate.[4]

4.15. Reason for failure of magnetrons

A magnetron may fail because its gas pressure is too high, due to a

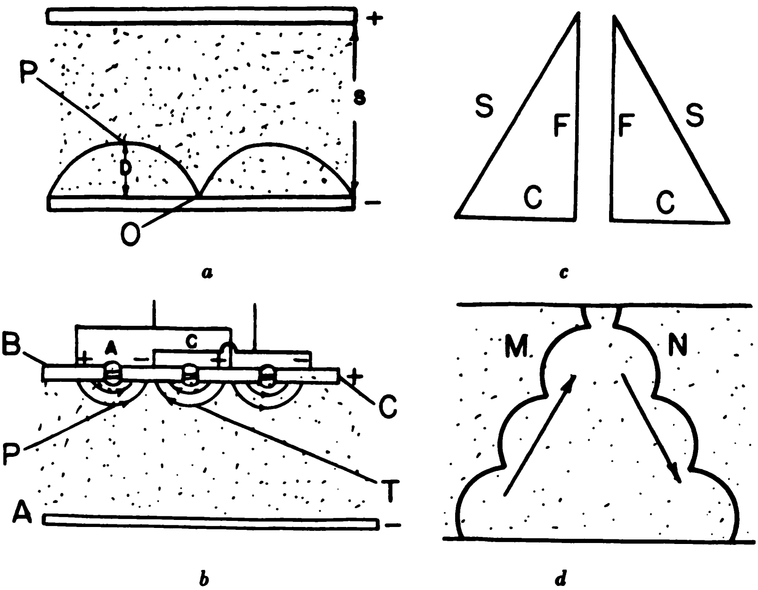

FIG. 4 : 8. MAGNETRON WITH PLANE ELECTRODES
(*a*) Cycloidal paths of electrons
(*b*) Magnetron in operation
(*c*) Resultant fields shown as vectors of fields in (*b*): F, direct component C, alternating component, S, resultant
(*d*) Favorable (M) and unfavorable (N) paths of electrons in magnetron

poor vacuum extraction process. This is easily tested by applying a low voltage to the magnetron; if the gas pressure is too high, a large current will flow. If cathode heater is burned out, or the filament is broken, the magnetron will not start. When a new magnetron is first put into operation, there is considerable internal arcing or sparking. This clears up rapidly as the voltage is slowly raised to the operating value when the output circuit is properly adjusted and the voltage, current, and magnetic field fall within specified limits.

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4.16. Operation of magnetrons

Electrons under the influence of an electric field alone travel in a straight line from low to high potential, that is, the electrons (negative charges) are attracted to the positive terminal (anode). When a magnetic field whose direction is perpendicular to the electric field is also acting on the electrons, the paths of the latter will be circular.

Electrons that leave the cathode with zero initial velocity travel in cycloidal paths (Figure 4 : 8 (*a*)). The electrons leaving the surface of the cathode are accelerated toward the anode (whose voltage is positive). As they travel and their speed increases, their path becomes curved because of the increasing effect of the magnetic field. The effect of increasing velocity of electrons is the same as that of increasing current; hence, the action of the magnetic field increases as the speed of the electrons rises. At some point, P, the force exerted by the electric field is equal to the force exerted by the magnetic field. The electrons will continue to move in a curved line toward the cathode and they will reach the point 0 with zero velocity.

If the distance D is less than the distance between the cathode and anode, S, no electrons will reach the anode. On the other hand, if the distance S is less than the distance D, all the electrons will reach the anode.

In the actual magnetron, where the anode and cathode are concentric surfaces, the electrons have a resonant frequency of oscillation in the clear path between the anode and the cathode. It is this resonance that can be utilized in the production of radio frequency power. The electrons draw their power from the D.C. field (produced by the high constant voltage) and feed it into the oscillation field of the resonant cavities.

To make the operation of the magnetron clearer, we will place the anode slots and the cathode in flat planes, as in Figure 4 : 8 (*b*). The curved lines or arcs are the lines of the electric field which run from positive to negative. The voltage between plates is assumed to be oscillating at a rate of resonance that corresponds to the time of travel from A to C. Some of the electrons will be so timed that as they pass point P they will be slowed down by the field. When they reach point T, the field will reverse and the electrons will be slowed down once more. Hence, as the electrons pass each slot, they will give up some of their energy (to the field that retards them). If the timing of an electron is incorrect, it will be speeded up and it will absorb energy from

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the field. If all the electrons were regarded as random carriers, one would suppose that the gains would equal the losses and no net energy could be available for the oscillating circuit. Actually, those electrons that tend to absorb energy are repelled into the cathode and are thus eliminated; those that release energy remain in the field.

Consider Figure 4 : 8 (*b*) in which the cathode and the anode lie in parallel planes. The anode is subdivided, alternate segments being connected together and to an oscillation source. The curved lines are those of the electric field produced by the oscillating voltage at a given moment. As there is a D.C. voltage producing its own steady field between anode and cathode (caused by the high applied voltage), every electron leaving the cathode will be acted upon by *both* fields. These produce a *resultant* field.

If we represent the direct field by F, which runs from anode to cathode, and the alternating field by C (in general, at right angles to F), then the resultant field will be S. The direction of the resultant field shifts as the alternating field reverses or varies. Fignre 4 : 8 (*c*) shows resultant fields for two positions.

The direction of the cycloidal paths described by an electron is perpendicular to the field. If the magnetic field is directed into the page (perpendicular to the electric field), the progression of cycloids will be upwards and to the right as shown at M, in Figure 4 : 8 (*a*). For the direction of S in N, the progression of cycloids will be downwards and to the right into the cathode. The electrons in M get their energy from the D.C. field, as they are now moving from cathode to anode; and as they are opposed by the oscillating field, these electrons are giving up energy to the latter. Similarly, the electrons in N are abstracting energy from the oscillating field and feeding it back to the direct field. From our viewpoint, it is desirable to encourage the electrons in M and suppress those in N. This is the condition that must prevail if oscillations are to be sustained.

When the electrons first emerge from the cathode, their velocity is zero. Those in N will therefore be turned back into the cathode before they have progressed more than a fraction of a cycloid. On the other hand, if the alternating field just reverses when the electrons in M reach N, then the situation in M will be repeated. By keeping the alternations of the oscillating voltage in step with the progress of the electrons from left to right, the cycloidal path will be continued until the electrons eventually strike the anode and give up their residual kinetic energy. In other words, if the horizontal speed of the electrons is such

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that they traverse a full plate distance in a half-cycle, then oscillations will be sustained.

The energy of the electrons reaches zero at the cusps[5] of the cycloids (where the velocity also becomes zero); therefore, all the energy of the electrons at such points is transferred to the oscillating field. When the electron, during the course of the last cycloid, however, strikes the anode, it gives up its energy accumulated from the time of the preceding cusp. This is wasted energy; hence, the smaller this quantity can be made, the greater will be the efficiency of the magnetron. Therefore,

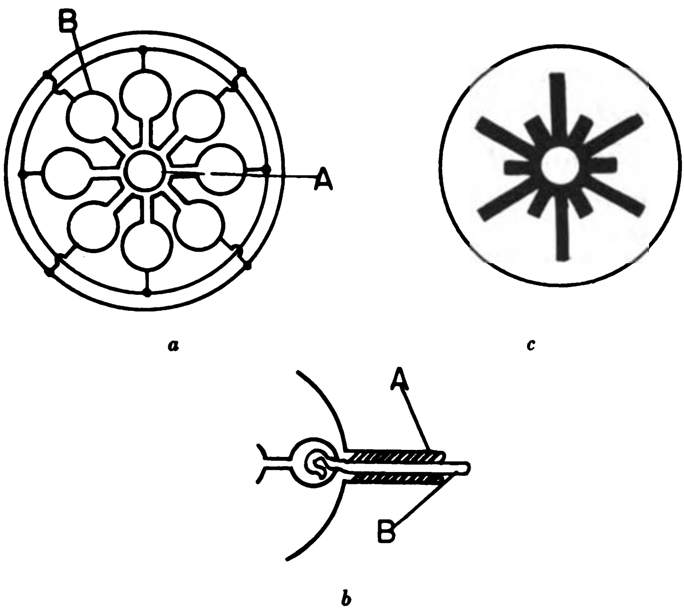

FIG. 4 : 9. CROSS-SECTION OF MAGNETRON
(*a*) Showing binding straps
(*b*) Detail of RF terminal, showing fold-back of glass insulator
(*c*) Rising sun magnetron, avoiding use of straps

the smaller we make the cycloids, the less energy will be conveyed per cycloid. The radius of the cycloid is determined for a given magnetron by the electric field, the D.C. voltage, and by the intensity of the magnetic field. As the magnetic field is increased, the radius of the cycloid becomes smaller; in fact, if we double the magnetic field, the length of

[5] For details, see Appendix.

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the cycloid is reduced to a fourth; if we halve the magnetic field, the length of the cycloid is increased by four.

In the actual magnetron shown in Figure 4 : 9 (*a*), where the anode is split up and is concentric with the cathode, each resonant cavity is closely coupled to its neighbors. We know from elementary study of alternating current that when two circuits are closely coupled, they do not resonate at the frequency of either alone, but at a pair of frequencies on either side of that frequency.

In a multi-cavity magnetron, there are more than two closely coupled circuits and more than two resonant frequencies. As the radar receiver is tuned to only one frequency, it is desirable that the magnetron oscillate only at this frequency. The bonds or straps between alternate segments of the anode serve to limit the magnetron to one frequency.[6]

4.17. Details of manufacture of magnetrons

The magnetron illustrated (Figure 4 : 9 (*a*)) deserves a few additional words of description. It is doubtful whether any component of a system ever exacted as much research under the enormous pressure of war as the ten-centimeter multi-cavity magnetron. The British succeeded brilliantly where the Nazis failed.

Although designed for an output of 150,000 watts (150 kw), for instance, the magnetron is remarkably small. A normal man can close his hand over it. Stripped of its cooling fins, it can be held by a child. As made by the Western Electric Company, the anode block is bored through for the accommodation of the cathode cylinder and the interaction space; then the end spaces in the block are turned out. Next in order, the eight resonator holes are cut through by means of a multiple drill. With the aid of a multiple tapered broach, the eight slots connecting the resonant chambers with the interaction space are cut through in one operation. The outer end discs, or external covers of the magnetron, are secured to the anode block by interposing a gold ring, thinly tinned, and then applying pressure while the entire structure is baked at a temperature sufficient to cause the whole metal assembly to fuse together.

At one time, a source of trouble arose from the external arcing over

[6] When segments are connected together or strapped, the oscillator will be in π form. When the magnetron oscillates in other modes, high currents will flow in the straps and hence, the inductance of the straps becomes important. The frequencies of the other modes will be much higher than that of the π mode.

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between the RF terminal and the body of the magnetron. This was corrected by lengthening the path over the glass insulator through folding it back as shown in Figure 4 : 9 (*b*). So that there will be no strain on the glass seal of the RF output, no metallic contact is made with the coaxial lead in feeding energy out of the magnetron, but it is choke-coupled to the transmission line (3.32). The cathode cylinder is supported by the radial outgoing filament (heater) leads. These leads cross the center of the resonator space so that RF energy coupling with them will be at the minimum. Note also that the disc at the end of the cathode cylinder is carefully proportioned, and serves to prevent excessive coupling between the cathode and the RF field.

The straps, or ties, that connect together alternate anode segments are extremely important. Their use has actually doubled the effective output of certain megnetrons by the suppression of undesired modes of oscillation.

We have already observed that it is possible to design a magnetron at a given frequency by scaling an existing magnetron (4.3). This, however, may result in dimensions or components that are impossibly small. Thus, in scaling down a ten-centimeter magnetron to three centimeters, the cathode becomes so tiny that it is impossible to place a heating coil within it (4.10), capable of carrying enough current. In such a case, the cathode is built of solid tungsten and the heater is placed in a relatively roomy *adjoining* cylinder, from which the heat is conveyed to the cathode by conduction. Because this scheme is commonly used in heating electric soldering irons in which the tips are solid copper receiving their heat from coils wound in a hollow cylinder, such cathodes are known as the "soldering iron" type.

As the frequency increases, the strength of the magnetic fields required by the magnetrons rises. To prevent the need of unduly large magnets, it is desirable to decrease the axial length[7] of the magnetron, for this determines the length of the air gap between the poles of the magnet. As nearly all the circuit reluctance (magnetic resistance) in a permanent magnet lies in its air gap, a reduction of the air gap permits a large reduction in the size of the magnet.

By making the end covers of the magnetron of steel instead of copper, it is possible to reduce the axial length still more. Furthermore, by supporting the cathode axially, rather than by radial leads, it is

[7] The axial length of a magnet is the distance from end cover to end cover (Figure 4 : 5).

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possible to make the end spaces smaller, and thus decrease the axial length of the magnetron. Reducing the axial length of a three-centimeter magnetron as suggested, permitted, in one instance, a decrease of the air gap in the magnet from 0.38 inch to 0.34 inch; yet this was sufficient to allow a decrease of twenty per cent in the weight of the magnet—equivalent to several pounds.

Mounting the cathode on an independent support (instead of radial leads) as in the soldering iron type, greatly increases the total length of the cathode structure (but not the cathode itself). As a result, the expansion from a cold to a hot state becomes appreciable. In fact, the shift of the cathode *axially* produced by heating is 0.008 inch. To compensate for this, the cathode is mounted off-center axially while it is cold.

So long as the cathode is perfectly centered *radially*, with respect to the surrounding anode, no physical force is exerted between them. In a three-centimeter magnetron, a shift off-center of only 0.015 inch produces a radial thrust of one pound on the cathode. With high voltages applied to magnetrons across the interaction space, precision in centering the cathode is important. In a three-centimeter tube with 15,000 volts applied, the clearance between cathode and anode is only 0.032 inch.

It has often been noted that a device or scheme designed to cure one defect may give rise to others not anticipated. We have remarked that providing the cathode with end discs reduced the coupling of RF energy with the radial leads and the cathode. It was observed at one time that as the magnetrons heated up the efficiency actually fell off. Investigation revealed that the end discs physically attached to the cathode structure, gave off parasitic emission. This effect was almost entirely corrected by mounting the cathode on an axial support as a base, rather than by radial leads, thus eliminating the end discs.

At one time, the efficiency of certain magnetrons (whose frequency could be varied externally by means of complicated gear work) and the Q developed were lower than theory indicated they should be. Investigation showed that during brazing operations required in assembling magnetrons, the copper plating and the steel it covered, diffused through each other. As a result, the copper-plated steel pins employed for changing the inductance[8] of the resonant cavities exhibited a higher skin resistance than if they had been plated with pure

[8] For details, see Appendix.

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copper. The greater losses from the surface decreased the Q and, consequently, also the efficiency.

To minimize oxidation during brazing operations on three-centimeter magnetrons the process was conducted in an atmosphere of carbon dioxide gas and alcohol vapor. This unwittingly gave rise to trouble of another kind. Carbon was caused to deposit beneath the copper plating of the steel pole pieces, thus lowering the Q and the efficiency of the magnetron in operation. By substituting a relatively inert gas, such as pure nitrogen, during the brazing process, this defect was obviated.

One of the wide-spread defects of high-vacuum tubes, whether radio, X-ray, or radar, is due to their becoming "gassy" (and gas tubes often show the opposite symptoms, i.e., they become too "hard"). Despite the greatest care exercised in evacuation, magnetrons at one time evolved hydrogen during operation. In anticipation of such liberation of gas zirconium "getters" (absorbers) were introduced. It was found that the hydrogen came from the steel pole pieces employed as cover plates in the three-centimeter magnetron. Thereafter, they were heated to a red heat in a vacuum and all the gases absorbed or adsorbed in the metal were driven off before the magnetrons were finally sealed.

Some idea of the precision required in the mechanical adaptation of parts may be gathered from the allowable limits imposed on three-centimeter magnetrons. The backlash of the gearing employed for shifting the pins to vary the frequency is so slight that it is possible to reset at will a given frequency setting within a margin of one megacycle in a total of 10,000 megacycles. The shift or displacement of the inductance pins corresponding to one megacycle is 0.0001 inch.

It has been found impracticable to strap (4.16) with reasonable precision when the frequency approaches or exceeds 10,000 megacycles (three centimeters or less), yet the need to suppress undesirable modes is greater than ever. By the use of cavity resonators shaped as in Figure 4 : 9 (*c*) it has been possible to suppress unwanted modes without employing straps. Because of its appearance, such a magnetron is called the "rising sun" type.

In a rising sun magnetron designed to operate at 24,000 megacycles (1.25 cm), the ratio of the resonant frequency of the large cavities to the small is 1.8. The sum of the lengths of a small and a large cavity is equal to a half-wave length. It may convey some idea of the difficulties encountered in production to give a few of the dimensions: Diameter of anode, 0.16 inch; length of axis, 0.19 inch; diameter of

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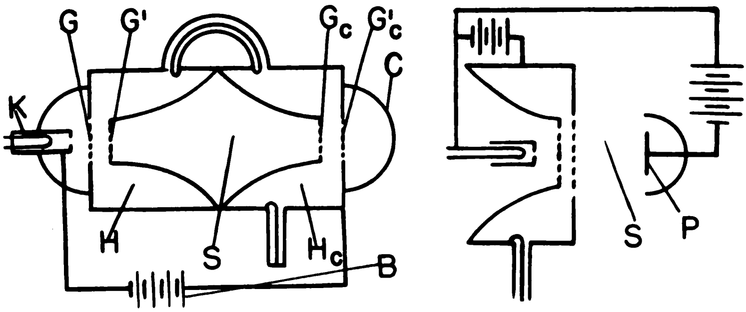
cathode, 0.096 inch; length of coated surface (cathode), 0.165 inch. Even to cut through the radial slots of the cavity resonators (for quantity production) required the exercise of considerable ingenuity. A process known as "hubbing" is employed, which may be vagnely described as a punching operation not unlike the cutting of the hub of a metal wheel.

4.18. Double chamber klystrons

The velocity-modulated tube known as the *klystron* is the nearest competitor to the magnetron as an oscillator. In Figure 4 : 10 (*a*), K is



a *b*

FIG. 4 : 10. DETAILS OF KLYSTRONS
(*a*) Double chamber: K, cathode; GG′, buncher grids; H, buncher; $G_cG'_c$, catcher grids; H_c, catcher; C, collector; S, drift space; B, source of high voltage
(*b*) Reflex klystrons: S, drift space; P, repeller

a source of electrons; G and G′ are a pair of metallic grids, closely spaced and part of the cavity; H is known as the *buncher*; G_c and G'_c are likewise a pair of metallic grids and part of the cavity, H_c is known as the catcher. C is the collector, and S is the drift space. The whole assembly is enclosed in a high vacuum.

The electrons emitted by K are accelerated by a high voltage, B. So long as no voltage is impressed across G and G′, the electrons will pass at a constant velocity through the drift space S, to the collector, C. Now, suppose that for any reason whatsoever, an alternating or oscillating voltage is impressed across the grids, G and G′. Those electrons leaving G′ at the moment its voltage is zero will pass on unaffected. Those passing through when G′ is positive will be accelerated; when it is negative, the electrons will be retarded. Thus the drift space, S, will be broken up into bunches of electrons. As these bunches

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pass through G_c and G'_c, they will set up an oscillating current. If the cavity, H_c, is tuned to the frequency of the bunches or pulses, the oscillations set up will be much amplified by resonance. If part of the energy is fed back to cavity, H, a regenerative effect (feedback) is created and we thus have a high frequency oscillator. The frequency of the oscillator is controlled or determined by the resonant frequency of the cavities, H and H_c.

This type is essentially a fixed-frequency oscillator. By varying the volume of the cavity, or by altering the separation of the grids, the frequency may be changed. In some types of klystrons, the cavity is an integral part of the tube; in others, the cavity is external to the tube. In the latter type, cavities of different sizes may be substituted; or, by the insertion of slugs into the chamber of the cavity, its volume may be decreased and its inductance lessened. In some klystrons where the cavity is an integral part of the tube, flexible metal walls permit a change in volume of the cavity, or a change in the separation of the grids.

It has been theoretically estimated that a klystron (double chamber type) can provide almost sixty per cent of the energy input, so as tubes go, it is an efficient device.

4.19. Single chamber of reflex klystrons

Instead of employing a tube with separate buncher and catcher chambers, we may use a single chamber which serves both functions. In Figure 4 : 10 (*b*), P is a repeller plate operated at a negative potential with respect to the grids. The electron bunches are slowed down and repelled as they approach P, whereupon they reverse their direction of travel and pass through the drift space, S, and the grids once more. By varying the voltage applied to P, the speed of the bunched electrons can be controlled. Thus the frequency of the reflex klystron can be affected not only by changing the volume of the cavity and separating the grid, but also by changing the voltage of the repeller. The efficiency of reflex klystrons is considerably lower than that of the double-chamber tubes, but they have the advantage of greater simplicity, smaller size, and more flexibility. Where the power output required is small, as in receiving sets, they are very widely employed in radar.

The double-chamber klystron type of oscillator has found very little use in radar. On the other hand, the single-chamber reflex klystron has practically usurped the field. The principle reasons for this are the

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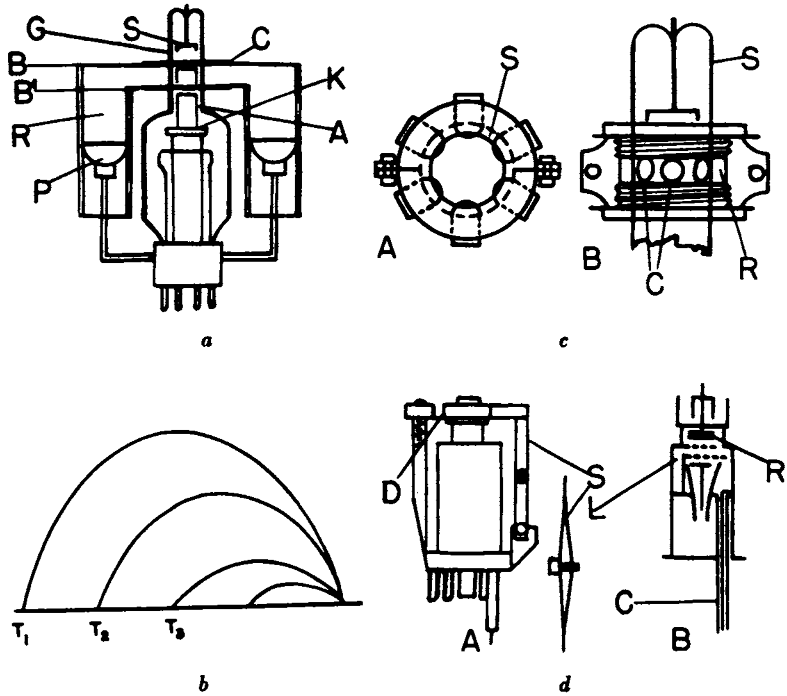

FIG. 4 : 11. DETAILS OF REFLEX KLYSTRONS
(*a*) With external cavity: S, repeller; BB, grids; G, glass envelope; C, copper disc; R, cavity of chamber; P, piston; K, heating chamber; A, cathode
(*b*) Curves showing paths of projectiles meeting at a common point
(*c*) With external cavity: A, cross section; B, longitudinal section; S, glass envelope; R, resonant chamber; C, tuning plugs
(*d*) With internal cavity: A, external view; B, interior; S, metal tuning bar; R, repeller; L, cavity; D, metal diaphragm; C, coaxial output

case of handling, the low voltage required for its operation, and the ease with which its frequency can be readily varied automatically. By changing the voltage applied to the repeller, the frequency can be altered over an appreciable range.

Figure 4 : 11 (*a*) shows one of the first velocity-modulated tubes adapted for use on ten-centimeter radar to produce beating oscillations for the IF output. As the resonant cavity is applied externally, it makes contact with the copper discs fused into the glass, and therefore, also with the buncher grids which are integral parts of the copper discs. The volume of the resonant cavity—hence, the inductance of the resonator (3.21)—is varied by means of the piston. The capacity of the

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resonant circuit is determined largely by the distance between the grids, and as these are sealed within the glass envelope it cannot be changed. The cathode is a cylinder whose flat upper surface is oxide-coated and heated by a separate heating filament within. Surrounding the cathode is a cylinder for the purpose of focusing the electrons into a beam which passes through the two grids and approaches the repeller. Because the voltage of the latter is negative the electrons (also negative) are repelled through the grids of the resonant chamber (now acting as a catcher). The grid marked A is a control, or intensity, grid. The grids of the resonator, B, B′, are highly positive with respect to the cathode (about 300 volts) and attract the electrons with a velocity sufficient to carry them almost to the repeller. The space between the second grid, B, and the repeller is the *drift space.*

The action of the electrons from the modulating grids of the resonator to the repeller and back has been likened to that of a number of projectiles shot up against the force of gravity. Even though the projectiles leave at different times, by adjusting their initial velocity they can all be made (within limits) to fall upon the same target in about the same time. So even though electrons leave at different stages of a cycle, their velocities will be different, and by suitable adjustments, they can all be made to return to the center of the catcher at the same moment.

Figure 4 : 11 (*b*) will make this clear. Several balls are thrown upward with varying velocities from T_1, T_2 and T_3, which represent successive moments in time in the order named. If the balls are thrown upward, at the maximum velocity from T_1 at a smaller velocity from T_2, and at the least velocity from T, then it is not difficult to realise that all balls may return to the earth at the same moment. We need but adjust the velocities to suit the decreasing intervals of time.

It is obvious that by varying the voltage of the repeller, the distance travelled by the electrons and their speeds can be controlled. As we make the repeller more highly negative, the electrons will be retarded more and they will come to a stop sooner. On the other hand, as the repeller becomes less negative, the electrons will be retarded less, and they will advance closer to the repeller. The closer they come to the repeller, the greater will be the distance in the drift space they will traverse. The power given up by the electrons will depend upon the timing of the bunches (produced by the action of the buncher) with respect to the frequency of the resonant chamber. If the time between bunches (that is, spacing in time, or time intervals) is the same as the

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periods of oscillation of the resonant chamber, the power given up by the electrons will be the maximum.

By varying the movement of the piston, the volume of the resonant chamber is changed and the inductance (3.21) is altered. As the movement can be made rather large, the resonant frequency can be varied through a large range (3.23). Figure 4 : 11 (*c*) shows another type of external resonant chamber which is more compact and suitable for smaller changes of frequency. The movements of the screw plugs in or out decreases or increases the volume of the chamber, and so its frequency is increased or decreased.

Though the type of reflex klystron with the external chamber resonator was workable up to 3000 megacycles (ten centimeters), it was far

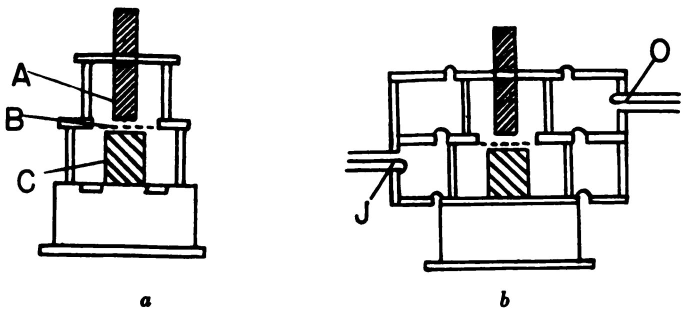

FIG. 4 : 12. LIGHTHOUSE TUBES
(*a*) Cross section: A, anode; B, grid; C, cathode
(*b*) Tube connected to coaxial input: (J) and coaxial output (O)

from ideal. In hot moist climates, the presence of moisture in the cavities and the rapid deposit of molds made the external cavities sources of trouble. Besides, as the demand for greater precision and resolution caused the frequencies to be stepped up (or the wave length to be decreased), it was found that the external cavity reflex tube was ineffective and undesirable.

A tube was designed which was entirely housed in a metal chamber and largely resembled the ordinary metal-clad vacuum tube of radio. In Figure 4 : 11 (*d*), A shows the exterior, and B, the interior of such a tube. Note that the resonant cavity is internal. The metal bar on the right is really composed of two straps, as shown, joined by a screw. By turning the screw, the bars can be made to separate or come closer. The overall length of this composite bar can thus be controlled with great accuracy. The bottom end of the bar is rigidly welded to the

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base of the tube. The other end of the bar is attached to the part of the tube that houses the repeller. This entire repeller cavity is seated on a flexible metal diaphragm which is part of the exterual covering of the resonant cavity. The movements of the diaphragm up or down—which follows the elongation or shortening of the tuning bar—cause the grids in the cavity to recede or approach. Thus the capacity of the resonator is varied, and hence, its resonant frequency. The output energy of the tube is fed by the coupling loop in the resonator chamber which is the center conductor of a coaxial cable that runs through the base of the receiver tube.

This tube is well suited for coupling its output to a wave guide. This is readily done for rectangular wave guides by running the coaxial cable from the tube into the wave guide, the end of the coaxial cables serving as a probe or minute radiator.

4.20 Lighthouse tubes

To overcome the deficiencies of the standard vacuum tube at very high frequencies, the lighthouse tube was devised. Its name is due to its apperance. This tube introduces no new principles but it radically changes the disposition or arrangement of its elements. As can be seen in Figure 4 : 12 (*a*), instead of the heater, grid, and anode being disposed as concentric cylinders, they are colinear, that is, they all lie in the same straight line. The structures are rigid and are brought very close together, thus minimizing transit time to the utmost. In one type of lighthouse tube, known as the GL464, the grid is composed of wires 0.002 inch in diameter, spaced 0.01 inch apart. The distance between cathode and grid is 0.005 inch; between grid and plate, 0.01 inch. Best of all, the disposition of its electrodes permits connections to be made with the least inductance and capacity of leads. Figure 4 : 12 (*b*) shows a lighthouse tube incorporated into a circuit for developing oscillations of 1000 megacycles.

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Chapter 5

THE RECEIVER

5.1. General requirements of radar receiver

As was previously explained, the difference between an ordinary radio receiver and a radar receiver lies essentially in the much greater sensitivity of the radar set. This is made necessary by the fact that it receives energy, not directly from a transmitter, but in the form of echoes. As the energy of an echo at its point of origin may easily be a billionth of the energy of the transmitter, the energy received from the echo may be a billionth of a billionth, or one quadrillionth of that of the transmitter. This extremely minute amount of energy must be detected by the receiver and made intelligible.

Usually, the indicator of a radar is not a telephone receiver or a sound device, but a visual display on the face of a cathode ray oscilloscope tube. Interference, static, "noise" in a radar receiver, produce visual disturbances known as "grass" (from its appearance on the screen) or " hash".

In addition to being extremely sensitive, the radar receiver must reproduce extremely sharp pulses. The type of receiver most commonly employed is the superheterodyne, but it has a larger number of intermediate stages than is usually employed in radio.

5.2. Limit of sensitiveness set by noise

At first sight, it would appear that there is no limit to sensitiveness, for by adding enough stages to an amplifier, we should be able to amplify to any degree. Theoretically, the noise of a worm crawling through the interior of an apple could be amplified to resemble thunder. Actually, there is a lower limit of signal strength (threshold), beyond which we cannot go. This is the limit for noise that is inherent in, or natural to, the receiver. When the signals to be amplified are so

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weak that they approach the voltages of the noise in maguitude, then any further magnification or amplification multiplies the noise as well as the signal to the same degree. In order to reduce noises to a minimum, we should know their sources and characteristics.

5.3. *Relation between noise and bandwidth*

Nearly all the noise in a receiver is generated by the receiver itself. If we attempt to analyze noise, we find it made up of an enormous number of sine waves or frequencies. Obviously, those frequencies that are not amplified by the receiver (falling outside of its range) will not occur in its output. The range of amplification of the receiver is a measure of its bandwidth; noise is present throughout the entire bandwidth. The sharper the pulse, the greater is the number of harmonics or components that it will contain.

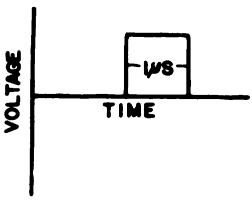

FIG. 5 : 1. SQUARE PULSE, ONE MICROSECOND

Figure 5 : 1 shows a square pulse, which can be analyzed into an infinite series of harmonics. To reproduce a pulse accurately, requires the amplification of a broad range of frequencies; that is, the bandwidth will be broad. This means the noise will be correspondingly large. Hence, to reduce noise, we compromise by keeping the bandwidth narrower than the desirable ideal.

5.4. *Noises of thermal origin*

"Noises" may be thermal noises, shot noises, and induced noises.

If we could magnify a wire so that its atoms, molecules, and electrons were made visible (purely theoretical), we would see them in a condition of rapid motion. This is known as the *thermal energy* and it is inherent in all matter, depending largely upon the temperature, the resistance, and the bandwidth of the frequencies. A very sensitive voltmeter, capable of measuring a tiny fraction of a microvolt (a millionth of a volt), placed across the ends of a piece of wire, will actually indicate minute voltages generated in the wire. These voltages will contribute a small amount of noise to the radar receiver.

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5.5. *Cause of "shot" effect*

One source of noise inherent in a vacuum tube is known as the "shot" effect. The electrons that leave the emitter (cathode) vary in number over small periods of time. The flow of current is not like a stream of water but rather like a rainfall of individual drops. It is the discrete character of electrons that produces the noise in a vacuum tube known as the "shot" effect. It resembles thermal noise in that it occurs uniformly over the frequency band.

5.6. *Cause of induced noise*

When an electric charge moves toward or away from a body, it induces a varying charge on the body (see **4.5**). As electrons carry the smallest charges we know of, they cause charges to be induced by their movements. In a vacuum tube, electrons are approaching and leaving the grid while the tube is in operation. If exactly the same number of electrons were involved in both motions—that is, if exactly the same number of electrons were approaching as were leaving the grid—the resulting induced charges would cancel each other. Because of the shot effect, however, the numbers of electrons coming and going with respect to the grid are never equal, and there is always a net, or balance, of induced charges in relation to the grid, which constitutes a tube noise. If a tube has several grids, this effect is more pronounced; therefore a pentode, which has three grids, has more induced noise than a triode, which has one grid. In general, then, induced noise varies with the number of the elements in the tube.

5.7. *Miscellaneous noises*

Besides the foregoing, there are noises set up in receivers such as those made by man: ignition systems, motors, bells, X-rays, diathermy radiations, etc. In addition, there are natural noises, commonly called *static*, produced by lightning discharges between cloud and cloud, and between cloud and ground. As there are daily over forty thousand lightning storms throughout the world, the crackle produced by lightning is omnipresent in ordinary radio in the form of static. These disturbances, however, produce negligible effects at microwave frequencies.[1]

5.8. *Noise effects in the receiver*

In a receiver, the effect of noisy disturbances will depend upon where they occur. If the noise is in the first stage of the amplifier, its

[1] Even the Aurora Borealis, which can and does turn radio receiving and transmission topsy turvy, has no appreciable effect on microwave radar.

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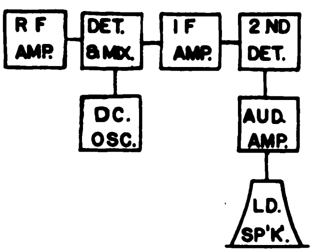
effect will be most enhanced. On the other hand, if the noise is generated, in a later stage, the over-all effect will be less severe. Accordingly, the first stage must be most carefully treated so that its inherent noise is a minimum. As the sensitivity of a receiver is limited by the noise it produces, it follows that by reducing noise we can obtain the same effect as by increasing the power of the transmitter.

5.9. *Relation between bandwidth and length of pulse*

At a frequency of 10,000 megacycles (10,000 million cycles), a pulse of one microsecond duration would contain 10,000 oscillations. Such a pulse would appear on the screen of the cathode ray tube as an extremely sharp peak. So far as it effects the receiver, it would mean that the receiver would have to reproduce with fidelity an extremely wide band of frequencies, for the bandwidth varies indirectly with the length of the pulse; the narrower the pulse, the broader the bandwidth.

5.10. *Superheterodyne of radio*

Figure 5 : 2 (*a*) illustrates in block form a superheterodyne receiver employed in radio. It comprises, usually, one or two stages of radio-frequency (RF) amplification, a detector or mixer[2] known as a *frequency converter* into which the RF feeds, as well as the output of a



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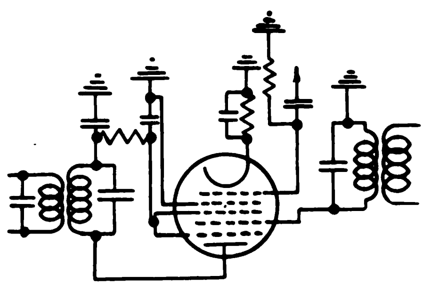

b

FIG. 5 : 2. SUPERHETERODYNE RADIO RECEIVER
(*a*) Block diagram
(*b*) Connections of pentagrid converter or mixer

[2] Mixers are often called *converters*. Most often, a mixer is employed to designate a tube and its circuit which combine a wave from a local oscillator with a modulated input wave. On the other hand, in the converter, the local oscillator and the detector are contained in one tube, in a single envelope.

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local or beating oscillator. The difference in frequency, or the beat frequency, between the RF and that of the local oscillator is known as the *intermediate frequency* (IF). This is a constant for a given receiving set. The IF amplifier consists of several stages which amplify the intermediate frequency and feed its output into a second detector where it is demodulated (detected). Thence, its output in turn (which is now at audio frequency) is again amplified and fed into a loudspeaker. A good type of frequency converter is shown in Figure 5 : 2 (*b*) where a pentagrid tube (having five grids) is employed. The RF output is fed into one of the grid circuits and the local oscillator is connected to the control grid. The beat or intermediate frequency is taken off the plate circuit.

5.11. Requirements of superheterodyne in radar

In microwave radar receivers there is no amplification of radio frequency. A compelling reason is that for frequencies of 3000 megacycles and over no effective amplifier tubes are available.

The frequency converter or mixer is not a pentagrid tube or any other vacuum tube, but a silicon crystal. Again, the reason is that there is no vacuum tube capable of serving as a mixer beyond 3000 megacycles. In the IF amplifier, the number of stages is considerably greater in radar than in radio, some times as many as ten. The output of the IF amplifier is fed into a detector which demodulates and prepares the output for further amplification in the video amplifier. Finally, the last stage is not of a loudspeaker, but the screen of a cathode ray tube, showing visible effects that are interpreted in terms of distance and angular bearings.

Figure 5 : 3 (*a*) shows a radar receiver in block form. The radio frequency amplifier is not used on all radar receivers; only when use of it will increase the signal power over the noise. Because of tube characteristics, radio frequency is amplified at wave lengths in excess of 30 cm (or frequencies below 1000 megacycles). As in the ordinary superheterodyne incorporated in radio receivers, the radar employs a local oscillator whose output is fed into a mixer or converter into which the RF output also feeds. The beat or intermediate frequency is produced in the mixer.

As stated previously, for frequencies equal to or in excess of 3000 megacycles (corresponding to 10 cm or less), the old-fashioned crystal (silicon, usually) makes the best rectifier. For longer wave lengths, diodes can be used. Figure 5 : 3 (*b*) shows an arrangement in which the

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RF signal and the output of the local oscillator are supplied to a pair of terminals of the mixer. Thence, the resulting IF output is fed into the IF amplifier. Figure 5 : 3 (*c*) shows a train of oscillations produced

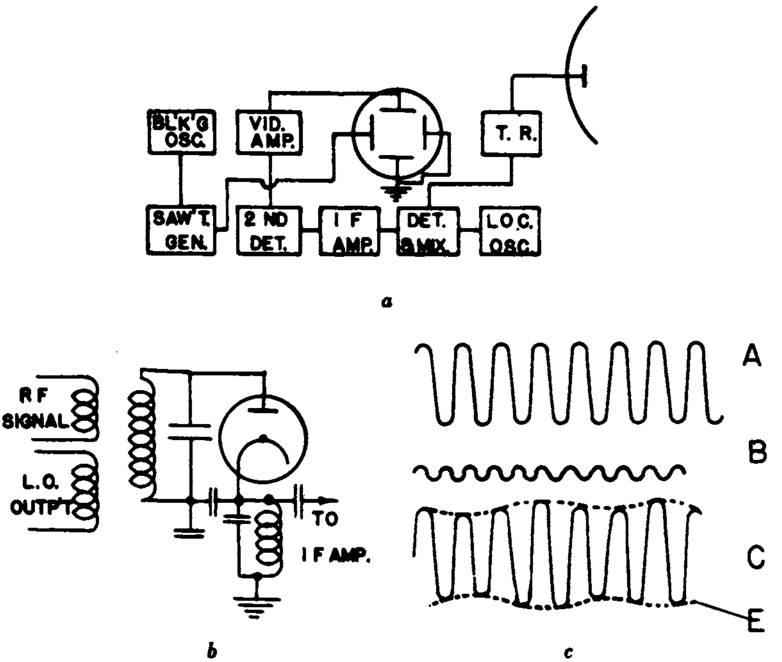

Fig. 5 : 3. Connections of Radar Receiver
(*a*) Simple receiver in block form
(*b*) RF signals and local oscillator output to pair of mixer terminals
(*c*) Trains of oscillations: A, output local oscillator; B, incoming signals; C, beat effect or IF wave train

by the local (beating) oscillator, A. The incoming signal which is heterodyned with A is shown in B. The combined effect is shown at C. The amplitude of B is shown enormously magnified. The ratio of the amplitude of the local oscillator to that of the incoming signal may easily be, in actual practice a million to one. It would therefore be impossible to show the incoming waves in their true proportions.

The contour of the C train is the envelope, which varies at a frequency equal to the difference between A and B. If A is 10,000 and B is 9000, then C will pass through 10,000 minus 9000 or 1000 waves or cycles in the same period of time. The intermediate frequency, IF,

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will therefore be 1000 cycles. This can be generated only in a non-linear device such as a diode or a crystal.[3]

5.12. Balanced converter or mixer

An excellent illustration of the use of the hybrid *T* or magic *T* connector (see **3.12**) is its application in balanced converters or mixers. By connecting a mixing crystal in each of the arms 1 and 2 (Figure 5 : 4 (*a*)), feeding the RF signal energy into R, and the output from

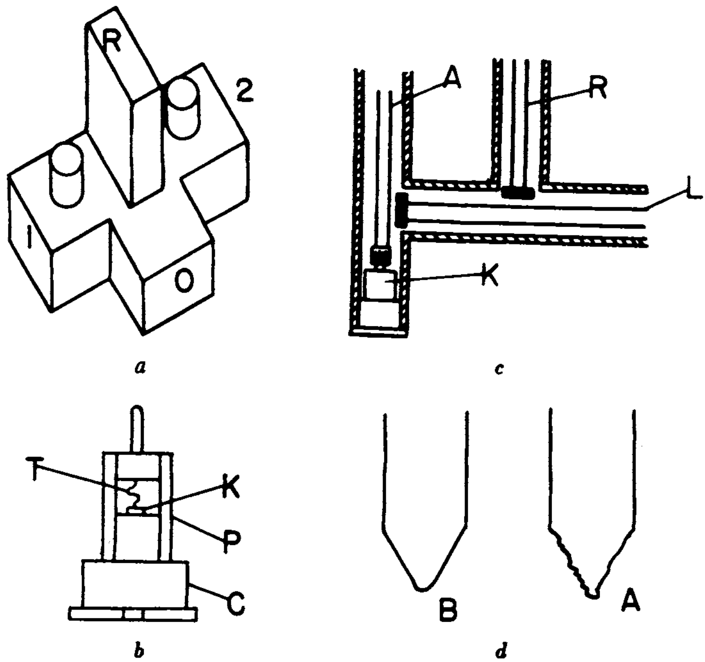

FIG. 5 : 4. DETAILS OF CRYSTAL ASSEMBLIES
(*a*) Balance of converter employing two crystals and Magic T: RF fed into R; output local oscillator into O
(*b*) Cross section of crystal assembly: T, tungsten wire (cat whisker); K, crystal; P, porcelain holder; C, metal base;
(*c*) Coaxial crystal mixer: K, crystal; L, output of local oscillator; R, output radio frequency; A, output to IF amplifier
(*d*) Normal point of cat whisker: A, before, B, after grinding

[3] If the mixing element is linear (that is, *not* nonlinear), then an attempt to add two frequencies will not result in beats but the resulting output will contain the two input frequencies. In a nonlinear mixer, that is, a crystal or a diode, the sum and difference appear as beats of much lower frequency than either original component; (also see Appendix).

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the beating oscillator into O, arm R is completely isolated from arm O. This, however, holds true for only one condition (see 3.12); that is, if arms 1 and 2 are matched to their respective loads (crystals, here). To state this otherwise, observing the restriction imposed, the oscillations of the signal and the beater are independent of each other. Furthermore, the noises in the two arms largely cancel each other thereby enabling a higher ratio of signal to noise in the IF output. Thus, variations in the impedance of the signal branch have little or no effect on the beating oscillator or its frequency. The tuning of the receiver is unaffected by variations of the impedance in the antenna (10.5) during the scanning cycle.

5.13. *Radar crystals*

As ordinarily used, a crystal, unlike a vacuum tube, cannot amplify; in fact, it causes an appreciable loss in signal strength.[4] It has, however, the redeeming virtue that it induces the minimum of noise and complexity.

Most of the crystal assemblies used in radar mixers consist of a cartridge (Figure 5 : 4 (*b*)) containing a crystal of pure silicon against whose surface a fine tungsten wire abuts. The pressure of the wire can be adjusted by means of a screw. Once adjusted in the factory, the cartridge is impregnated with an insulating compound which excludes moisture and preserves the mechanical stability of the arrangement. To protect the crystals from mechanical shock and electrical disturbances, they are usually wrapped in a heavy lead foil which is removed immediately before use. Even a discharge like static electricity from one's body, such as normally accumulates in dry cold weather, may impair, if not ruin, a sensitive crystal.[5]

The cartridge containing the crystal is fitted into a hollow receptacle that permits it to be coupled to the RF source, the local or beating oscillator, and the IF amplifier. Figure 5 : 4 (*c*) shows a crystal in a setting adapted for purposes of mixing.

It is quite misleading to say that we are once more using the old-fashioned crystal silicon detector in radar. As a matter of fact, there is a greater difference between the crystals formerly employed in radio and those now used in radar than there is between Stephenson's

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[4] For details, see Appendix.

[5] Before handling a crystal, one's body should be grounded so that any accumulated charge is drained away.

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Rocket and a modern stream-lined locomotive. To the eye, however, there is little difference.

The silicon (germanium is also now being used) now employed is obtained in a form that is already 99.8% pure. Research has shown that *pure* silicon is not a good material for a rectifier. Certain substances known as "dopes" must be added to impart the right properties: boron, aluminum, and beryllium are widely used as doping agents for silicon crystals. Boron lends the proper conductivity to the semi-conductor, silicon; aluminum and beryllium greatly increase the hardness and toughness. In the crystals produced by one manufacturer, 0.0015 to 0.005% by weight of boron, 0.1% of beryllium, and 0.4% of aluminum are alloyed with the pure crystals of silicon.

The doping agents are added as a powder and the whole is fused in an electric furnace for several hours. When thoroughly melted (either in a vacuum or in an atmosphere of helium, the mass is permitted to cool into an ingot. Cooling is done with deliberation and may take several hours. The uniformity of the resulting crystalline structure is largely dependent on the cooling process.

The ingot of silicon measuring about 4.5 × 1.85 inches (in the Bell Telephone Laboratory melts) is not entirely usable. Only the upper part—about 2.5 inches—has the correct characteristics, but this is sufficient for about 2500 crystals.

By the use of a fast-rotating copper disc impregnated with diamond dust, the ingot is cut into slabs. Then, one surface is polished with emery paper (000 fineness) for fifteen minutes which makes the surface appear mirror-like. It is then throroughly cleaned and heated in air for a half hour at a temperature ranging between 900° and 950°C. The reverse side of the crystal slab which is unpolished is carefully plated with nickel. The purpose of this is to present an easy base for soldering. After the nickel plating process, the slab is broken up by knife into small pieces ready for mounting. From 15 to 18 pieces can be cut from a square centimeter.

The "cat whisker", which in the early days of radio was just a stiff wire, is now prepared with meticulous care. For silicon crystals, tungsten wire is employed. As this is extremely hard, the point of the cat whisker that presses against the polished silicon surface will not flatten too much. The gauge (thickness) of the wire is determined by the amount of force it must exert on contact. Crystals to be employed at 3000 megacycles (10 cm) require a relatively large force and contact surface. The diameter of the wire is 0.008 inch.

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The end of the cat whisker is ground down to a conical point; the angle of the cone is 70° to 80°. When the point is finally prepared, its diameter will be less than 0.0001 inch. After it has made contact under pressure with the silicon surface, however, the point will flatten somewhat and the contact area will be increased. If in grinding down the point, small burrs or irregularities are left (see magnification in Figure 5 : 4 (*d*)), the crystal may become excessively noisy, thus losing its outstanding virtue. The Western Electric Company has devised a special electrolytic method for removing these burrs.

The double bend imparted to the cat whisker is impressed upon the wire by means of a jig. Its shape gives the cat whisker resilience and preserves the perpendicular thrust against the surface of the crystal. Depending on the type of crystal the over-all length of the cat whisker will range from 0.1 to 0.15 inch.

In the crystals produced by the Bell Telephone Laboratories, the cat whisker is then carefully plated (hot-dip method) with an alloy of 69% gold, 6% platinum, and 25% silver. After plating, the tungsten wire is forced into a hole and finally soldered fast to its base.

All the metal parts are usually plated with silver or gold. In assembling the cartridge, the stud holding the crystal is held in place by a set-screw. Pressure is then applied by means of a micrometer screw which thrusts the stud-mounted crystal against the point of the cat whisker. The crystal and its contacts are all placed in a testing circuit (Figure 5 : 5 (*a*)) and a one-volt potential applied to it, causing a flow of current, which is measured on a microammeter. The pressure of the point of the cat whisker against the crystal is increased until the resistance from front to back of the crystal is 300 to 400 ohms, and the back-to-front resistance is 10,000 ohms. The cartridge is then gently tapped with a light mallet, whereupon the front resistance should fall to between 200 and 300 ohms, while the back resistance should *rise* to a value between 20,000 and 100,000 ohms. The effect of the tapping produces changes for the better that are almost unbelievable. It is customary for the resistance from back to front to change by a factor of ten—sometimes, by as much as one hundred; from front to back a change of ten is common. Both the loss in conversion and the noise of the crystal are substantially reduced by this tapping process.

If all the foregoing has been carried out, the crystal cartridge is finally impregnated with a special wax. This excludes moisture from the contact surfaces and also holds the parts securely, thus lending greater mechanical stability to the crystal. After extensive research,

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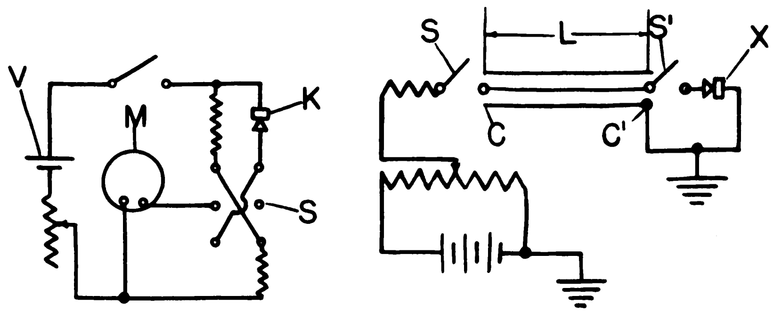
the wax finally adopted by the Bell Telephone Laboratories is a mixture of 80% Paratac and 20% Opal waxes. It has the exceptional quality of preserving its physical consistency—a heavy grease—over a temperature range from —40° to 70° C.

Most crystals are rendered inoperative, or are ruined, by burnouts. One of the ways of decreasing burnouts is to increase the path of the current between the cat whisker and the surface of the crystal; the greater the contact surface, the less the density of the current. By increasing the pressure of the point of the cat whisker against the crystal, we can increase the flattening and, hence, the area of contact.



a *b*

FIG. 5 : 5. TESTING CIRCUITS FOR CRYSTALS
(*a*) Diagram of wiring: V, 1-volt cell; K, crystal; M, microammeter; S, reversing switch
(*b*) Connections for generating high voltage testing spike for crystal: CC′, short length coaxial cable; S,S′, switches; X, crystal

Unfortunately, the efficiency of rectification of a crystal depends on the ratio of the backward resistance (more accurately, impedance) to the forward resistance. This, in turn, depends on the smallness of the area of contact. Hence, we have opposing qualities: great endurance to burnout (large contact surface) and low efficiency. Also, with a given contact, the efficiency of conversion falls off with a rise in frequency. This is equivalent to saying that as the wave length is decreased the contact area of the crystal must be decreased to minimize losses. Therefore, the pressure from the cat whisker of the higher-frequency crystals (those for 3 cm, 1.25 cm, etc.) must be lessened and their sensitiveness to burnout is increased.

Burnouts are recognizable because they cause crystals to lose their sensitiveness. When the back resistance falls off rapidly, this is most

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probably due to burnout. When the current in the reverse direction exceeds an allowable minimum standard it signifies a burnout, and this warrants rejection of the crystal.

It is a common factory practice now to test crystals by actually applying a "spike" (a high momentary voltage) and then measuring the crystal for burnout. A voltage pulse of 2.6×10^{-9} second duration (2.6 billionths of a second) and about 100 volts intensity is applied to the crystal which is thereafter measured for burnout.

The method of generating this spike (whose magnitude and duration are actually encountered in a radar set) and applying it is shown in Figure 5 : 5 (*b*). C C′ is a short length of coaxial cable. The battery of 100 volts is connected across the outer and inner conductors of the coaxial cable which behaves like a condenser (two conductors separated by an insulator). The voltage quickly charges the small condenser. Then the switch, S, is opened and the switch, S′, is closed simultaneously and the condenser discharges through the crystal. Observe that although we referred to the coaxial cable as a condenser, it is really a small transmission line and the capacity is actually distributed throughout its whole length (3.8). This is important, for a discharge from a condenser (a lumped capacitance) would be exponential and taper off; here, because the capacity is distributed throughout the entire line, the discharge remains uniform throughout the pulse. The impedance of the crystal must be matched to the characteristic impedance of the coaxial line.[6] (3.25). If this condition is satisfied a pulse equal to $V/2$ and of a duration equal to $2l/c$ will pass through the crystal (where V is the applied voltage, l is the length of the cable, and c is the velocity of light).

Let us take a concrete example. As we require a pulse of 2.6×10^{-9} seconds, then 2.6×10^{-9} equals $2l/c$ which (substituting the actual figures in the formula, $2l/3 \times 10^{10}$) is 39 cm or 16 inches, approximately. In other words, to obtain a pulse of 2.6 billionths of a second, we require a length about 16 inches of coaxial cable.

What accounts for the effectiveness of crystals at microwave frequencies? Their inherent quietness (lack of noise), their small size, the absence of accessory heaters and plate voltages, and their extremely small transit times are what commend their use. It will be recalled that the reason vacuum tubes (4.1) are ineffective at microwave frequencies is because the transit time of electrons across their active

[6] For details, see Appendix.

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elements is comparable to a period of a cycle of oscillation. Even in lighthouse triodes where the spacing (4.20) between cathode and grid is 0.005 inch, the frequency limit is between 3000 and 4000 megacycles.

In a crystal rectifier, the active portion of the crystal across which rectification takes place, the so-called *barrier depth* (Figure 5 : 6 (*b*)), is 10^{-6} cm (one millionth of a centimeter). This is about 12,000 times smaller than the spacing even of the afore-mentioned lighthouse tube.

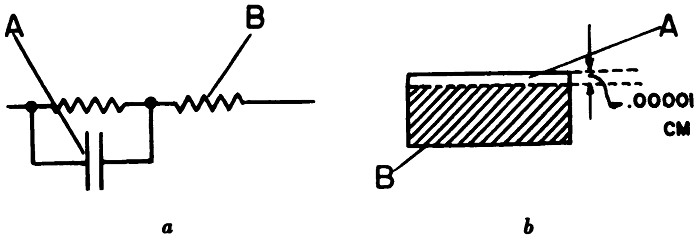

FIG. 5 : 6. DETAILS OF CRYSTALS
(*a*) Simple equivalent circuit representing crystal: A, capacity of crystal; B, spreading resistance
(*b*) Cross section of crystal (much magnified: A, barrier resistance; B, spreading resistance

Thus far, we have said nothing concerning the method by which a crystal rectifies, i.e., why it conducts better in one direction than in the other. To explain this adequately would involve an excursion into the electronic theory of matter, taking us far beyond the scope of this elementary book. Let us accept the fact, for present purposes, that at a point of contact between a metal and a semi-conductor (such as silicon or germanium) the flow of current from the metal to the silicon is greater than from the silicon to the metal when an oscillating voltage is applied across the common junction.

Even though the crystal conducts somewhat, nevertheless the metal of the whisker and the active layer of the crystal in immediate contact with the metal, known as a barrier layer, make up a condenser having some capacity. This capacity behaves as though it were shunted across the barrier resistance where rectification occurs; see Figure 5 : 6 (*a*). The capacity is about one *mmf* (one millionth of a millionth of a farad). Small though this seems, at 3000 megacycles it produces a reactance of about fifty ohms. As it is shunted across the barrier and is always present, the capacity affects the conversion efficiency of the crystal—(it being to some extent a side path for the high frequency current).

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This capacity depends upon the area of contact of the point of the metal whisker, another reason why surface contact should be made as small as possible. As the frequency rises, the reactance of the crystal capacity rises; hence, this is another reason for still further decreasing the area of contact as the microwave frequency is increased.

The barrier resistance occurs close to the surface of the silicon crystal (within 0.000001 cm of the surface) where the rectification takes place, as shown in Figure 5 : 6 (*b*). The spreading resistance is the resistance of the crystal mass (almost the whole bulk of the crystal), depending on its size and conductivity. It is in this resistance that the heating takes place and the losses of crystal occur. As with increasing frequency, more current is by-passed by the capacitance, more heat and resulting waste occur in the spreading resistance. For this reason, it is important to decrease the body or spreading resistance.

A method of improving the conductivity of the crystal, and therefore lessening the spreading resistance is by the heat-oxidizing treatment. This causes a layer of silicon dioxide to form on its surface. It is the impurities (the doping agents) in the silicon that contribute to its conductivity. The heat treatment causes the impurities to diffuse out of the surface into the adjoining layers of the silicon. The layer of oxide is dissolved away by hydrofluoric acid, leaving a layer of silicon exposed from which all impurities have been removed. Thus, the resistance of the surface, or rectifying layer, is increased (improving rectification). The impurities that have left the surface or rectifying layer have gone into the remaining mass of the silicon, thus increasing its conductivity and diminishing its heat losses. The presence of boron, even in the amount of 0.001%, is sufficient to cause appreciable differences in the electrical qualities of the crystal.

5.14. Local or beating oscillator

The beating, or local, oscillator of a radar, unlike that of superheterodynes employed in radio, must be very stable. In a 3-cm radar receiver where the frequency is 10,000 megacycles, a drift of 0.01 per cent in frequency means a variation of one megacycle (one million cycles)—which is already a good part of the total bandwidth of the receiver. Special devices are employed to prevent drift.

We observed (5.11) that the ratio of strength of signal to that of the output of the local oscillator may easily be one to a million. The power required by the local oscillator, therefore, is very slight: a few milliwatts will usually be sufficient. Because it is very loosely coupled to

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the mixer (to prevent the last RF stage from being affected), only a small amount of the power available—perhaps a milliwatt—will reach the crystal. To make provision for drift in the local oscillator, as well as in the transmitting device, the frequency of the local oscillator should be adjustable.

Fortunately, because of the slight amount of power required (unlike a transmitter), there are a number of ways of generating the local oscillations. We may employ acorn tubes, doorknob tubes, lighthouse tubes, or reflex klystrons. Where the frequency is 3000 megacycles or more, only reflex klystrons have found wide favor (4.19).

5.15. Intermediate amplifier: details and characteristics

Just as the intermediate frequency amplifier is the heart of the superheterodyne in ordinary radio, its use in radar is equally vital. Frequencies varying from ten to seventy megacycles per second are not unusual in radar receivers.

How wide shall we make the bandwidth of the IF amplifier? The limit is set at such a point that any further increase will generate more noise than signal strength. The output of the converter (the crystal mixer) is fed into the IF amplifier. If an RF amplifier is employed in addition, then the signal supplied to the IF amplifier is determined by the noise, the converter, and the RF characteristic. The maximum gain of the IF amplifier is also set by the degree of feedback, which increases with the number of stages and the amplification. Generally, the maximum amplification is about 110 decibels (an amplification of 100,000,000,000). As elsewhere, the best working conditions call for a compromise between a reduction in noise and the maximum gain in signal strength.

What frequency shall we adopt for the IF amplifier? The higher the frequency the more effective will be the elimination of the IF signal frequency from the video output. Also, AFC (automatic frequency control), an absolute essential in radar (5.18), is made easier by the use of high frequency. On the other hand, the tube and circuit minimum capacities favor a low IF; also, the stability of the frequency becomes greater as frequency is lowered. After weighing all the factors, the IF adopted for airborne radar is sixty megacycles, whereas that of naval and ground radar is thirty megacycles. The higher frequency permits the use of more compact and lighter equipment.

Because of the greater number of components it contains, a pentode

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tube is more noisy (5.6) than a triode. Of course, the pentode has a much greater gain and a much smaller interelectrode capacity. In experimental equipment, triodes have been used with neutralizing condensers, as in the neutrodyne radio. For practical purposes, the greater complexity involved and the difficulty of neutralization in the field, have discouraged the adoption of triodes in IF amplifiers. The use of the very small pentode, 6AK5, with its small capacity and low consumption of power is well nigh universal in radar receivers.

The character of the coupling between the stages of the IF amplifier may be of several types. The single-tuned stage is simple and easy to align in the field. To obtain the maximum gain, the shunt capacity per stage should be the minimum. The smallest possible capacity results from the capacity of the tube components themselves and the capacity of the associated wiring (for connecting purposes). The inductance of the coupling coils is varied through moving their cores by means of actuating screws. In each stage, the inductance is brought to resonance with its associated capacity at the midband of the IF.

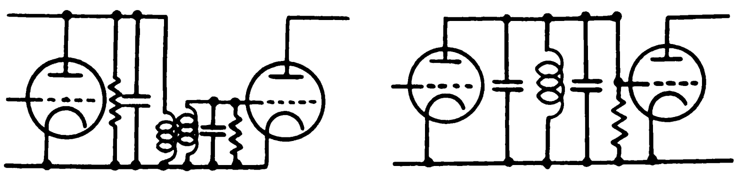

FIG. 5 : 7. COUPLINGS BETWEEN STAGES
(a) Single tuned; (b) double tuned

As the number of stages is increased, the over-all bandwidth decreases slowly over that of a single stage. In addition, the total gain or amplification slowly decreases per stage. As the number of stages is increased, the over-all shunt capacity is increased, causing a decrease in the total gain. A concrete illustration will make this clear. For example, an IF amplifier having an over-all bandwidth of five megacycles with six intermediate stages may show a total gain of 80 decibels (100,000,000 amplification); yet a single stage yields an amplification of 250 (24 decibels).

In the double-tuned circuit, the gain per stage is greater. Here both the primary and the secondary coils of the transformer are tuned to resonance at the midband of the IF. There is an appreciably greater gain per stage over that of a single-tuned stage; the increase in gain

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slowly diminishes as the number of stages increases. For example, an IF amplifier with six double-tuned stages, passing a bandwidth of five megacycles, may show a gain of 125 decibels even though one stage may develop a gain of 27 decibels (amplification of 500).

Figure 5 : 7 (*a*) shows a schematic diagram of a single-tuned coupling between stages. Figure 5 : 7 (*b*) shows a schematic diagram of a double-tuned coupling between stages. The inductances are varied for maximum amplification. By increasing the number of stages, we can increase the amplification of the IF amplifier. Unfortunately, the bandwidth decreases at the same time. As fidelity in reproducing the shape of the pulse depends on broad band amplification, a compromise must be effected. In radar, it is not unusual to encounter IF amplifiers with eight stages. In the double-tuned coupling, if the coupling (spacing) between coils is too loose, the gain between stages is decreased; if the coupling is too tight (too close), the resonance curve will exhibit a double hump; and the pulse, instead of ending sharply, will display a series of damped oscillations. When the coupling is just right (critical), the resonance curve will show a single sharp peak. We have remarked that double-tuned coupling circuits give more amplification than single. Roughly, three single-tuned couplings are equal in effect to two double-tuned couplings.

5.16. The diode as a second detector

Both triode and diode vacuum tubes can be employed as second detectors in radar. In this respect, radar is not different from ordinary commercial radio. The output from the IF amplifier should be sufficiently great to allow the detector to function effectively on the weakest signals to be observed. Regardless of the type of detector employed, it must pass on in full measure to the video amplifier the pulse envelope in undistorted form; it should suppress as completely as possible the intermediate frequencies. If the latter precaution is not observed, it is possible for the video amplifier to amplify the IF and cause objectionable feedback.

Figure 5 : 8 (*a*) shows a diode vacuum tube detector linking the IF amplifier on one side and the video amplifier on the other. The diode feeds into an RC (resistance and condenser) circuit and thence into the video circuit. A drop in voltage occurs across the resistance, R, and when the diode (a rectifier) is non-conducting, the charged condenser, C, will discharge through R, thus helping to maintain the voltage across R. This has a two-fold effect: it increases the video pulse, but, because

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of the large time constant, it also decreases the slope of the edges (sharpness) of the pulse. Again, we must effect a compromise between conflicting requirements.

The usual voltage is the drop across the resistance which should be very large compared to the drop across the diode when it is conducting. It would appear obvious that an open circuit at R would give us maximum resistance. In order to preserve the correct time constant, as R

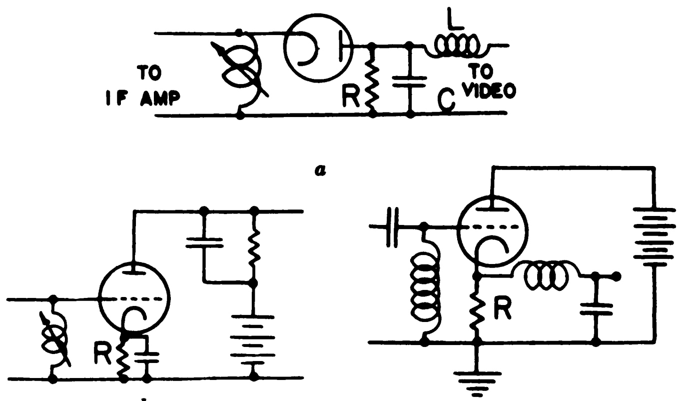

FIG. 5 : 8. DIAGRAMS OF VACUUM TUBES
(*a*) Diode linking IF amplifier and video amplifier
(*b*) Triode as detector: R, resistor for biasing grid
(*c*) Triode as detector with cathode follower

is increased C must be decreased (for the time constant is R $\times$ C). But C is the total capacity shunted across R; C′ is the capacity of the diode itself between its plate and its cathode. As C approaches C′ in magnitude, the voltage will be apportioned between C and C′ when the diode is conducting, and when it is non-conducting, C will feed into C′. It follows from the foregoing that the internal capacity and conducting resistance of a diode vacuum tube detector should be very low. A five-element tube (pentode) still functions better as a detector by joining all three grids to the plate, creating, in effect, a diode; the internal capacity of the pentode is very small and the conducting resistance between cathode and plate (the nearest point is the control grid when all grids are connected to the plate) is very small. The inductance, L, in the circuit aids in keeping out IF components from the video circuit.

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5.17. The triode as a second detector

More common than the diode vacuum tube is the triode whose grid is biassed[7] so highly that the tube operates near cut-off. For many reasons, the polarity of the video pulse may be important. If the output is taken from the plate circuit, the pulse will be negative; if across a cathode resistor, the pulse will be positive. A negative pulse may be employed to prevent blocking.

In Figure 5 : 8 (*b*) the video pulses generated in the plate circuit inductance are applied to the resistor, R. The purpose of the resistor, R, is to furnish bias for the grid. With large signal swings applied to the grid, the grid voltages will vary from below cut-off to a point far above the conducting stage. In order that the relation of the output to the input may be distinctly linear (that is, one is directly proportional to the other and so free from distortion), the cut-off must be sharp and the characteristic of the tube must be a straight line. Not only will the triode behave as a detector but it will also act as a linear amplifier.

In Figure 5 : 8 (*c*), the incoming signal spans between grid and ground, and the resistor in series with the cathode serves as a cathode follower. Though this produces an amplification of less than unity, it has the advantage of decreasing distortion, which means the linearity between output and input is improved.

5.18. Need for frequency control

It is one thing to make assumptions as to an ideal circuit; it is another to make the practical conform to the ideal. It has been tacitly assumed that when a circuit produces an oscillation, a pulse, or a band of frequencies, the frequency remains unaltered and does not drift. As we go up in the frequency scale, the effects of slight variations of physical surroundings produce marked shifts in frequency. What would cause a negligible shift at low frequencies—a change in temperature, for instance—produces a moderate change at higher frequencies; and at very high frequencies, relatively great variations.

The causes of variations in frequency are manifold. The dimensions of the magnetron change with heat, altering the size of the resonant cavities size and, of course, the operating frequency. A mismatch between the magnetron and the transmission line leading to the antenna into which it feeds causes a change in frequency. As the antenna

[7] A negative voltage applied to the grid gives it a bias; if sufficiently high, the tube will stop conducting and the grid has caused cut-off under the high negative voltage.

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rotates, its impedance will vary because of the difference in reflection of nearby objects. It is practically impossible to obtain a perfect match at a rotating joint because these joints must permit the antenna to be rotated and yet remain always connected to its transmission line. Again, the local beating oscillator (reflex klystron tube) is extremely sensitive to temperature changes, which cause alterations in the dimensions of its resonant cavity, which, in turn, determines its frequency (4.19). Even slight changes in supply voltage produce a shift of frequency. A variation of only one per cent in the voltages of anode and repeller will introduce a shift of five megacycles (five million cycles) in a three-centimeter reflex oscillator. A change in temperature of one hundred degrees will introduce a shift of twenty-five megacycles. Ordinary aging of the amplifier tubes in the IF circuit will introduce a shift of frequency.

These are but a few of the causes of variations in frequency that may indicate the need for automatic frequency control (AFC). It is a fact that efficient radars were made possible only after the introduction of AFC.

In order that the radar receiver may continue to operate steadily, it is customary to vary the frequency of the local oscillator automatically in order to offset involuntary changes of frequency elsewhere. This is known as automatic frequency control (AFC). We saw (4.19) that the frequency of the reflex klystron could be varied by changing the voltage on the repeller plate. In brief, part of the output of the IF amplifier is fed into a discriminator. The output of the discriminator is fed to the repeller whose voltage is varied so as to keep the frequency constant.

5.19. *Details and operation of discriminator*

The principle of the discriminator is identical with that of frequency-modulated receivers. A schematic diagram of a simple discriminator is shown in Figure 5 : 9. Circuits 1 and 2 are each tuned to the intermediate frequency; hence, they are both resonant. To prevent either circuit from taking over control of the other, they are coupled together rather loosely; therefore, each circuit depends upon its own parameters (inductance and capacitance) for resonance. By keeping the Q of circuit 1 low, its resonance curve is relatively flat, and the voltage across 1 changes but little in the vicinity of resonance (the intermediate frequency). Because the voltage in 2 is induced by 1, it, too, varies but little near resonance. The winding of 2 is such that the

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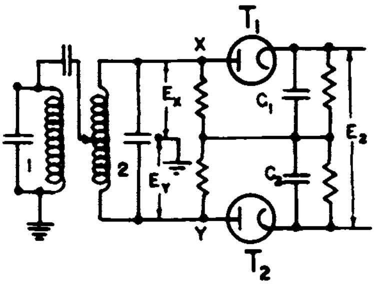
voltage across it and across 1 are in phase. Because of the loose coupling, the voltage across 2 is much less than that across 1. As in all resonant circuits, the current in 2 is very large, for only the resistance of the circuit limits it. As is also characteristic of resonant circuits, it is inductive above, and capacitive below, the resonant frequency. The voltages between X and Y and the ground bear the following relations to the voltages across circuits 1 and and 2:

$$E_x = E_1 + E_2/2$$
$$E_y = E_1 - E_2/2$$



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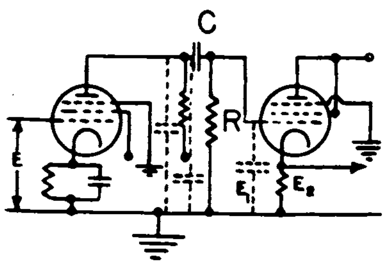

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FIG. 5 : 9. SIMPLE DISCRIMINATOR
FIG. 5 : 10. VIDEO AMPLIFIER
(Parasitic capacities shown dotted)

Suppose that the frequency of the repeller is slightly low; then, the circuit off resonance will be capacitive and the current will lead the voltage. At this frequency below resonance, the voltage of the coil in 2 will be below the drop in voltage across the condenser in circuit 2. The resulting voltage, E_{x2}, will be larger than E_y, and a positive voltage will be available for application to the repeller. This will raise the voltage of the repeller and increase the frequency.

Suppose that the frequency is too high (above resonance); then the circuit off resonance will be inductive, and the current will lag behind the voltage. At the frequency above resonance, the drop in voltage across the coil in 2 will be above the drop in voltage across the condenser in circuit 2. The resulting voltage, E_x, will be smaller than E_y and a negative voltage will be available for application to the repeller. This will lower the voltage of the repeller and decrease the frequency.

In the detector part of the circuit, the resistances and capacitances in both arms are equal. The voltage, E_x, is applied across the diode, 1,

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from plate to cathode; the voltage, E_y, is applied to diode 2 from plate to cathode. The diodes rectify the voltages across them and the voltages across the condensers C_1 and C_2 will be the same as across E_x and E_y (less the slight drop in the diodes). E_r, being the resulting voltage, will be positive when E_x is larger and negative when E_y is larger. When E_x exactly equals E_y the resultant E_r is zero and the frequency is that of resonance.

5.20. *Function of preamplifier*

By locating an IF preamplifier of one or two stages at the converter, only a very short transmission line will be required from the crystal output to the input of the IF amplifier. As the output impedance of a crystal is of the order of 400 ohms, it is difficult to obtain a cable to match with a characteristic impedance (3.5). Upon a moderate amplification in the preamplifier, its output may be fed by a standard coaxial cable (75 ohms impedance) transmission line to the main IF amplifier. The gain of a two-stage preamplifier is about one thousand (30 decibels).

5.21. *Video amplifier*

The output from the detector is fed into the video amplifier, which, in radar, is resistance-capacitance coupled between stages (Figure 5 : 10)). Observe that the output is taken from across a cathode follower (a resistance in series with the cathode). Though the amplification is less than unity in such a stage, the response and fidelity are improved. As the input voltage of the second tube includes the output voltage, E_2, it follows that E_z is less than E_1, and the amplification is less than one.

The flatness of the response of the video amplifier will fall off at high frequencies because of the shunting effect of the capacities at such frequencies. Figure 5 : 10 shows the common capacities that assert themselves as the frequency is increased. To keep the shunting capacity down, pentodes are employed in the video amplifier, as these tubes have inherently low capacities.

The need for a video amplifier arises from the fact that the video signal, as it leaves the detector, is in a final form to be presented to the cathode ray tube, but its intensity is too low; it must be further amplified. The requirements of the video amplifier (which closely resembles that of a television amplifier) are less exacting than those for a television cathode ray receiver. Faithful reproduction of the pulse in radar is not strictly essential, as it is in television—except, perhaps, in

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the directing of guns or bombing radars. Furthermore, the low limit of frequency of a radar is about 250 PPS (pulses per second), as compared to one per second in television.

The limits of a video amplifier are determined by the high and low frequency responses, as indicated already. The principal reason for the falling off in gain at high frequency is the presence of minimum shunting capacity. The load imposed upon a video amplifier in radar is usually more severe than in television. It is quite common to require a hundred volts or more for the cathode ray tube. We can lower the low frequency cut-off point by increasing either the capacity (C) or the resistance (R). As shown in Figure 5 : 10, R is the input resistance to the grid, and C is the capacity of the coupling condenser. The internal resistance of the tube itself, between grid and cathode, sets the least possible resistance. On the other hand, if we make the coupling condenser too large, several problems will develop: the greater its physical bulk is, the larger will be its parasitical capacity (4.1) and the high-frequency output will be lowered by its shunting effect; too large a condenser will produce blocking (similar to "motor-boating"[8] in ordinary radio) when very large signals come in.

[8] So-called from the nature of the sound; see details in Appendix.

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Chapter 6

MODULATORS AND WAVE SHAPERS

6.1. Phase relations

In the ordinary well-designed alternating current generator, the graphic representation of the alternating current voltage and current waves is essentially a sine wave, as shown in Figure 6 : 1 (*a*). A wave of any other shape, such as the one in Figure 6 : 1 (*b*) (which repeats

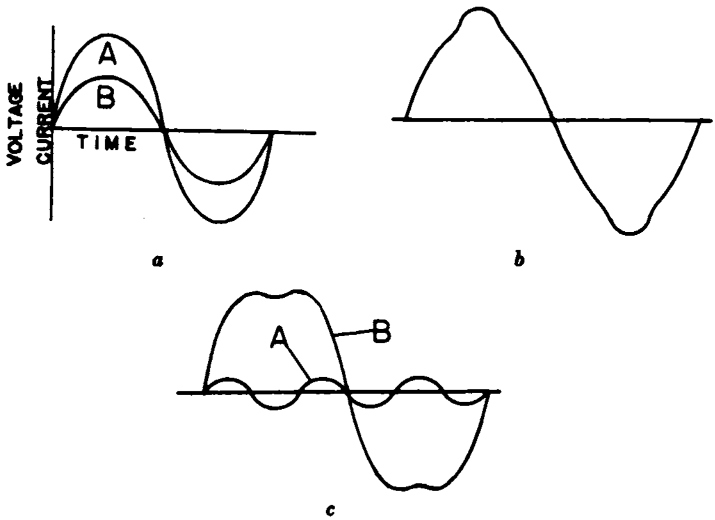

FIG. 6 : 1. CURVES ILLUSTRATING ALTERNATING CURRENT
(*a*) Sine wave of current (A); sine wave of voltage (B) (Both in phase)
(*b*) Alternating compound wave;
(*c*) Combination of fundamental and (A) 3rd harmonic; resultant (B)

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itself or goes through cyclic changes), can be considered as a compound wave made up of simple sine waves. Thus, if we add a third harmonic to the fundamental in Figure 6 : 1 (*a*), we obtain the wave form shown in Figure 6 : 1 (*c*).

If the voltage of a pure sine wave is applied to a pure resistance, the voltage and current will appear as in Figure 6 : 2 (*a*). Here, each reaches its maximum or minimum at the same instant. Under these circumstances, the voltage and current are said to be in phase and are sine waves.

Now, let us apply the pure sine voltage to a pure capacity (a condenser) as in A of Figure 6 : 2 (*b*); the voltage and current will appear

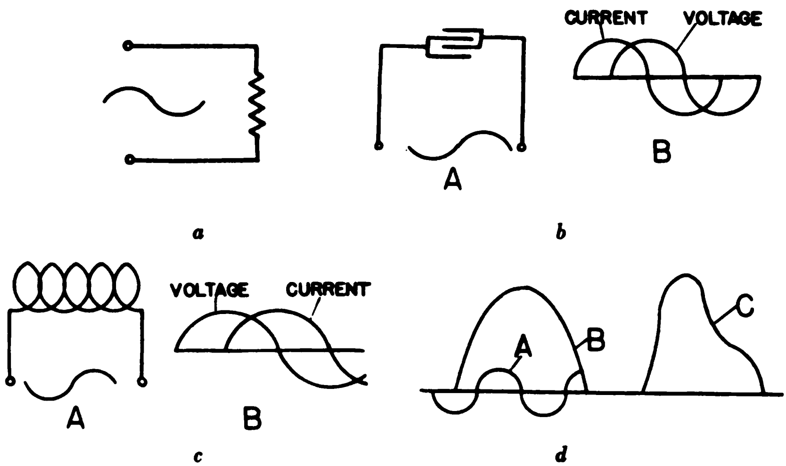

FIG. 6 : 2. EFFECTS IN SINE WAVES
(*a*) Pure sine wave current flowing when sine wave voltage is applied to pure resistance
(*b*) A, sine wave voltage applied to pure capacity; B, resultant current and voltage
(*c*) A, sine wave voltage applied to pure inductance; B, resultant current and voltage
(*d*) Combination of A, 3rd harmonic, B, fundamental out of phase; C, resultant

as in B. Here, voltage and current are no longer in phase, i.e., they do not reach their maxima or minima together. Observe that the current is at the maximum when the voltage is zero; that is, the current is said to *lead* the voltage by a quarter-cycle, or 90°. On the other hand, if we apply the voltage of a pure sine wave to a pure inductance (a coil

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without resistance) as in A of Figure 6 : 2 (*c*), then the current is retarded, or lags, as in B. The current lags a quarter-cycle (90°) behind the voltage.

6.2. Modulation and beats

Let us again consider a pure sine wave combined with a third harmonic. In this instance, the third harmonic has been shifted in phase with respect to the fundamental. Observe that the compound wave, as shown in Figure 6 : 2 (*d*), is no longer symmetrical but it is nevertheless made up of a fundamental and a third harmonic.

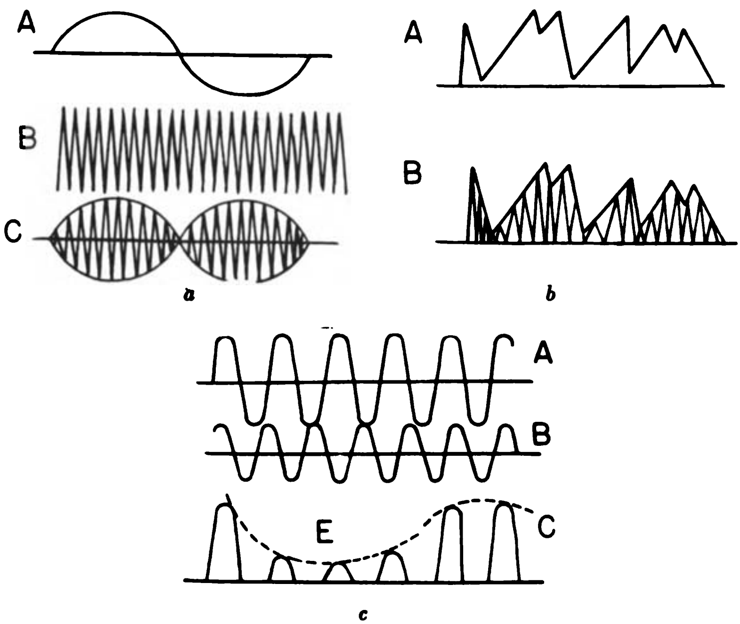

FIG. 6 : 3. EFFECTS OF MODULATING CARRIER
(*a*) A, low-frequency modulating wave; B, high-frequency wave (carrier); C, modulated wave
(*b*) Complex modulating wave: A, modulating wave; B, modulating carrier
(*c*) Beats produced by two wave trains: A, B, slightly different frequencies; E, resulting frequency

Figure 6 : 3 (*a*), A shows a sine wave of a frequency within the audible range (that is, under twenty thousand cycles a second), and B is a representation of a radio frequency wave (exaggerated). If both are impressed on a circuit such as shown in Figure 5 : 9 (*a*) (5.16), the resultant wave is as shown in C. The envelope or boundary is

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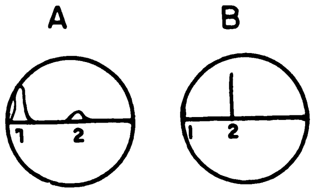
of the same shape as the audio wave—which would be called the *modulating wave*; B, is the *carrier wave.*

In A of Figure 6 : 3 (*b*) is shown a complex audio wave such as that produced by the human voice. This can also be impressed on the carrier or RF wave (6 : 3, (*a*), B) thus producing a modulated wave with the envelope, as shown in Figure 6 : 3 (*b*), B.

In Figure 6 : 3 (*c*), A and B present two waves that differ *slightly* in their frequencies; and C, is the result of combining them, producing beats that are equal to the frequency of the difference.



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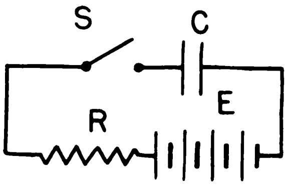

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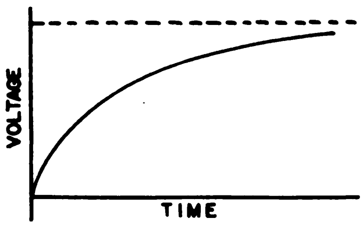

6:5(*a*)

FIG. 6 : 4. SCREENS OF CATHODE RAY TUBES, SHOWING BROAD (A) AND SHARP (B) PULSES

FIG. 6 : 5. SIMPLE CIRCUIT FOR CHARGING CONDENSER

(*a*) Curve showing growth of voltage as condenser charges

6.3. Relation between pulse power and average power

Let us assume that we have generated oscillations of very high frequency and of great power. For purposes of radar, we must break the oscillations into pulses of extremely short duration but at relatively long intervals; thus, we can obtain great power with the use of little average power, and also obtain a period of silence between pulses, so that we may observe the echoes.

Suppose we employ one hundred watts of power and that the

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duration of a pulse is one microsecond (1/1,000,000 second). If the interval between pulses is one thousand microseconds, then there will be one thousand pulses in a second. These thousand pulses will take up 1/1000 of a second. But the average power is one hundred watts; therefore, the power available in one thousand microseconds will be 100 × 1000 or 100,000 watts, which is 100 kilowatts. With one hundred watts of power, the power in our pulse is 100,000 watts. In a stroke of lightning, lasting a microsecond, there may be a current of 10,000 amperes at 100,000,000 volts (a moderate lightning bolt). The power of the stroke will be 100,000,000 × 10,000 or 1,000,000,000,000 watts. As this acts for only a microsecond, the energy distributed over a whole second, or *average* energy per second, will be 1,000,000,000,000 divided by 1,000,000. This is one million watts for a second. As there are 3600 seconds in an hour, this is equivalent to 1,000,000 divided by 3600 or 300 watt hours, approximately.

In other words, the tremendous power of this lightning stroke, because of its extremely brief duration, is only sufficient to light ten thirty-watt lamps for an hour.

6.4. Need for sharp pulses in radar

In Figure 6 : 4 are shown two screens of cathode ray tubes, A and B. The numbers 1 and 2 on each screen represent the location of the transmitting "pip" and the returning "echo" pip respectively. The distance between 1 and 2 represents the distance or remoteness of the object from the transmitter. What is the distance between 1 and 2 on screen A? Because the slopes are gradual, exact measurement of the interval becomes difficult, if not impossible. Where the use of A is to detect approaching planes, sharpness may not be absolutely necessary. When, however, the radar is employed in anti-aircraft fire, where an error of fifty feet in five miles may be critical, screen A would be absolutely useless, and B, indispensable.

6.5. Function of modulator

Thus, we see that in radar precision, as required in gunnery and in bombing, demands the production of extremely sharp pulses, accurately spaced. The train of high-frequency oscillations produced by the magnetron (transmitting tube, **4.16**) is the carrier wave; the production of pulses or sharp groups of oscillations is the process of modulation. The shaping of the pulses, their duration and frequency of repetition, are all performed or controlled by the modulator. How the latter operates is our present concern.

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6.6. Production of sawtooth waves

Suppose we arrange a circuit as in Figure 6 : 5. This comprises a resistance, a capacity, a switch, and a battery, all joined in series. Let us close the switch. The voltage of the battery (E) is then across the circuit containing the condenser (C) and the resistor (R). As C initially is an unchanged condenser, the momentary voltage across C is zero and the entire voltage is across R. This will produce a flow of current into C, which thereby becomes charged; that is, its voltage increases until it equals the applied voltage of the battery. When this equality is reached, the condenser is fully charged and flow of current ceases (because a flow of current is due to a difference of potential).

If we were to plot the rise of voltage and time, it would appear as in Figure 6 : 5 (*b*). This curve is known as an *exponential curve*. Its rate of growth is greatest at the beginning, and then it tapers off. How fast it will grow with a given applied voltage will depend on the size of the condenser and of the resistor. Obviously, the larger the condenser, the longer it will take to charge (or fill). The higher the resistance in the

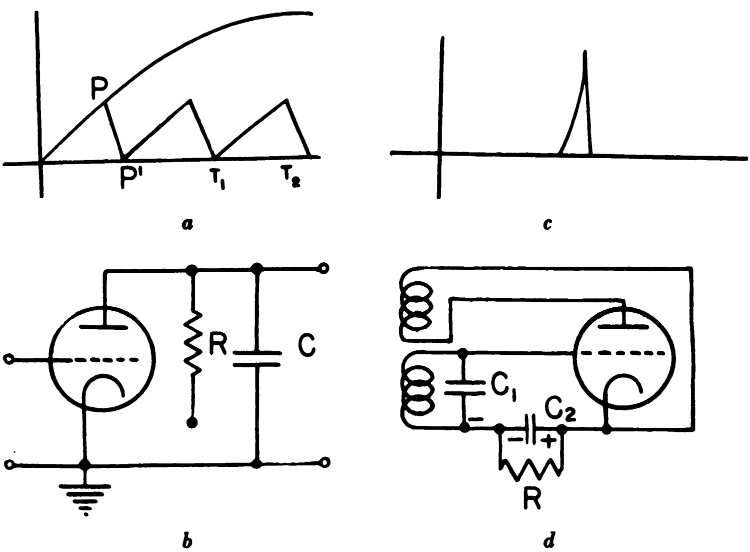

FIG. 6 : 6. SAW TOOTH WAVE TRAINS
(*a*) Schematic diagram
(*b*) Arrangement for producing wave train of (*a*)
(*c*) Effect of making time constant (RC) very small
(*d*) Sweep circuit more effective than one shown in (*b*)

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circuit, i.e., the smaller is the channel of flow, the smaller is the charging current, and the longer will be the time required for charging. The product of R and C is known as the *time constant.*

Suppose we desire to use only the initial part of the exponential curve shown in Figure 6 : 6 (*a*). Then, we must arrange to terminate the charging process at some point, P, where the discharge takes place with great rapidity to point P′. A simple way to accomplish this is by means of the circuit shown in Figure 6 : 6 (*b*). The grid of the triode is biased to cut off by a negative applied square wave (we shall see shortly how a wave of this shape is generated). During this cut-off period, the tube cannot conduct and the condenser will charge between T_1 and T_2. At T_2, the voltage of the grid rises to zero (a negative voltage *rises* when it approaches zero), whereupon the tube will become conducting and the condenser will suddenly discharge and remain discharged as long as the voltage of the grid stays at zero. Note that the discharge is much more abrupt (as indicated by the slope) than the charge. In charging, the current is kept small by means of the large resistance, R; at discharge, there is a gush of current through the tube whose resistance then is very low. From its shape, this curve is known as a *saw-tooth wave*, and it finds wide use, for example, in radar circuits, sweep circuits for oscilloscopes, and range markers.

If we make the time constant, RC, very small, then both the charging and the discharging periods can be made very small and the saw-tooth will appear as in Figure 6 : 6 (*c*).

A more effective sweep circuit is illustrated in Figure 6 : 6 (*d*). This employs a high vacuum triode whose plate and grid circuits are inductively coupled so as to produce oscillations. The condenser (C_2) is charged by the current from the grid which flows through the very large resistance (R). The charge on C_1 will increase because it cannot leak through fast enough. As a result, the charge on C_2 will build up until the negative bias (the grid side of the condenser (C_2) being negative) on the grid exceeds the cut-off voltage, whereupon the tube will stop oscillating. Thereafter, during cut-off, the charge on the condenser (C_2) will slowly leak off until the negative bias on the grid drops sufficiently for oscillations to start once more. The period of charge and discharge, or the period of the sweep current, depends on C_2 and R. This period can be made much smaller (or the frequency much higher) than that of a gas tube circuit, for no deionization period is required because of the high vacuum tube employed. This circuit, which shows the employment of a high resistance, is satisfactory to

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illustrate the principle but it lacks practical effectiveness. By substituting a pentode tube in place of R as shown in Figure 6 : 7 (*a*), the sweep circuit becomes entirely feasible. Here, the plate voltage E, should be so high that its current remains constant, regardless of alterations in voltage. This is obvious from the flat appearance of the characteristic of the pentode tube which is shown in Figure 6 : 7 (*b*).

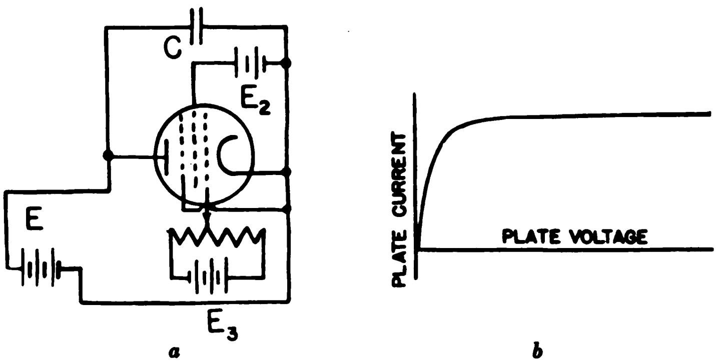

FIG. 6 : 7. EFFECTS WITH PENTODES
(*a*) Diagram of sweep circuit
(*b*) Characteristic of pentode tube showing relation of current to voltage in plate

The grid control permits variations in current by varying the bias. As the condenser, C, can be charged quickly by a large current and slowly by a weak current, it is obvious that the grid control gives us a means of easily changing the sweep cycle.

6.7. *Production of square waves*

In Figure 6 : 8 (*a*), the cathode is connected to the positive side of the battery, B. A sine wave voltage is impressed upon the tube through the resistance, R. In a diode, current can flow only from cathode to plate (the reverse of the conventional direction); that is, from the negative emitter (filament) to the plate. So long as the maximum sine voltage does not exceed the battery voltage, the plate of the tube can never become positive, and the tube will not conduct. Thus, the output voltage, E, will equal the input voltage. Should E ever exceed the battery voltage, the plate will then become positive and the tube will conduct. This causes the tube to act like a short-circuit, which means the output voltage will equal the battery voltage, and the peak of the wave (sine) will be cut off as shown. To be effective, R should be many

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times larger than the resistance of the tube. Observe that this cuts off or squares only the positive peaks.

It would be possible to clip the negative half of the sine wave by using another diode, as shown in Figure 6 : 8 (*b*) in reverse. More effective than this is the use of a triode amplifier that is *overdriven*. In Figure 6 : 8 (*c*) the alternating voltage to be clipped or squared is the

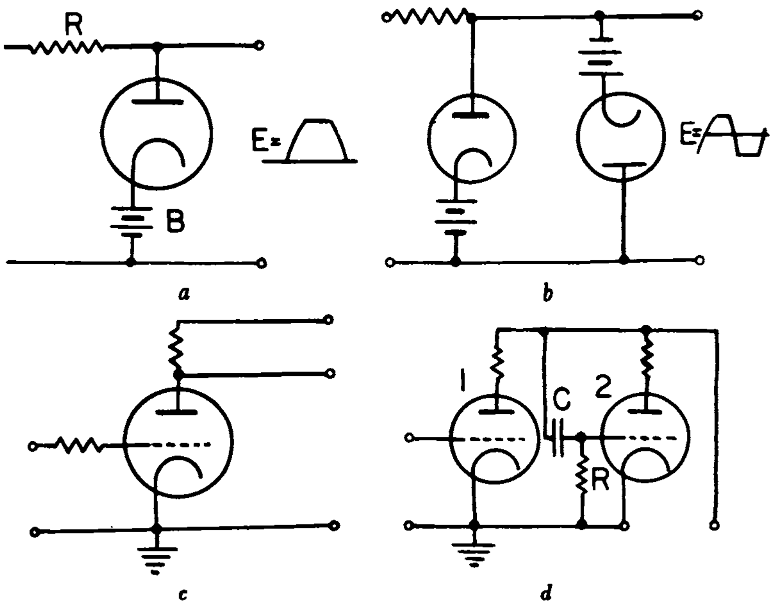

FIG. 6 : 8. EFFECTS WITH DIODES AND TRIODES
(*a*) Square wave with simple diode
(*b*) Positive and negative square waves with two diodes
(*c*) Square waves with overdriven triode amplifier
(*d*) Peaked waves with two triodes and small time constants

input, applied to the grid and cathode. By itself, this part is exactly like the dipole in which the grid acts as the plate. No battery is included in the circuit. The high positive voltage applied to the grid causes a very large rush of current through the tube, and the output voltage falls from the voltage value of the plate to almost zero. When the grid swings to a very low negative voltage, the current from the plate is cut off and the output voltage rises to the voltage value of the plate, where it stays until the voltage of the grid rises enough to make the tube a conductor once more. Thus, both sides of the wave are

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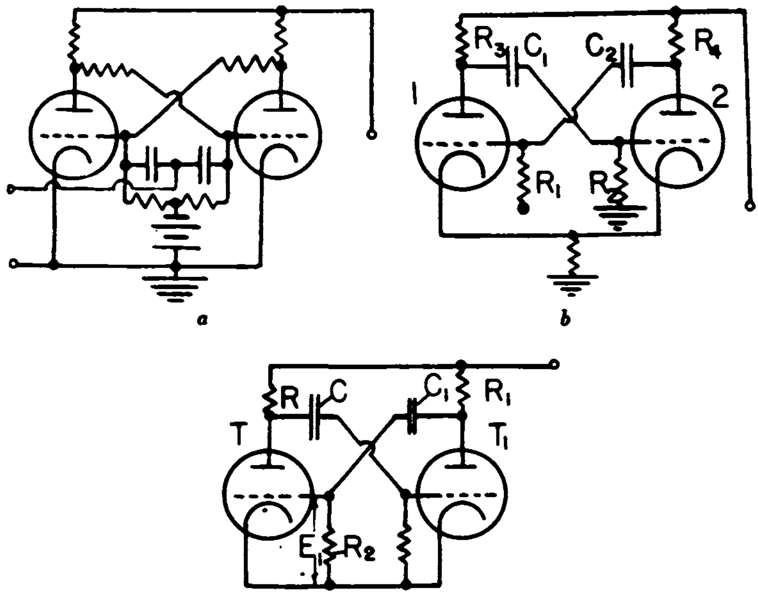
clipped or squared. If it is desired to make the squaring more abrupt, a second amplifier may be used in cascade, or in step, with the first.

6.8. *Production of sharp peaks*

We have noted (see 6.6) how the combination of a diode, a condenser, and a resistance could be used to produce a sawtooth wave, and, by the use of very short time constants, to produce sharp or peaked waves. A more effective method for obtaining such waves is shown in



c

FIG. 6 : 9. TYPES OF MULTIVIBRATORS
(*a*) Start-stop, (*b*) Free-running, (*c*) One shot

Figure 6 : 8 (*d*) where the voltage of a square wave is applied to the grid of the tube (I). This appears like a two-stage amplifier. It differs from the latter in so far as the capacity (*C*) and the resistance (*R*) are unusually small. When the voltage of the input (a square wave) is negative, tube 1 is cut off, and the voltage between plate and cathode of 1 rises to a very high value. The voltage will remain constant until the grid voltage of 1 suddenly rises, whereupon it will become conducting and the output voltage of 1 will drop very suddenly.

When this happens, the voltage across the small condenser which

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has been fully charged, quickly discharges through R, and the voltage applied to the grid of 2 takes the form of an extremely sharp peak.

6.9. Purpose of shaped waves

Most of the circuits employed in radar are used for purposes of either timing or control. To accomplish these, we use square waves, rectangular waves, trapezoidal waves, sharp pulses, and so forth. Sharp pulses may be used for triggering, marking, range timing, and synchronizing parts of a radar that must operate in unison. A square wave pulse may also be employed for intensifying or for blanking, depending on whether it is positive or negative. Such square wave pulses are also known as *gate pulses* and may be used to control repetition rates, duration of pulse, and so forth.

6.10. Multivibrators

A very interesting form of oscillator that employs only resistances and capacitances is the *multivibrator* shown in Figure 6 : 9 (*a*). This is a symmetrically arranged circuit in which the plate of each tube is coupled to the grid of the other. It is commonly utilized for producing rectangular pulses or square waves. In one form, known as the *start-stop multivibrator*, a trigger pulse is fed into the multivibrator, which initiates a cycle of operations, but then becomes inactive until another trigger pulse is applied. On the other hand, in the free-running multivibrator (Figure 6 : 9 (*b*)), there is an alternation of plate current from one tube to the other at a rate determined only by the circuit constants. Because of the coupling between plate and grid, this form is known as *plate-coupled.*

Let us assume that the plate voltage is applied as shown: Current will flow in both tubes. Because of some minor difference in the circuit, let us assume that there is more current in tube T_1. Then the drop of voltage in resistance, R_1, will increase, because the current through it is increasing, and the plate voltage across tube T_1 will decrease. As the voltage across a condenser cannot change instantly, the voltage from grid to cathode E_1 will decrease. The decrease in the voltage of the grid produces a decrease in the current through T. This means that the drop in voltage in E will cause an increase of plate voltage of T, and, hence, an increase of voltage from grid to cathode of T_1, producing a further increase in current in tube T.

The grid voltage of T will cause cut-off when it is sufficiently negative. This will be determined by conductor, C. When T stops conducting, the charge on C_1 will leak off through resistance, R_2. The voltage of

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the grid of T will gradually rise toward zero and T will begin to conduct. The current through R will increase, the drop across it will increase, and the voltage from grid to cathode of T will decrease. This will continue until T is cut off. There is thus a switching action back and forth from T to T_1. Although it takes some time to describe the operation, the actual switching takes only a fraction of a microsecond. The repetition frequency of the cyclic period is controlled by the circuit constants in this type of multivibrator, the *free-running*.

Timing pulses are often produced by a multivibrator. For purposes of radar, a multivibrator known as the "one-shot" type has been widely used. Note that this arrangement (Figure 6 : 9 (*c*)) is *not* symmetrical; the grid of tube 1, goes to a B-supply through resistance R_1; the grid of tube 2 is connected to the ground through the resistance, R_2. Because the grid of 1 is highly positive, it will pass current. As this flows through R_3, the drop in potential (negative) across it is applied to the grid of 2, thus keeping this tube cut off.

Now, let a brief negative pulse be applied to the grid of 1, thus cutting it off (stopping its flow of current) and thereby increasing both the plate voltage of 1 and the grid voltage of 2. Thereupon, 2 will become conducting. The flow of current through it and R_4 will produce a drop of potential in it, and decreased voltage at the plate of 2—which means also decreased voltage to the grid of 1. Tube 1 will conduct less and less, until it is eventually cut off entirely, and tube 2 will conduct and remain conducting so long as the condenser, C_2, continues to discharge through the resistance R_1, and the grid of 2 remains negative. As soon as the charge on C_2 has dropped to a point where the grid of 1 goes above cut-off, 1 will conduct, starting a progressive reduction of current of 2 until it, in turn, is cut off.

6.11. *Delay networks*

A transmission line may be considered as made up of units of resistance, capacitance, and inductance, as shown in Figure 6 : 10 (*a*). With electromagnetic waves travelling at the rate of 186,000 miles a second (30,000,000,000 cm) a line one thousand feet long will require roughly a microsecond for the passage of a wave. Suppose we desire to delay operations in a radar system between stages of a sequence for a short interval, one-microsecond, a fairly common delay time in radar. A transmission line a thousand feet long could serve but it would hardly be practicable in a compact space such as the interior of an airplane. By using a delay network as shown in Figure 6 : 10 (*b*) we can

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accomplish this end. Networks may also be employed for shaping pulses.

6.12. Pulse-forming networks

Let us consider an arrangement like that in Figure 6 : 10 (*c*). If the current I, that flows when the switch is closed, is square in shape as in A of Figure 6 : 10 (*d*), the discharge of C will be a straight line, for the

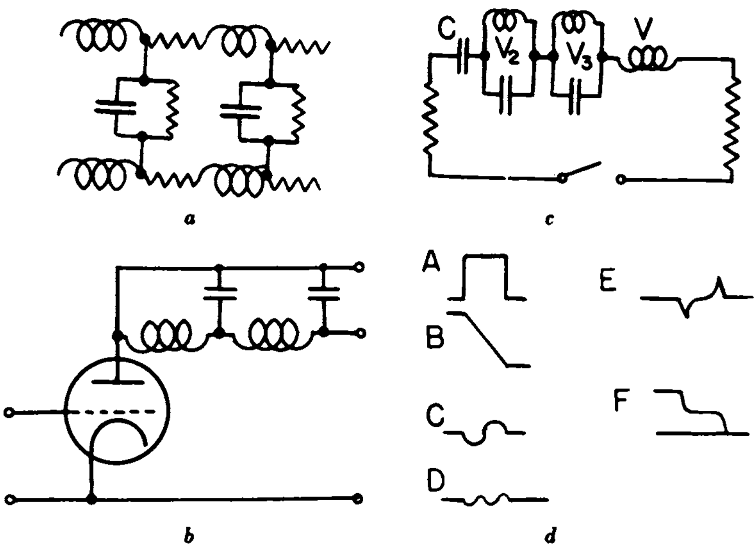

FIG. 6 : 10. TYPES OF NETWORKS
(*a*) Component network unit of transmission line
(*b*) Simple delay network
(*c*) Pulse-forming network
(*d*) Various pulses produced in components of (*c*); F, resultant of combination

pulse current is constant. The voltage across C during the discharge will appear as in B of (*d*). For this voltage to drop to zero at the same moment that the pulse terminates, C must be carefully selected. In the condenser-coil combination, the current pulse will start an oscillation so long as the resistance in this circuit is below the minimum. The values chosen for inductance and capacitance are such that the time of one cycle or complete oscillation will equal the time of the pulse in the current; the appearance of the voltage, V_2, will then be as in C of 6 : 10 (*d*).

Similarly, the oscillations are started and terminated in the condenser-coil combination of voltage, V_3. Here, the values of capacity

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and inductance (called *parameters*) are chosen so that two complete cycles of oscillation occur during the pulse of the current. The voltage across this will appear as in D. Across V, which is simply an inductance, the voltage produced by the leading and trailing edges of the current will consist of two sharp peaks in opposite directions at the ends of the pulse as in E.

As all the voltages are in series, the total combined voltage will appear as in F, a two-step affair with almost vertical sides. A pulse-forming network must be charged and discharged at fixed intervals. No simple switching arrangement will suffice. Where intervals of time as small as a microsecond must be controlled, the margin for variation is very small; that is, the precision must be very high. As the voltages involved are usually high, the device must be capable of operating safely at peak voltages. It should be stable and durable.

6.13. Electronic switch

An electronic device that might be employed for switching utilizes two gas-filled diodes as shown in Figure 6 : 11 (*a*). The resistances, R and R′, are equal, and as they are connected in multiple across the tubes, the drops in voltage across the tubes will be equal and one-half the total of the network voltage. This is normally insufficient to operate the tubes.

If a large positive pulse or *trigger* is applied as shown, tube 2 will become conducting and the voltage across it will drop to a low value; thereupon, most of the voltage will be across tube 1, which then becomes conducting and its voltage will drop in turn. In the meantime, tube 2 is deionizing, that is, losing its conductivity. As this process continues its resistance will gradually increase (as the free ions within the tube vanish by combination) until the voltage reaches a point high enough to repeat the cycle. Although this arrangement is workable, it is open to the objection that high-trigger pulses are required to initiate conduction. Furthermore, the exact moment when firing commences is uncertain; that is, the arrangement lacks precision.

6.14. Blocking oscillator

A popular form of pulse producer is known as the *blocking oscillator*, shown in Figure 6 : 11 (*b*). As the plate is coupled back to the grid through a transformer, only a single tube need be used. Here, the grid is deliberately "driven negative" to cut-off after a number of cycles. When this occurs oscillations cease, and the charge on the grid slowly leaks off until oscillations once more start. By this means,

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intermittent oscillations are produced with wave forms similar to that of a multivibrator (**6.10**).

Pulses may be generated directly by means of the blocking oscillator shown in Figure 6 : 11 (*b*). The plate and grid are coupled by a transformer and the grid is isolated from the ground by means of a capacitor.

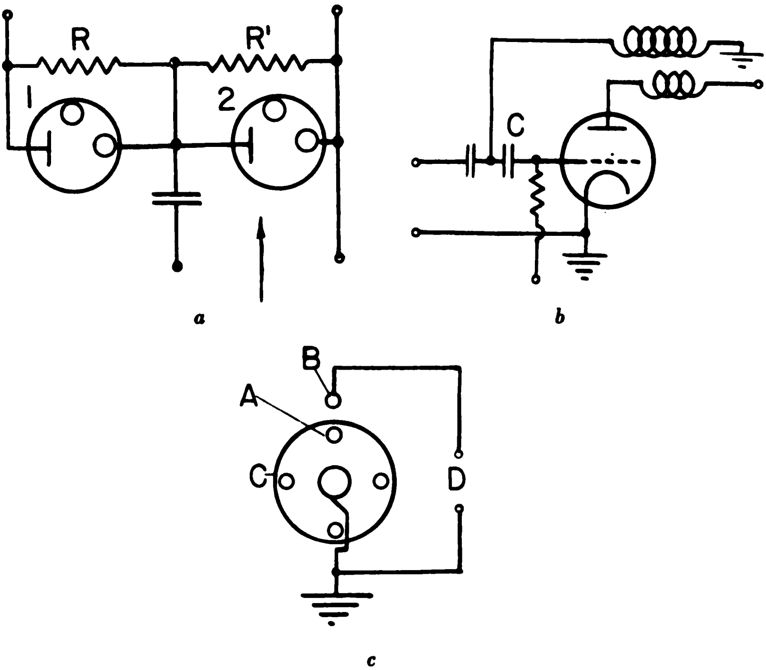

FIG. 6 : 11. MISCELLANEOUS DEVICES
(*a*) Electronic switch employing two gas-filled diodes
(*b*) Simple blocking oscillator
(*c*) Rotary spark gap: A, rotating electrode; B, stationary electrode; C, disc-bearing electrodes; D, terminals

The connections to the transformer are such that when the voltage of the plate drops, the voltage of the grid rises; therefore the change in voltage at the grid is amplified and fed back to the grid in the same polarity.

We will assume that the plate current has been cut off by a negative voltage at the grid which originates in the charge of the condenser. As the condenser discharges to the ground through the series resistance, the voltage of the grid will rise above cut-off, whereupon the tube will pass current from the plate. This current passes through the

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transformer and induces a further positive charge on the grid. Thus, the latter is "driven positive" very quickly, and the grid will begin to draw current. When this happens, the capacitor (C) charges and the voltage of the grid will reach equilibrium at zero. As the voltage of the grid levels off, the increase in the current from the plate will cease; the polarity of the transformer will reverse, behaving as though it were forming the first cycle of an oscillation.

6.15. Rotary spark gap switch

An interesting switch that is widely used in radar modulators is a purely mechanical device known as the *rotary spark gap*, shown in Figure 6 : 11 (*c*). It is sturdy, simple, and reliable. It produces gases by its spark discharge, which also produces interfering oscillations, for this becomes a spark transmitter. In a confined space, as in an airplane, the spark gap is enclosed in a sealed metal container under pressure. The metallic shielding minimizes radio interference, and the gases liberated, which are corrosive, are absorbed by porous (activated) carbon. The disc—(usually made of aluminum)—rotates at high speed with the projecting pins passing the fixed electrode. The electrodes are connected to the pulse-forming network. When the distance between electrodes reaches the fixed minimum, a spark will jump across. The path of the spark is then highly conducting (for it is metallic vapor) and bridges or shunts the network, causing it to discharge. As the disc continues to rotate, the electrodes will separate and the discharge of sparks will cease. In the interval between sparks, the network will charge.

This type of switch will carry huge currents—easily up to one thousand amperes—and it can operate on voltages as high as 30,000. It requires frequent adjustments, however, and it is low in precision.

6.16. Saturable core reactor switch

An interesting switch, non-electronic in nature, yet with no moving parts, is the *saturable core reactor*. A coil is wound on a magnetic core that is saturated magnetically. When the core is unsaturated, the variation in inductance is large and the reactance or impedance is large. When the core is saturated, the inductance drops to a very low value, similar to that of a coil with an air core, and the impedance drops accordingly. It is not uncommon for the ratio of the inductance in unsaturated and saturated conditions to reach 10,000 : 1. The effect when saturation occurs is not unlike the effect of discharge of the sparks in a rotary gap. With no moving parts and no delicate

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components, the saturable core reactor is rugged and dependable; on the other hand, its efficiency is low and the pulses are of poor shape.

6.17. Modulator with rotary spark gap switch

In Figure 6 : 12 is shown a complete modulator employing the rotary type switch. The pulse-forming network, N, is charged through the rectifying tube, V, and the large smoothing inductance, H. A voltage doubler with two rectifying tubes, V_2 and V_3, supplied by a high

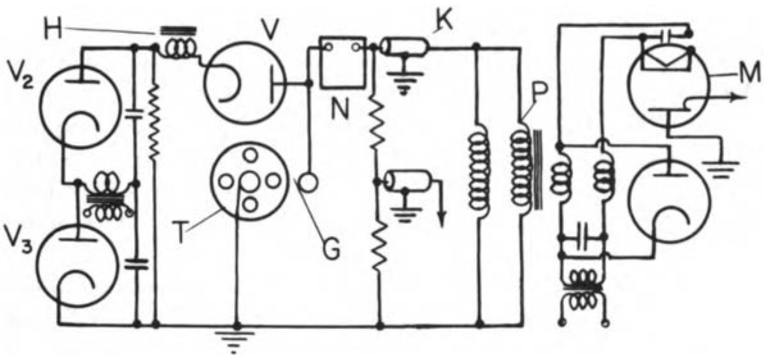

FIG. 6 : 12. DIAGRAM OF MODULATOR EMPLOYING ROTARY SPARK GAP

voltage transformer, produces several thousand volts, sufficient in amount and steadiness to charge the pulse network in the interval of time between spark discharges (say 1000 microseconds or 1/1000 second). This charging time will vary with the inductance of the smoothing coil and the capacitance of the network (the time constant of the combination). At 1000 microseconds, the repetition frequency of the pulses cannot exceed 1,000,000/1000 or 1000 per second.

Upon discharge, the pulse from the network—commonly one microsecond in duration—is applied by means of the coaxial cable, K, to the pulse transformer, P, where it is stepped up several times to the operating voltage of the magnetron (usually from 15,000 to 30,000 volts).

6.18. Pulse transformer

For practical reasons, it may be necessary that the indicator of a radar be located at a considerable distance from the radar receiver and the video amplifier. This would make it necessary to transmit the amplified video pulses to the indicator by means of a coaxial cable, making some form of step-up desirable to compensate for losses in

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transmission. Here is where a pulse transformer could serve most effectively.

To transmit a pulse, especially a narrow one, requires the ability to pass a wide band (4.13). A transformer adapted to this purpose should have small leakage, extremely low core losses, few turns, and the highest possible permeability in its core. The width of the band passed by a transformer depends upon the ratio of the mutual flux, which cuts both primary and secondary coils, to the leakage flux. As the material of the transformer core becomes more permeable, the leakage flux decreases and the bandwidth increases.

An alloy known as Supermalloy, composed of nickel, iron, and molybdenum, has a permeability five hundred times as great as that of ordinary iron. Use of this material for cores has substantially decreased the leakage of pulse transformers. In gun-director radar, where the utmost precision is required, pulse transformers have been designed which can pass a bandwidth considerably in excess of six megacycles.

By means of a pulse transformer, the voltage for the magnetron can be suitably stepped up after leaving the pulse network, thus relieving the pulse network from the burden of high voltages and the difficulty of appropriate insulation. Another function of a pulse transformer is as a matching device, for it matches the low resistance network to the high resistance of the magnetron.

Observe that the secondary of the pulse transformer in Figure 6 : 12 has two secondary coils. The same voltage is induced in both coils, and as both coils are connected to the filament of the magnetron, the resulting voltage across the filament is zero (for the same voltage with the same polarity is applied to the filament terminals). As each coil is also connected to the low-voltage filament transformer, a low voltage from this source is applied to the filament. This arrangement permits a high voltage to be applied across the cathode and plate of the magnetron and a low voltage across the filament.

If the secondary of the pulse transformer had only one coil, insulation against very high voltage would be required between the coils of the filament transformer.

6.19. Modulator with saturable core reactor switch

In Figure 6 : 13, is shown a modulator employing a saturable core reactor. We will assume a moment during which tube 1 is not conducting, and condensers C_1 and C_2 are fully charged. Now, 1 is made conducting

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by applying a positive voltage (gate pulse) to its control grid. The current from the plate that then flows through 1 comes from several branches: thus, one arm includes the inductance, L, leading to the plate supply source; another branch of the supply current is through the saturable core reactor, L_2, and L_3, which also leads to the plate supply. Meanwhile, C_1 is also discharging its current through L_2. So

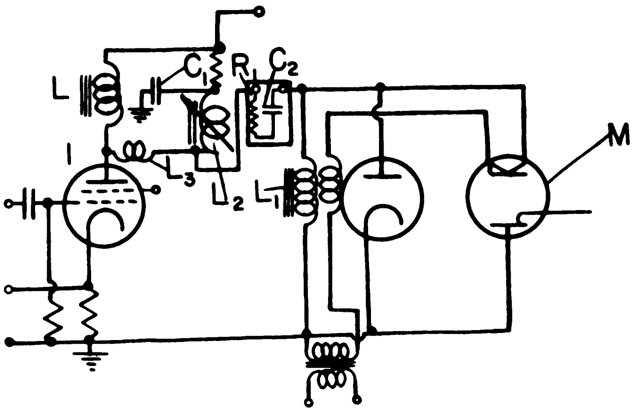

FIG. 6 : 13. DIAGRAM OF MODULATOR EMPLOYING SATURABLE CORE-REACTOR

long as the current through this part is small, the reactance will remain very high (core unsaturated) and it will supply but a small current to tube 1. In addition to the foregoing, condenser C_1, part of the pulse-forming network, is also discharging through the plate circuit of tube 1. The latter current dies out quickly because C_2 is smaller and holds but little charge. Notice that the latter condenser, C_2, also discharges through the magnetron. To prevent this slight pulse from causing the magnetron to radiate, the inductance L_3 is inserted to further choke out, or cut down, the current.

As the current in L_2 increases, thus causing saturation in the reactor, its inductance—and hence its reactance—falls to a very small value (perhaps 1/10,000 of its former value). Thereupon, the current increases enormously in a huge pulse. This quickly discharges the condenser, C_1, and now only the resistance, R_1, limits the flow of current. During the time that tube 1 is conducting, the current through inductance L is accumulating. When the current through the tube reaches

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a predetermined value—say, one ampere—the drop across the resistance R_1 becomes sufficiently large to trigger the multivibrator (see **6.10**) that supplies the gate control pulses to tube 1.

As tube 1 cuts off, the current through the inductance, L_2 (whose inertia is large), continues into the only available path, that is the pulse-forming network where C_2 becomes charged to a very high voltage which is many times the voltage of the plate. This is caused by the inductive kick, or impulse, of coil L. As we noted before, C_2 is very small so it charges in a few microseconds. When tube 1 cuts off, the current through the saturable core reactor tapers off rapidly and enters the unsaturated region where the inductance is multiplied manifold, creating the effect of a practical open-circuit. The value of the inductance, L, is such that the current through L reaches its maximum saturation value at the same moment that the voltage across the pulse network also reaches its maximum. At that time, the saturable core reactor is a practical short-circuit and the network discharges through a path which includes C_2 and the magnetron in series.

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Chapter 7

INDICATORS AND CATHODE RAY TUBES

7.1. Types of indicators

How is the output of a video amplifier observed? What do we wish to learn? In a search radar, we seek to determine the position of a possibly hostile craft; that is, we must ascertain the exact direction along which it lies and its distance. No method of detection is superior to the presentation of the information sought on the screen of a cathode ray oscilloscope.

A radar indicator is the cathode ray tube and its associated circuit which produces the display on the screen of the cathode ray tube. Indicators are designated by letters to describe the character of the data displayed by the cathode ray tube. In the A type of indicator, a beam sweeps across the diameter of the screen of the tube, producing a luminous line. When the echo from an object returns to the receiver, a small vertical luminous arrowhead, called a "pip", is produced on the tube screen. The distance of the pip from a point of reference on the screen is a measure of the distance from the radar to the object detected.

In the position plan indicator (PPI), the beam of the cathode ray sweeps radially from the center across the face of the screen. As the antenna rotates, the radial luminous path on the face of the screen rotates also in synchronism. The presence of an echo causes the luminosity of the screen to intensify. The distance from the center of the face of the screen to the brightened spot is a measure of the distance to the reflecting object. Its direction with respect to the radar receiver is indicated by the displacement of the position of the radial line from a zero line of reference.

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There are more than a dozen types of screen presentations; the A and the PPI types are among the most common. The sweep of the type J, for instance, is identical with that of the type A, but instead of describing a line along a diameter of the screen, the sweep marks out a circle, as shown in Figure 7 : 1 (*a*).

The display with type A gives range only, i.e., it shows the distance of the target from the radar; the PPI furnishes range and bearing, i.e., distance and direction on the horizon. Off the earth's surface, in free space, we require three separate dimensions (coordinates) to locate an object; its range, its bearing, and its altitude (height above the earth).

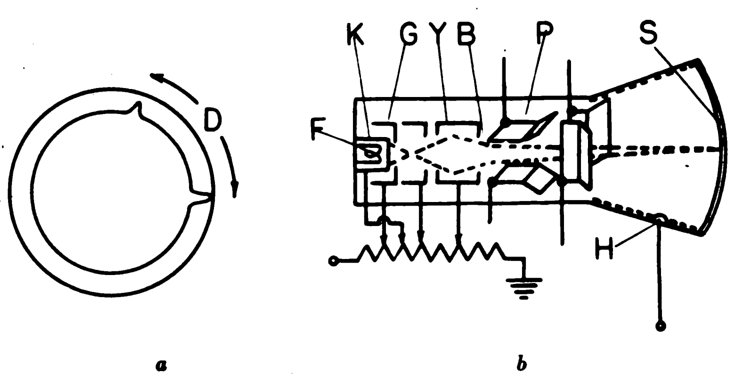

FIG. 7 : 1. DETAILS OF CATHODE RAY TUBES
(*a*) Screen of Type J tube: D, distance between pips, measured circumferentially
(*b*) Components of cathode ray tube: F, filament; K, cathode; G, control grid; Y anode cylinder; B, beam; P, deflecting plates; H, high voltage; anode; S, screen

In the type A, which is commonly used to locate an object on the surface of the earth, we need to know both the range and angular bearing. The latter information is obtained from the directional property of the antenna.

In addition to the types of indicators mentioned, there are, among others, the following:

B: this gives range and azimuth and employs rectangular coordinates; GPI gives ground range and bearing and employs polar coordinates; C gives elevation and azimuth and employs rectangular coordinates; D gives azimuth and elevation and employs rectangular coordinates; E gives range and elevation and employs rectangular

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coordinates; H gives azimuth and range and employs rectangular coordinates; K gives range and signal intensity and employs rectangular coordinates and lobe switch antennas; pips appear in couples and when of equal size, the antenna is directed toward target. L is like K but signals from lobes placed back to back; M is like A, but contains a range step and by aligning the pip with the notch or step enables us to read the range directly; N is a combination of K and M.

A and J are used mostly in fire control radar. B is operated for narrow sector rapid scan fire control systems. For low altitudes, PPI suffices; for high altitudes, too much distortion is introduced with PPI, and GPI (ground plan indicator) becomes a necessity, especially for high altitude bombing; Type C is used for aircraft interception.

In gun-directing radar,[1] such as that of anti-aircraft, we must know three sets of coordinates: range, elevation (angular relation to the horizon) and azimuth (bearing—angular relation to reference line). As an indicator will show only two dimensions, it is a common practice to employ two different types of indicators, thus ensuring all the required information.

By the use of the PPI display which yields information over a sweep of 360°—the entire horizon—an actual map of the region appears on the indicator screen. Where the radar is located either on or close to the earth's surface there is little distortion, and the map is substantially true in its proportions. On the other hand, if the radar is mounted on an airplane flying at a great height, the map is distorted on the ordinary PPI screen. Such distortion becomes extremely serious in radar employed for high-altitude bombing, where it might disastrously affect the precision of the bombing. Accordingly, a correction factor is employed in the sweep (7.7) which is non-linear, the departure from linearity being based on information supplied by the plane's altimeter. An indicator employing this type of screen presentation is known as a GPI (ground plan indicator).[2]

[1] In one type of automatic tracking radar, a gun will follow its target with an angular error not exceeding 0.05° (3 minutes). The angular data are fed into a computer which, in turn, directs either a gun or a searchlight. After the target is brought within range of the radar, it is possible for the other data such as range, elevation, and azimuth to be automatically supplied to the computer. The gun will then aim at, follow, and shoot at the target without the intervention of a human operator.

[2] Not all range-sweep wave forms are linear. In one form, the sweep is hyperbolic instead of linear. The initial part of the sweep is delayed in proportion to the time required for the pulse to travel from the airplane to the ground and return. This type of sweep corrects the distortion in a PPI display caused by the curvature of the earth at great heights; it is the sweep that is used in the GPI display.

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7.2. *Cathode ray tube: parts and accessories*

The cathode ray tube as employed in radar consists of a highly evacuated glass tube, which contains a "gun" for producing a cathode ray beam; a means of focusing it; an arrangement to deflect the beam; and a screen on which it impinges and produces visual indications. The beam may be focused by magnetic fields or by electrostatic fields; similarly, the beam may be deflected by electric or by magnetic fields.

7.3. *Comparison of types of deflection*

Each type of cathode ray tube has special advantages and characteristic drawbacks. The magnetic tube, for example, is shorter, more sturdy, and gives a spot of higher intensity. It is especially suitable for the PPI indicator, because the brighter spot persists longer on the screen after the beam has swept onward. On the other hand, the focusing and deflecting coils are heavy and add to the total weight. Hence, where weight must be kept down to the minimum, electrostatic tubes are preferred; furthermore, the sweep circuits of electrostatic tubes are simpler.

The electrostatic type requires a lighter tube and lighter accessory equipment. In airborne equipment, these may be determining factors. On the other hand, as a partial offset, electrostatic tubes are longer than magnetic ones. Because magnetic tubes are stubbier (shorter), where space is at a premium, this may be important. They give much brighter images, because of the higher voltages that can be employed. Increasing the voltages of electrostatic tubes results in a decreased sensitivity. The magnetic tube, however, requires heavy focusing and deflecting coils, and substantial power to operate them.

7.4. *Operation of electrostatic cathode ray tube*

In Figure 7 : 1 (*b*) is shown an electrostatic cathode ray tube. To produce the electron beam, the tube requires a "gun". A filament heats a coated cathode cylinder, which emits a rich supply of electrons. These are grouped and focused into beams by passing through cylinders that are colinear. By successively raising the voltages of the cylinders through which the beam passes, the speed of the electrons is increased; by placing a negative voltage on the grid, the electrons are slowed up and the velocity of the beam is decreased. The focusing action is brought about by varying the voltage relations between the cylinders. The path and shape of the beam is shown by the heavy dotted line. Observe that the beam passes through the two pairs of deflecting plates. It is correctly focused when it strikes the screen in a small intensely luminous spot about a millimeter in diameter.

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Remembering that an electron consists of a pure negative charge, we can see that negative charges will repel it and positive charges will attract it. When a beam of electrons passes through a charged hollow cylinder, it will contract if the cylinder is negatively charged and expand if positively charged.

The deflection of the beam by the deflecting plates is based on the same principle of attraction and repulsion of charges. Suppose, at one moment, the upper plate is positive and the lower plate is negative; then the electron beam (which is negative) will move upward. If, at the same time, the nearer plate (the horizontal deflecting plate) is positive, the beam will also move toward the reader. If an alternating or oscillating voltage is impressed on only one pair of plates, the beam will move back and forth in a straight line, appearing as a luminous streak on the screen. The greater the voltage on the plates, the farther the beam is deflected.

The brightness or intensity of the focal spot on the screen will depend upon the energy of the electrons in the beam. The energy of the electrons (which have mass) will depend upon their speed; this, in turn, varies with the accelerating voltage. The smaller the focal spot, the brighter it will be, for the energy of the beam is then concentrated upon a smaller surface (on the screen).

As the speed of the electrons in the beam is increased, it becomes more and more difficult to deflect them.[3] Thus, the sensitivity of the beam (ease of deflection) is decreased by the increase in intensity. To overcome this defect, the tubes in radar have a high-voltage anode placed between the deflecting plates and the screen. Thus, the speed of the electrons in the beam is increased *after* they have been deflected. The purpose of the high-voltage anode is to obtain additional brightness without loss of sensitivity. To prevent defocusing the beam by deflection, it is necessary to keep the average voltage of the deflecting plates close to that of the second anode. Another defect, known as *astigmatism* (like the optical form),[4] prevents the simultaneous focusing of the spot in both vertical and horizontal directions on the screen.

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[3] As the speed of the beam of a cathode ray tube is increased, its energy is directly increased. In a beam composed of particles whose energy will be determined by their speed, the degree of energy required to deflect or cause a particle to move from its directed path is proportional to the degree of energy contained in the beam.

[4] One method of removing astigmatism is to apply a voltage between the second anode and one pair of deflection plates, so that the beam is focused at the same spot in each plane. Then, by adjusting the main focal control, it is possible to bring the point of convergence back to the screen.

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This is caused by the fact that the electric fields of both sets of plates do not act on the identical point in the tube.

The brightness of the focal spot is usually manipulated by changing the voltage on the control grid. By increasing the negative voltage on the grid, the electrons in the beam passing through the grid are decreased in number and the spot dims; vice versa, by increasing the positive voltage of the grid, the electrons are increased in number and the spot brightens.

7.5. Cathode ray tube screens

The screen of a cathode ray tube consists of a glass surface coated with substances in a finely divided state. The coating material is known as a *phosphor* and has characteristics related to its chemical composition. The two qualities that concern us are color and persistence. For medium persistence (suitable for type A indicators), willemite (zinc orthosilicate) is commonly used. The color of the light emitted under the impact of an electron beam is a yellow-green; its persistence runs to some thousandths of a second. This material is employed by itself where the scan is rapid. Its rate of decay (how fast the light diminishes) is such that its intensity has decreased to 1/100 in 1/20 of a second.

Where long and slow sweeps are required, as in PPI indicators, the persistence should extend over a good part of a minute—at least several seconds. Such screens are *cascaded*, that is, they are built up of two layers: the inner layer (nearer to the gun) is a fast sensitive chemical; the outer layer is a phosphor excited by the first layer, and of long persistence. In radar oscilloscope tubes, the fast layer is zinc sulfide, activated[5] by silver; the persistent and slow layer is zinc cadmium sulfide, activated by copper. The zinc sulfide emits a very bright blue-white light; the zinc cadmium sulfide layer emits pale yellow light.

Even though the brilliance of the blue layer is screened by the yellow, it is customary to interpose an amber plastic transparent screen between the observer and the screen of the cathode ray tube. Aside from its long persistence, the slow-acting screen has a cumulative quality, so that successive sweeps, if not too slow, serve to increase the brightness of the echo from the target, in contrast to the surrounding background light or "grass". This corresponds to the background

[5] Without the activator or "doping" metal in the phosphor, the screen material would not phosphoresce at all; it is the presence of these adulterants in the screen material that makes it effective or responsive to the impact of the electron beam.

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noise—"clutter" or "static" in a radio,—and the visual signal or echo must exceed this to stand out against the background. It becomes obvious that the fainter is the "noise" or "grass", the fainter are the signals that can be detected.

Electrostatic tubes employ tubes of medium persistence. To obtain long persistence with a given screen, the energy of the beam should be high, that is, the accelerating voltage should also be high. As the electron beam hits the screen, it gives up some of its charge, making the glass and the screen negative. Were this to continue, the accumulation of negative charge would soon become so strong as to repel the incoming beam. Also, because of the impact of the electrons, other secondary electrons are liberated by the screen. The velocity of the secondary electrons is variable. Those that do not exceed the minimum fall back into the screen; those of greater velocity reach the second anode or the Aquadag[6] coating and so make their way back to the power supply. When equilibrium is reached, the number of electrons returning to the power supply is equal to the number of electrons that reach the screen in the beam.

7.6. Details and operation of magnetic cathode ray tube

Thus far, we have discussed the electrostatically focused and deflected tube almost exclusively. Let us examine in detail a cathode ray tube that is focused and deflected magnetically. Figure 7 : 2 (*a*) is a sketch of such a controlled tube. The emission of electrons is the same in both kinds of tubes; that is, the gun structures are alike. The presence of the first grid performs the same function in both tubes; thereafter, the magnetic tube differs from the electrostatic tube. Coil C is a circular compact coil surrounded by a fairly heavy magnetic shield, open at one end of its inner circumference. This is where the magnetic field leaks out and exercises its functions of control.

Coil L is really made up of two coils whose magnetic axes are at right angles to each other; both magnetic axes lie in a plane perpendicular to the page. Focusing is accomplished by coil C. As the current through it is increased, the magnetic field external to it increases in intensity. The effect of such an increase is to cause the electrons in the beam to move toward the center of the axis of the tube (in the type A indicator). As an electron is an elementary charge of electricity, a beam

[6] Aquadag is a suspension of finely divided graphite in water, employed as a lubricant and for coating non-conducting surfaces with a conducting coat.

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of electrons (electrons in motion) is a current. As we know from our study of elementary electricity, the effect of a magnetic field upon a wire carrying a current is to cause the latter to move at right angles to the magnetic lines of force. This is what occurs in the ordinary electric motor. In the cathode ray tube, the beam of electrons resembles a wire-carrying current, with the enormous advantage that the beam has practically no mass or inertia. As a result, it responds instantaneously (for our purposes) to a thrust or force.

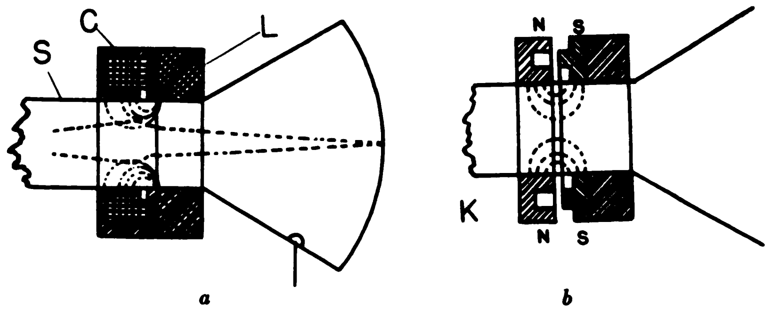

FIG. 7 : 2. DETAILS OF MAGNETIC CONTROLLED CATHODE RAY TUBES
(*a*) Focusing (C) and deflecting (L) coils; S, glass envelope
(*b*) Permanent magnet for focusing beam: K, magnetic field

Only at the center of the tube, along its axis—which should coincide with the axis of the focusing coil—will the electron beam moving parallel to the magnetic field be unaffected. Thus, the effect of the focusing coil is to cause all electrons in the beam not parallel to the axis to move toward the axis. If the current through the focusing coil is suitably adjusted, the electrons in the beam can be brought to a focus, or meeting point, exactly on the screen surface.

Not only is the focusing coil heavy but its current requirements make a supply of current necessary. All this means additional weight and additional requirements of space. Where space and weight are at a premium, as in a small airplane, it is most desirable to curtail both if possible. With this in view, permanent magnets, circular in section, can be employed. Figure 7 : 2 (*b*) shows such a focusing magnet. As the parts are brought together, the external field decreases or shrinks; as they separate, the external field expands. Thus, by the movement of the component parts, focusing is accomplished.

The beam is deflected by two or four focusing coils placed within a

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single shield. When the deflection is along one axis only, two coils are employed. This is adapted for the PPI indicator where the beam travels from the center of the screen to the circumference. Examining Figure 7 : 3 (*a*), we note that the magnetic fields of the two coils oppose each other through the yoke but aid each other across the gap through which the neck of the cathode ray tube passes. If one employs the "left-hand motor rule" of elementary electricity, the direction of deflection of the beam will prove to be toward the right (represented by the thumb).[7]

For those cathode ray tubes where the deflections occur along two axes, mutually at right angles, as in the type A indicators, four coils are employed, as shown in Figure 7 : 3 (*b*). Here, windings A and B produce fluxes through the yoke, opposed to each other, but aiding through the open space. These coils will move the electron beam horizontally, either to the right or to the left. Coil windings C and D also produce opposing fluxes through the yoke, but the resulting flux through the air gap will deflect the beam up or down. Thus, by the simultaneous use of two pairs of coils, deflections in directions perpendicular to each other may be obtained.

7.7. *Sweep circuit and amplifier*

The problem that confronts us is how to reproduce accurately the electromagnetic pulse known as the "echo" upon the face of the screen of the cathode ray tube, and at the same time to orientate it so that its distance from a known point of reference will also indicate its distance from the object emitting the echo.

We have seen that the beam of a cathode ray tube may be deflected simultaneously in mutually perpendicular directions. Suppose we apply an alternating voltage to one pair of deflecting plates of a cathode ray tube whose focused beam is centered on the screen. The alternating voltage will sweep the beam back and forth on the surface of the screen. Because of optical persistence, a luminous line will appear across the face of the screen, as shown in Figure 7 : 3 (*c*). This will tell us nothing about the wave of alternating voltage (its shape or frequency), save the extent of its swing or range. This voltage, A, will produce line A; voltage B will produce line B.

[7] Extend the thumb, index, and middle finger of the left hand at right angles to one another, and point the index finger directly downward to represent the direction of the magnetic field, as in the figure. The middle finger, representing the electron beam or current, will then be toward the reader; and the deflection of the beam, represented by the thumb, will be toward the right.

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If, at the same time the line is swept out, we impress the voltage of a sawtooth wave (Figure 6 : 6 (*a*)) on the other pair of deflecting plates, then the cathode ray beam will describe a luminous path that accurately mirrors the shape of the alternating current voltage. In an electrostatic cathode ray tube employed in radar, a sawtooth (range

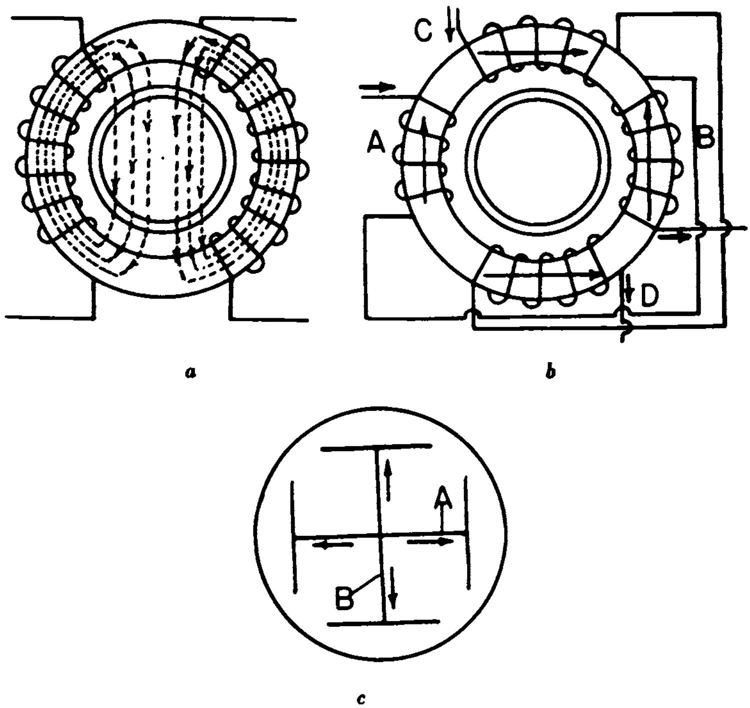

FIG. 7 : 3. DEFLECTING MAGNETIC FIELDS
(*a*) Two coils, producing deflection along one axis
(*b*) Four coils, producing deflections along two perpendicular axes: A,B, horizontally; C,D, vertically
(*c*) Luminous lines on screen of cathode ray tube, produced by deflecting coil operating in opposite pairs

sweep) voltage would be applied to the horizontal deflecting plates, and the output of the video amplifier would be applied to the vertical deflecting plates. The pulse from the radar transmitter would produce a pip at the beginning of the sweep and the echo would produce a pip somewhere along the horizontal line (in the type A indicator). If the sweep or sawtooth were a perfectly straight line in relation to time, the

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interval between the reference pip (transmitter pulse) and the echo pip would accurately gauge the range of the target generating the echo.

In order that the return path of the beam from the cathode ray tube (corresponding to PP′ in Figure 6 : 6 (*a*)) shall not appear visible on the screen, a blanking pulse (6.9) can be applied to the grid of the cathode ray tube during this period, thus increasing the negative voltage to a point beyond cut-off. When the sweep recommences, the blanking pulse is removed.

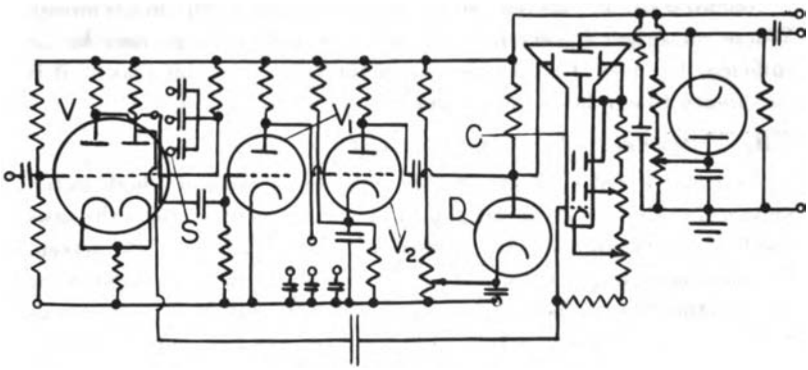

FIG. 7 : 4. SCHEMATIC ARRANGEMENT OF INDICATOR FOR PRODUCING A DISPLAYS

Figure 7 : 4 shows a schematic arrangement of the wiring of an indicator employed in type A displays. Tube V, a double triode in a single glass envelope, plus its associated wiring, is a multivibrator (6.10). At the same time that the transmitter sends out its pulse, a positive trigger pulse is applied to the grid of the multivibrator. The latter thereupon produces a negative *rate pulse* (rectangular wave) whose duration will depend upon the range of the target. The length of this negative pulse is controlled by the range switch, S, which varies the time constant of the RC circuit in the plate output. Tube V in Figure 7 : 4 produces the sawtooth voltage only when a highly negative pulse is applied to the grid of V, for the current through the tube is thus cut off. When the tube, V, is cut off, the plate voltage rises in a sawtooth whose rate of increase is controlled by the time constant, RC.

The range switch, S, permits different capacities to be selected for this purpose. The positive-sweep sawtooth is fed to the grid of the amplifier tube V, whose output is amplified and reversed. It is then

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applied to the horizontal deflector of the cathode ray tube. Observe also that a positive gate pulse is also applied at the same time to the control grid of the cathode ray tube, serving as an intensifier which brightens the beam of the cathode ray tube. The video amplifier output from the receiver is applied to the vertical deflector plates of the cathode ray tube. By applying D.C. voltages (through taps on the potentiometer) to the deflecting plates, the position of the pattern can be shifted up or down, right or left.

We have noted (6.6) that by employing only a small portion of the exponential rise in voltage, we could obtain a practically linear sweep. Where the target is very distant, however, such a sweep may be insufficient to cover the entire screen of the tube. For this reason, it is customary to employ a sweep amplifier as we have done.

7.8. Necessity for an amplifier

We could avoid such an amplifier by the use of very high sweep voltages, so that even the initial part of the exponential rise of the sawtooth would be sufficient to sweep across the full length of the screen. This would mean the use of very high voltages in the sweep generator (several thousand volts). If the initial part of the curve of the exponential voltage is substantially straight for, say, five per cent of its total length (see Figure 6 : 6 (*a*), P-P) and the diameter of the cathode ray tube across its screen is five inches, a voltage of 250 would be required to cover the entire screen. This assumes that fifty volts on the screen produces a deflection of one inch which is a fair estimate. If 250 volts is 5 per cent of the total curve of exponential voltage, we should have to employ 250 × 20 or 5000 volts. Such a high voltage for the plate supply would require very heavy insulation, which is bulky and expensive. On the other hand, if the amplifier multiplies by only ten, the voltage produced in the sweep condenser is 250/10 or 25 volts.

7.9. D.C. restorer

An examination of the video amplifier (see Figure 5 : 10) will reveal that the D.C. component[8] has been blocked by the coupling condenser, C. Upon feeding the output of the video amplifier into a type A indicator, the location of the base line when the signal strength is zero will depend upon the form of the video signal. Accordingly, we should insert the D.C. component once more into the signal before it appears on the screen. This is accomplished by means of a D.C. restorer, also

[8] For details, see Appendix.

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known as a "clamping" circuit, because it clamps or fastens the pulses to a given reference line, the zero line.[9]

If the D.C. component were omitted, the average signal would be zero as the positive and negative swings are equal. Impressing such signals on a PPI indicator, the average brightness would be unaffected. With the D.C. component reinserted by the restorer, the signal swings can be wholly positive.

A simple two-element tube (Figure 7 : 5), a diode, will perform this function. When the signal is negative, the diode will conduct and the flow of current through it will rapidly charge the condenser up to the maximum negative voltage. When the signal becomes positive, the

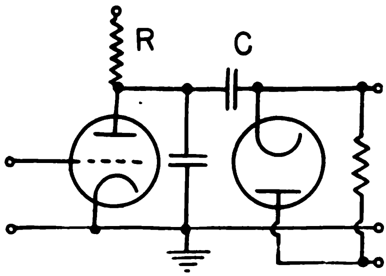

FIG. 7 : 5. SCHEMATIC ARRANGEMENT OF CONNECTIONS OF D.C. RESTORER USING DIODE

triode will conduct. The negative charge on the condenser in series with the positive flow will offset part of this but the resultant will be entirely positive. R and C are chosen so that the time constant (their product) is great in comparison with the rate of repetition. In consequence, the offset effect will persist throughout the remainder of the signal period. When the diode is passing current its resistance is extremely low, which makes the time constant very small. For this reason, a very slight negative pulse will be adequate to return the grid to zero.

7.10. Use of permanent magnets in indicators

By the use of a short cylindrical magnet, made of Alnico V, roughly an inch long and an inch in radius, but magnetized as a short bar, it is

[9] A clamping circuit is really an electronic switch. It differs from a mechanical switch in its very great speed of operation. It usually conducts in one direction only; the impedance of the switch is never zero. In the vacuum diode, the tube conducts while the plate or anode is positive and cuts off with extreme rapidity when the anode becomes negative.

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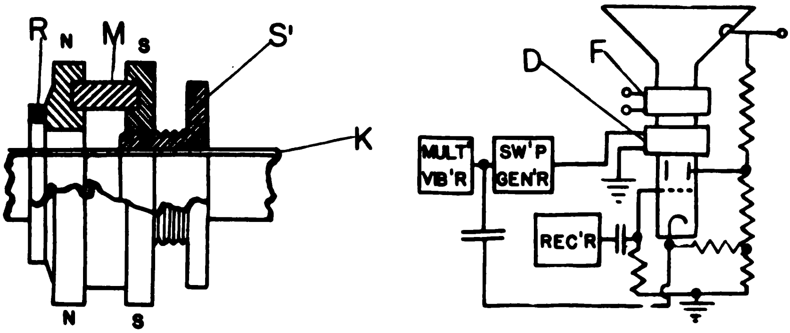
possible to center and focus the electron beam, and dispense with coils for this purpose. By employing a magnetic shunt, as shown in Figure 7 : 6 (*a*), the intensity of the magnetic field can be varied. Also, by means of a ring which can be shifted eccentrically, it is possible to distort or bias the magnetic field and center the electron beam.

Among the outstanding advantages of the permanent magnet assembly are stability despite changes in temperature, and minimum weight, because no auxiliary equipment is required to supply current.



a *b*

FIG. 7 : 6. PERMANENT MAGNET FOCUSING ARRANGEMENTS
(*a*) Sectional view (partial) of R, centering ring; N,S, pole pieces; M, magnet; S′, shunt; K, cathode ray tube
(*b*) Block diagram of connections of magnetically controlled indicator: F, focusing, D, deflection coil

7.11. Producing sweeps for magnetically controlled indicators

Thus far we have been discussing the electrostatic type of cathode ray tube, in which the deflections are proportional to the applied voltages. In the magnetic types the deflections are produced by magnetic fields which, in turn, are set up by currents. So, instead of sawtooth voltages, we must generate sawtooth currents.[10] In Figure 7 : 6 (*b*), we show a magnetically controlled indicator in block form. Observe that the receiver output is applied to control the grid of the tube. In other words, this is an intensity-controlled cathode ray tube in which the echo produces a variation in brightness of the beam. In the intervals between sweeps, the tube is cut off by a blanking pulse (high negative pulse); during the sweep a sawtooth current is sent through the deflection coils.

[10] For details, see Appendix.

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In the PPI indicator, the deflection coil causes the beam to move radially from the center of the screen to its circumference. The radial beam is itself caused to rotate like the spoke of a wheel at the same rate as that of the antenna in scanning the horizon (sweeps in azimuth). Either of two methods may be employed to rotate the beam of the cathode ray tube. The deflection coil may be rotated mechanically through motors and gearing; the deflection winding may consist of two sets of coils in quadrature which set up a rotating magnetic field, as in a two-phase induction motor.

When a given voltage is applied to a coil, the current through it rises or builds up exponentially, as shown in Figure 7 : 7. The speed with which the current builds up will depend on the time constant, which is the ratio of the inductance (L) to the resistance (R) in the circuit, or L/R. If we consider a short interval of time, T, the rise in current may be practically a straight line. If the range or distance from a target is short, this may be sufficient for sweep purposes. If the range is great, then some means must be found to amplify or extend the sweep through the deflecting coils.

Figure 7 : 8 shows a sweep circuit employing an exponential rise. A positive rectangular voltage pulse or gate is applied to the grid of tube T. This causes T to conduct and the current through it to rise exponentially. This exponential current through the coil will cause a similar magnetic deflecting field. How fast the current will increase (rate of rise or slope) will depend upon the applied plate voltage and the time constant in the circuit, that is, the total inductance and resistance in the circuit. The total inductance is the sum of the inductances of both coils; the total resistance will include the resistances of both coils, plus the resistance of tube T. By shorting out the coil (L_2) by means of the switch, the inductance, and hence the time constant can be decreased; hence, the speed of the sweep can be correspondingly increased. In order to terminate the sweep, the tube T is rendered non-conducting by ending the gate pulse applied to the grid. The voltage of the latter then falls below cut-off and the current in the sweep circuit falls swiftly to zero.

Every coil has its own distributed capacity caused by the capacity between its turns and layers. If the current through a coil is suddenly interrupted, oscillations are set up in the coil, of which the period is determined by its inherent capacity and inductance, and the duration, by its resistance. These unwanted oscillations are suppressed by means of the tube T (a diode) and the resistance R in series with it. The

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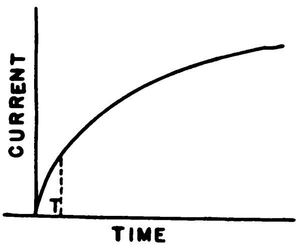
resistance serves to dampen the oscillations; the diode permits current to flow only when the plate (anode) is positive. During the sweep, the diode blocks the current through the resistor, effectively disconnecting it.

The foregoing explanation and description of the generation of a saw-tooth current is applicable to the so-called type A indicator in which a pair of coils is applied to the neck of the cathode ray tube to produce



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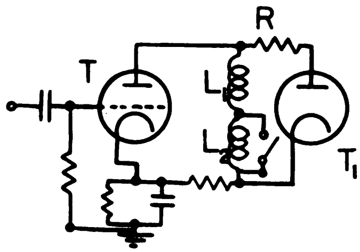

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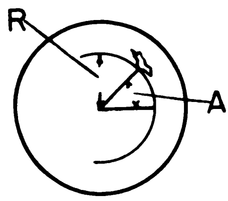

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FIG. 7 : 7. CURVE SHOWING EXPONENTIAL RISE OF CURRENT IN A COIL
FIG. 7 : 8. CONNECTIONS FOR PRODUCING CURRENT IN SWEEP CIRCUIT
FIG. 7 : 9. SCREEN OF CATHODE RAY TUBE, SHOWING HOW RANGE (R) AND ANGULAR DISPLACEMENT (A) ARE MEASURED

the required sweeps. (We mentioned in 7.1 the PPI, in which the sweep is radial from the center of the tube to the circumference.) The range of a target is given by the distance of a bright spot (caused by the video output of the receiver applied to the control grid), marking the echo, from the center of the tube. The bearing (angle) the target makes with the radar is measured by the rotation of the sweep about the center. Figure 7 : 9 shows the face of the cathode ray tube screen and the range

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and angle (azimuth). The rotation of the sweep is locked in step (synchronized) with the rotation of the antenna.[11]

As the antenna rotates about the horizon, the beam emitted by it must also rotate, and the sweep path on the screen marks the path of the beam. Common speeds for the rotation of an antenna are one to sixty revolutions a minute (1–60 RPM).

In Figure 7 : 10 (*a*), A shows a pair of magnets spanning the neck of the cathode ray tube. If the magnetic field produced by the magnets is

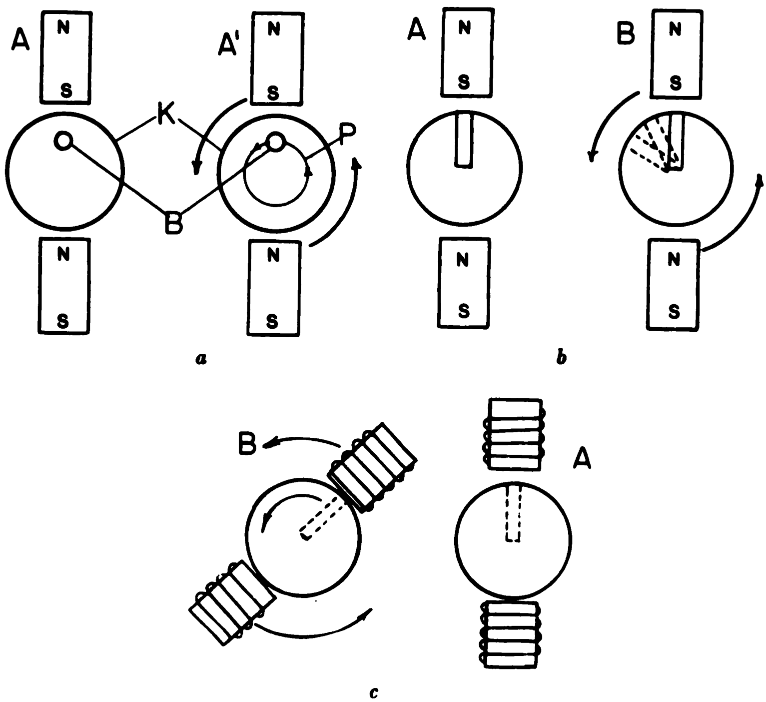

FIG. 7 : 10. EFFECTS OF CHANGES ON SPOTS
(*a*) Deflection of beam spot by permanent magnets: B, beam spot; P, path of spot; K, screen
(*b*) Change of magnetic intensity on beam spot (A); rotation of magnets (B) while intensity changes
(*c*) Change of coil current on screen spot (A); rotation of coils (B) while current changes

[11] In the intensity-controlled tube, such as a PPI, the beam is on continuously. The effect of the signal that is applied to the grid of the cathode ray tube is to increase or diminish the intensity of the beam and this causes the light on the screen to brighten or diminish.

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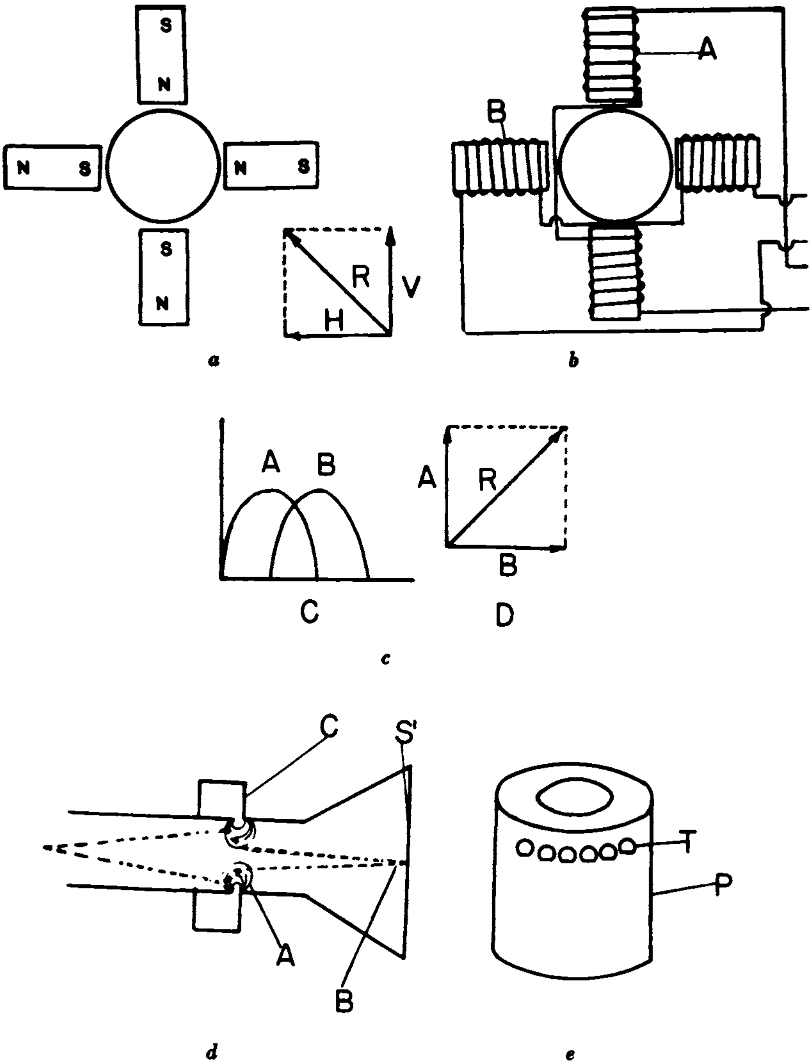

Fig. 7 : 11. Comparable Effects Produced by Magnets and Coils
(*a*) V, vertical, H, horizontal, R, resultant magnetic component
(*b*) Sets of coils that perform same function as magnets in (*a*)
(*c*) Curves Showing Displacements of Sine Current 90° apart (C); instantaneous values at a given moment and resultant (D)
(*d*) Movement of magnetic field (A): issues from annular opening of coil (C), shapes beam (B), and comes to point at S′
(*e*) Plastic container housing deflecting coils: T, terminals; P, plastic case

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sufficiently strong, the beam will be deflected off center, i.e., off its normal neutral position. Now, with all else left unchanged, we cause the pair of permanent magnets to rotate about the neck of the tube, as shown in A′. The spot on the screen will travel in a circle. Let us suppose the strength of the magnets could be made to fluctuate from zero to the maximum and back to zero (but never reversing) while the magnets remain stationary. The spot on the screen will produce a linear sweep as in A of Figure 7 : 10 (*b*). Once more cause the now fluctuating magnets to rotate. The radial beam on the screen will rotate as in B. This is exactly what happens on the screen of a PPI indicator.

Using a pair of coils in a single envelope to produce the deflection by means of a sawtooth current as in A of Figure 7 : 10 (*c*), the sweep will move in the direction indicated by the arrow as long as the magnetic field varies in intensity. Let us now turn the coils through an angle of 45°. The sweep will now move in the direction of the arrow, as in B.

By gearing the coil to a motor, the sweep could be made to rotate continuously. If, at the same time, the antenna is also driven by a motor (synchronous), then both antenna and coil would keep in step. Better than the synchronous motor drive is the use of a synchro transmitter and receiver (see Chapter 8).

Another method of producing a rotating sweep for the PPI indicator avoids the use of any mechanical moving parts. Its chief virtue is that the magnetic field rotates but the coils remain stationary.

In Figure 7 : 11 (*a*) are shown two pairs of magnets placed at right angles to each other. The magnetic field produced by the vertical magnets is represented by the vertical arrow; similarly, the horizontal magnets produce a field represented by the horizontal arrow. If the magnets are equal in strength, the resulting magnetic field is represented by the diagonal arrow. Its length, you will note, is equal to the diagonal of the square. From simple geometry, the square of the diagonal of a rectangle is equal to the sum of the squares of the two adjacent sides (Pythagorean theorem); or, the diagonal is the square root of the sum of the squares of the two sides.

In the place of the permanent magnets, let us substitute two sets of coils arranged at right angles to each other, as shown in Figure 7 : 11 (*b*). An ordinary sine wave alternating current is passing through one pair of coils and the magnetic field varies exactly like the current. Through the other pair of coils, a similar current is passing but it differs in phase from its fellow by 90°; that is, the current (and so the

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magnetic field) in one coil is at the maximum when the current in the other is just starting, as in C, of Figure 7 : 11 (*c*). The currents (and the magnetic fields produced by them) are then said to be ***sinusoidal*** and ***cosinusoidal***, which means that the currents through the coils vary as the sine and the cosine, respectively.[12]

At a given moment, the currents and magnetic fields will appear as in D of Figure 7 : 11 (*c*). The resultant current, and hence the resultant magnetic field, will be represented by the diagonal. As the diagonal is equal to the square root of the sum of the squares of the adjacent sides, the intensity of the resultant field is the square root of the sum of sine squared and cosine squared. But from simple trigonometry, the sum of the squares of the sine and the cosine of an angle is one. Thus, the intensity of the resultant field is constant in length (its vector), always remaining equal to one, and it rotates.

Disadvantages of a rotating deflection coil are: the mechanical complexity encountered; the fact that the yoke should be rigidly mounted; and the further requirements that there should be no play in the bearings, or backlash in the gearing.

On the other hand, in the fixed-yoke PPI system, the stationary coils are energized simultaneously. The resultant deflection of the beam is produced by the vector force (sum of the individual forces produced by the currents) in the coils. Variation of the coil currents can be made to rotate the beam 360°.

Although we have a rotating field that is constant, this hardly will function as a linear sweep; not only should the field rotate but it should also produce a sawtooth traveling from the center to the circumference of the screen.

7.12. Electronic markers

When we mention range, it implies that we have some means of measuring quickly the distance of the echo from the zero reference point. An obvious device is a permanently calibrated scale applied to the face of the cathode ray tube and extended across the screen. This may be adequate for many purposes, but for extreme precision, as in gun directors and in bombing, the errors introduced—from parallax for example—are too large.[13] Even though they require auxiliary

[12] For details, see Appendix.

[13] In reading the indications of an ordinary meter, the closer the needle or pointer is to the face of the dial, the more accurately it can be read. The reading will be exact when the needle is viewed perpendicularly to the face of the dial. The greater the departure of the angle from a right angle, the larger is the error. This angular error is

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circuits and add to the existing complexity and maintenance, electronic markers that space off the targets by calibrating pips are the only effective means of measurement.

Figure 7 : 12 presents a scheme for introducing such markers on the screen of the cathode ray tube. A starting pulse from a multivibrator is fed to the grid of 1. When no signal is applied, the bias of the tube is zero and the current through it is therefore large. This produces a

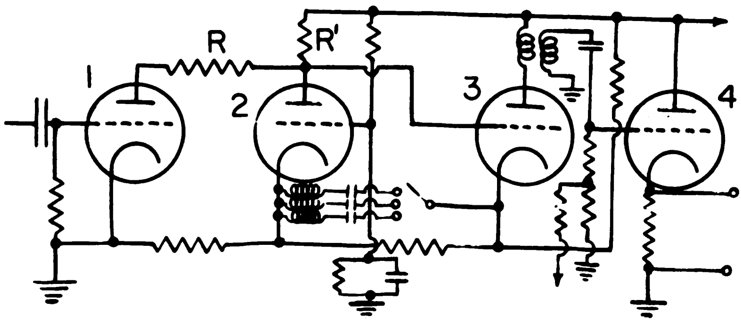

FIG. 7 : 12. DIAGRAM SHOWING MEANS OF PRODUCING ELECTRONIC MARKERS ON SCREEN OF CATHODE RAY TUBE

large drop in voltage in the resistances, R and R′, and a consequent reduction of the voltage to the plate of 2 and the grid of 3. The large positive voltage applied to the cathode of 3, which has the same effect as increasing the negative potential of its grid, keeps 3 cut off, and, consequently, not oscillating. So long as the negative pulse from the multivibrator is applied to the grid of 1 it will remain cut off, and its plate voltage and the grid voltage of 3 will rise, causing 3 to oscillate. The frequency of the oscillations is controlled by the series resonant circuits which supply the feedback to sustain the oscillations. By passing the output of 3 through the air core transformer,[14] the sine waves are converted into peaked waves. By applying these to the highly biased amplifier tube, 4, the negative peaks are cut off and only the positive peaks appear as range markers.

called the *parallax* error. To minimize parallax, the dial is often equipped with a mirror. To avoid parallax error when the meter is being read, the needle and its mirror image should coincide.

[14] One that contains no iron or other magnetic core.

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7.13. Limiting gain

It is a common practice to limit the maximum gain of signals in radar.[15] This prevents paralysis of the amplifier by powerful signals, and minimizes the time of recovery when the amplifier is overloaded. Besides, as the signal applied to a PPI is increased, the increasing brightness sets up "blooming"; defocusing occurs, and the entire screen may be suffused with light. Excessive strength of signal[3] also produces "halos" in cascade screens (7.5), which cause a confusion of images and signals.

The minimum brightness is set by surrounding conditions. What we observe on a screen is contrast. In a perfectly dark room with well-rested eyes, we may observe light that easily evades us in twilight.

To prevent overloading, double amplifiers are sometimes employed, each with a separate outlet; one operates until it reaches its maximum, whereupon the other takes over for signals of greater amplitude.

7.14. Details of coils

In magnetically focused cathode ray tubes, a coil surrounding the neck of the tube sets up a magnetic field. Except for an annular opening through which the magnetic field emerges, as shown in Figure 7 : 11 (*d*), the entire coil is surrounded by a magnetic shield. The electron beam is centered by the addition of a coil whose distorting field shifts the beam.

For the type A indicator, two deflection coils with mutually perpendicular axes are required. These are housed in a single plastic container (Figure 7 : 11 (*e*)). For the PPI, in which the beam is deflected from center to edge, only one coil is employed.

Some deflection coils have air cores; others are wound on Permalloy cores. For fast sweeps (type A, for instance), the inductance must be kept low, and air core coils are employed; for slow sweeps (PPI), the greater inductance produced by the Permalloy core makes the tube more sensitive (7.1). The radial beam of the PPI is rotated by physically (in one type) rotating the coil in synchronism with the azimuthal rotation of the antenna (8.2). Currents are supplied to the moving coil by means of slip rings and brushes.

It is not unusual for the temperature inside the plane of an airborne

[15] As the focused beam produces a spot on the screen that remains unchanged in size, it may well be that the two objects may appear as single on a long range scale but they will appear as double if the scale is sufficiently short. Also, as the receiver gain (amplification) is increased, the pips may spread and blend into one. Momentarily, the gain should be kept low to ascertain whether the target is multiple, but it should then be turned up to increase the sensitivity.

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radar to vary 100°F in a matter of minutes, as the aircraft rises from ground level to thirty thousand feet or more. A beam in a cathode ray tube, focused near its limit, might well become defocused by the variation in the resistance of its coil caused by the changes in temperature. To offset this, a small rectifier (oxide type known as a Varistor) is placed adjacent to the focusing coil to compensate for temperature changes by introducing opposite or neutralizing changes.

7.15. *Microwave oscilloscopes*

The cathode ray oscilloscope has been widely employed for visually presenting radio-frequency and low-frequency oscillations and waves. In measuring microwave frequencies, a limit has been set by the distortion caused by the finite time required for electrons to cross the field of deflection. In order to enhance sensitivity of the oscilloscope, we must decrease this distortion by minimizing the time required for crossing the field. Two means suggest themselves: to increase the velocity of the beam; or decrease the length of the deflection plates.

In one type of oscilloscope, the plates are only 0.5 mm in length and the accelerating voltage is 50,000; the diameter of the focused beam is only 10^{-2} mm (1/100 mm) as compared to half a millimeter for the ordinary oscilloscope. Because of the extremely high voltage and minute deflection plates, the time of passage (transit time) of the electron beam is only 4×10^{-11} seconds (4/100,000,000,000 seconds).

Another type of oscilloscope employs a beam one millimeter in diameter accelerated by a voltage of only 5000 volts, before the beam passes through the deflection plates; then, before it strikes the screen, the beam is greatly accelerated by a voltage of 20,000 volts. The deflection plates are eight millimeters long, separated by 0.05 inch. The transit time is 3×10^{-10} seconds (3/10,000,000,000 seconds).

7.16. *Dark-trace screens*

The ordinary screen employed in the tubes of cathode ray oscilloscopes shows a luminous trace when the electron beam moves across its surface. Certain salts such as potassium chloride (belonging to a group known as the alkali halides) exhibit a dark trace against a white background. Such screens, which are employed in tubes known as "skiatrons", are used for projection purposes. By applying an intense external light, the design on the screen may be magnified several diameters. Among the unfavorable features of this screen are the low contrast and the tendency for the signals to burn in, leaving permanent traces on the face of the screen.

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Chapter 8

ROTARY INDUCTORS

8.1. Rotary inductors; functions and limits

A rotary inductor is an arrangement of coils or inductances in which one or more stationary coils and one or more rotatable coils can change their coupling by means of a rotating shaft. They are extensively used to transmit information on the amount of turning in degrees,[1] or *torque* to distant points, for modulating electric signals by mechanical information, or for demodulation. They may be employed in power circuits ranging from milliwatts to kilowatts; for transmitting torque, the range may fall between milligram-inches to hundreds of pounds-feet. In general, the units are small.

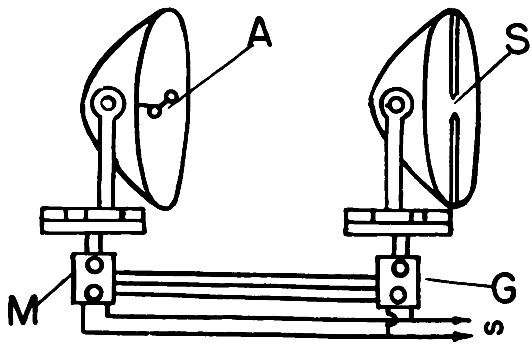

FIG. 8 : 1. SYNCHRONOUS TIE-UP BETWEEN RADAR ANTENNA (A) AND SEARCHLIGHT (S); M, SYNCHRO-MOTOR; G, SYNCHRO-GENERATOR

[1] The torque is the ability of a motor to rotate under a load. If the radius of the motor shaft is in inches and the force or load applied to it is in ounces, the torque is in ounce-inches; in large motors, it may be expressed as pounds-feet.

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8.2. *Synchros*

We have referred to the synchronous movements of the beam of a cathode ray oscilloscope and the scanning antenna with which it is associated. We may also have a synchronous tie-up between a radar antenna and a searchlight, as shown in Figure 8 : 1, or between a radar antenna and a gun director. The distance between the radar and the associated apparatus will often be too great to permit of direct connections in gears or even of belting and pulleys. It is under these circumstances that synchromotors and generators fulfill the part of a

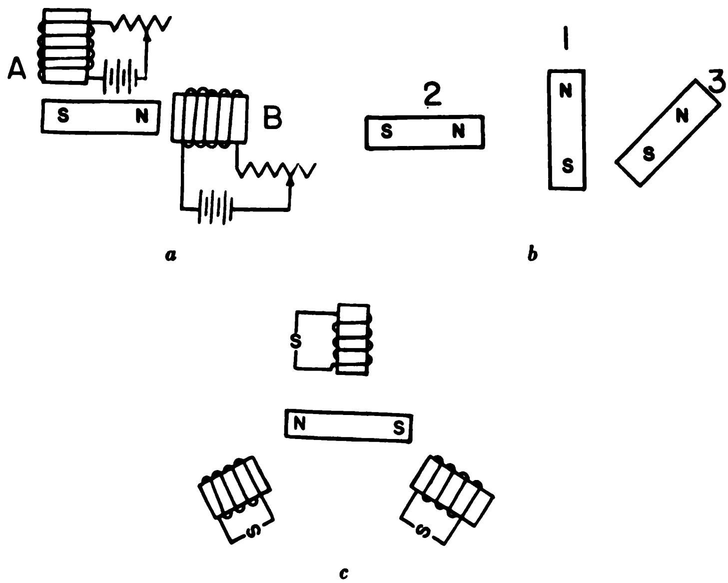

Fig. 8 : 2. Relationships among Magnets
(*a*) Two electromagnets at right angles and simple magnet
(*b*) Positions taken by bar magnet of (*a*) when coil A is energized (1); when coil B is energized (2); when both coils are energized equally (3)
(*c*) Bar magnet that can be influenced by three coils spaced 120° apart

connecting link and enable the rotary motion of one component to be exactly duplicated by another without regard to the space between them.

Figure 8 : 2 (*a*) shows a bar magnet free to turn about its center; B and A are two electromagnets placed respectively in line with, and at right angles to, the bar magnet. Each coil is connected to a source of current that can be varied.

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Suppose that in Figure 8 : 2 (*a*) the switch in *B* is open. Only coil *A* will be energized and the bar magnet will assume the position shown in (*b*) at 1, because the S-pole of the coil will attract the N-pole of the bar magnet. Now, let us close the switch of B and open the A circuit. The magnet will assume a position as in 2 (Fig. 8 : 2, *b*). Finally, let us close both switches, and if the currents in both coils are alike, the bar magnet will take the position in Figure 8 : 2 (*b*), 3, at an angle of 45° with either of the positions previously assumed.

By varying the currents in either coil from zero to maximum, it is possible to cause the magnet to assume any intermediate position from vertical to horizontal; in other words, any position through an angle of 90°. Now, by reversing switches inserted in both circuits or other measure, let us arrange not only to vary the currents but also to reverse their flow through the coils. If this can be done, the bar magnet can be made to assume any position over a complete circle, 360°.

A better arrangement for effecting this would employ three coils placed 120° apart, as in Figure 8 : 2 (*c*). By connecting a source of voltage to each pair of coils in turn, and making provision for reversing connections, every position may be assumed by the bar magnet.

In an actual synchro-motor, there is no permanent magnet. The coupling between a primary coil and a secondary coil is varied by rotating one with respect to the other. Usually, the rotor is the primary coil, which is wound on a laminated core of magnetizable material. The secondary coil, which commonly surrounds the rotor, consists of a slot-wound coil on a core of magnetizable material. When the rotors turn over a limited angle, they employ flexible leads for connections; if the rotation is unlimited, connections are made to slip rings. Among trade names employed for synchros are Selsyns (General Electric), Autosyns (Bendix), Teletorque (Kollman), Diehlsyn (Diehl). As previously mentioned, synchros are most commonly employed to transmit an amount of turning data or torque, where the distance of transmission is too great for gearing or belting, the form of electrical wave may be modulated by synchros; vectors may be resolved or split up into their components, or the components may be combined, as in computing devices.

8.3. *Types of synchro combinations*

1) *Synchro-generator*: The rotor is driven mechanically, thus generating electrical signals (as in a dynamo) which will correspond to the angular position assumed by the rotor. In the synchro-motor, the rotor

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turns freely, depending upon the character of the electrical siguals received from the generator (see **8.4**).

2) *Differential generator*: This is a rotating mechanism which is driven to change the received signal. It transmits an electrical signal which corresponds to the sum or difference of the impressed and modified signals. In the synchro-differential motor, the freely turning rotor takes up a position which reflects the sum or difference of the electrical signals received from two individual sources.

3) *Synchro-control transformers*: This device produces a single-phase voltage whose amplitude varies as the sine of the angle of rotation of its rotor with reference to the magnetic field of its stator.

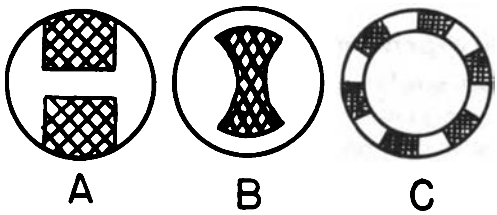

FIG. 8 : 3. CROSS-SECTIONS OF TYPES OF ROTORS USED ON SYNCHROS
A, Dumb-bell (or H); B, umbrella; C, cylindrical (or drum)

4) *Synchro-capacitor*: This serves to counteract or neutralize the lagging component of the exciting current drawn by a differential unit or control transformer. It thus reduces the heating effect of the rotors and increases the efficiency of the system.

In appearance, most synchros resemble the typical three-phase generators. The stator is made up of laminations which, when assembled, produce a slotted cylinder. The winding, a three-phase V- or Δ-connected arrangement, threads the slots and makes up the secondary coil of the synchro. It is common practice to twist, or *skew*, the laminations a little, so that the slots formed are slightly inclined with respect to the axis of the rotor. By this means, the errors arising from different rates of rotation are lessened and "slot-locking" is avoided.

Though resembling a three-phase winding, in reality all of the voltages are actually in phase, in time; in space, the three legs are separated by 120° from one another.

Rotors are of three types:

1) *H-Type*: The salient pole is known as the dumb-bell or H-type (Figure 8 : 3, A), so-called because of the shape of its cross-section; it

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is employed on synchro-motors and synchro-generators. It is wound in single-phase; this is the primary or exciting winding of the synchro. For connections, this requires two slip rings; the voltage applied to it is constant.

2) *Umbrella Type*: Control transformers usually employ a winding known as the umbrella rotor (Figure 8 : 3, B), As can be readily seen, this is a slight modification of the H-type.

3) *Drum Type*: In the cylindrical or drum type of rotor (Figure 8 : 3, C) the rotor is wound in the slots of a laminated frame and the coil is a single-phase winding connected to a pair of slip rings. In differential units, three-phase windings are connected to three collector rings.

8.4. Synchro-generator

In the ordinary synchro-generator, a single-phase voltage is applied to the winding of a dumb-bell, or salient pole, rotor. This produces an exciting current in the primary (as in a transformer) which, in turn, produces a magnetic flux. The magnetic lines link with the stator winding (secondary), producing a voltage which will depend upon the angular position of the rotor with regard to the stator windings. For every set of voltages in the stator, there is only one position taken by the rotor; the reverse is also true; for each position of the rotor, there is only one set of stator voltages. In other words, there is an exact correspondence between the position of the rotor and the voltages of the stator.

8.5. Synchro-motor

Though a synchro-motor and a synchro-generator are indistinguishable, electrically, there is a slight mechanical adaptation of the synchro-motor that sets them apart. An oscillation damper is mounted on one end of the motor shaft. This device which consists of a flywheel whose moment of inertia is that of the rotor, can rotate freely on the shaft. Between the rotor and the shaft, a friction coupling furnishes a method for transmitting energy from the rotor to the flywheel; limiting stops confine the free rotation of the flywheel with respect to the rotor shaft to an angle not greater than 45°. When the motor oscillates, the friction coupling dissipates energy. To prevent the motor from running away, damping is absolutely essential. Without a damping element, a synchro-motor or a differential-synchro has a strong propensity to race.

A synchro-motor bears a close resemblance to a single-phase induction motor and, like the latter, it cannot start of its own accord; that

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is, the synchro has no starting torque. At low angular velocity (low rate of rotation), the synchro-torque is greater than the motor torque. When the speed of rotation is high, the torque of the motor exceeds the synchro-torque, and the synchro-generator loses control. Because of the flywheel effect, momentary oscillations in velocity never exceed the critical value because of the dissipation of energy and effects of inertia.

Though a synchro-motor can be used as a synchro-generator, for the reasons just explained, the reverse is not true, especially at low fre-frequencies, e.g., sixty cycles. At high frequencies, namely, four hundred cycles and more, no damping devices are required, as there is no tendency to run away.

8.6. Differential synchro

In the differential synchro, both the rotor and the stator are wound with three-phase Y-connected coils. Each element (stator and rotor) is a slotted structure. A sixty-cycle differential synchro is ordinarily connected between two salient (dumb-bell) synchros. The primary of the differential is the stator, which is fed from the stator of the synchro-generator to which it is connected. The three voltages across the terminals of the synchro-generator produce currents in the three-phase stator windings of the differential. These, in turn, produce a magnetic flux in the differential stator which bears the same relation to its stator winding as the exciting magnetic flux in the generator does to its stator windings. Hence, the magnetic field of the differential corresponds to the position of the rotor of the synchro-generator.

The magnetic field in the secondary coil of the differential synchro induces voltages that depend upon the relative positions of the magnetic field and coil windings. Therefore, the arrangement and polarity of the voltages in the secondary of the differential indicates the combined effect of the rotation of the synchro-generator and the differential, referred to the stator.

The differential generator is excited from an external source, namely, the synchro unit to which it is connected. Because of losses in the coil windings it is obvious that if an applied voltage, V, is connected to the primary (stator), the loss in the winding will cause the induced voltage in the rotor to be less than V (in a 1 : 1 relationship. To obtain V in the secondary, the ratio of the windings should be one-plus to one. In other words, the stator (differential) is always primary and always connected to the stator of the synchro-generator.

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In another of its possible uses, the synchro differential may be employed as a differential generator from which correcting signals may be superimposed on those of a synchro-generator. When a synchro is employed as a differential motor, it should be equipped with a slip device to prevent excessive oscillations.

8.7. *Synchro-control transformer*

A synchro-control transformer is equipped with a cylindrical rotor wound with a single-phase coil. The primary is wound in the slots of the stator, which is supplied with current from a synchro-generator. The current in the primary sets up a magnetic field of which the polarity is determined by the voltages applied to the stator. The magnetic flux produced in the rotor will depend upon the rotation of the rotor in relation to the magnetic field of the stator. If the angle of torque is most favorable, it will cut the lines of magnetic force and generate the maximum voltage. At a position 90° removed from the maximum, the voltage induced in the rotor will be zero.

Zero voltage will be generated in the rotor in two positions, 180° apart. By a slight rotation away from these zero points, similar voltages will be generated. These will show by their polarity which position has been occupied.

A control transformer possesses a much higher impedance than either a synchro-generator or a synchro-motor of the same or comparable size. Because of the high impedance, it should never feed into a load of low impedance. Because of its high impedance, the stator will draw a small exciting current; the high impedance of the rotor as it turns enables the transformer to change more quickly from its minimum to its maximum.

8.8. *Synchro-control motor*

In what is known as a synchro-control motor, both the rotor and the stator rotate independently of each other. There is no distinguishable difference between a synchro-control motor and any other synchro-motor except that the synchro-control motor as a whole can be rotated. Often, control transformers can be mounted in this way. The additional freedom of movement creates the effect of inserting a differential generator and thus preserves the accuracy, which would be decreased by the actual use of a differential generator.

By increasing the magnetizing power of a synchro, we can increase the torque. In the ordinary synchro-generator or motor the magnetizing power is applied to the terminals of the rotor coil. The heat

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produced in the copper wiring and the loss of iron in the rotating core is radiated away and dissipated through the air gap between the rotor and the stator. Thus, the stator receives a good part of this heat, which it, in turn, must radiate to the surrounding air. If the rise in temperature is fixed, we may increase the power fed into the synchro by applying the exciting current to the stator, rather than to the rotor. Change in torque varies with the ratio of resistance to reactance of windings.

Because the input and output are reversed, this form of synchro is known as a *reversed synchro*. A disadvantage in such an arrangement is the fact that the current must pass through slip rings, and hence through brushes. Because of the presence of dust or dirt, the resistance may become quite high. Because the voltages are low, they may be insufficient to burn through the foreign material, thus causing inaccuracies and lack of correct operation in the combination with the synchro to which it is tied.

8.9. Synchro operations and connections

In any given position of the rotor of a synchro-generator, the voltages between the stator leads are fixed, the same condition applies to a synchro-motor. If the stator connections and the rotor connections of two synchros are in the similar positions, there will be no current in the stator windings. If, then, one rotor is displaced with reference to the other, the voltages in the stators will no longer be matched, and an unbalanced voltage will cause a flow of current in the stator coils. The currents will set up a magnetic field which will cause a torque in both synchros and the rotor in the motor will move synchronously with that of the generator. If, for instance, the rotor of a generator is fixed to the indicating card of a gyro-compass,[2] the synchro-motor connected to the generator will also indicate the condition of the compass card.[3] Several synchro-motors may be operated from one synchro-generator.

8.10. Use of different synchros

The motor of a differential synchro indicates the difference between positions, corresponding to two different siguals. Reversing one pair of leads causes the direction of rotation to reverse; the differential will then indicate the sum of the respective positions. Reversing one pair

[2] Compass based on the rotation of a gyroscope.

[3] Circular card calibrated to indicate cardinal directions over which the compass needle moves.

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of rotor leads, produces a like result. When used as a differential generator, damping is not necessary. Thus used, the differential superimposes on the output voltage of the synchro-generator an electrical signal which reflects the position of the rotor of the differential generator. This apparatus is a suitable means for correcting errors in a synchro indicating system. As a differential synchro normally derives its exciting current from another synchro, it is common to employ a synchro-capacitor (see 8.12) to assist excitation.

8.11. Increasing accuracy by multiplying speed

Should the accuracy of a synchro system be less than required, it is possible to gear up the synchro-generator. It will thus turn faster than its driving mechanism. Similarly, the synchro-motor attached to it will have to be geared down in the same ratio. The accuracy of the system will be increased in the same ratio as the gearing is increased.

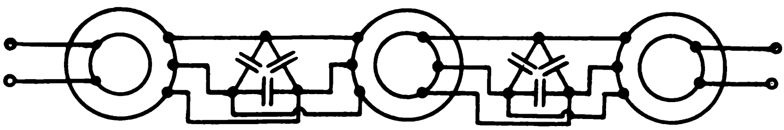

FIG. 8 : 4. SYNCHRO-CAPACITORS CONNECTED TO IMPROVE POWER FACTOR

If, for example, the speed is stepped up ten to one by gearing, the accuracy of the system will be multiplied by ten. On the other hand, gearing introduces involvements as an off-set. If the ratio is increased by ten, there will be ten positions in which the generator and the motor will be perfectly synchronized. Thus, if for any reason, a motor should slip or shift a pole (half a cycle, in effect), its position will not be correct, and yet there will be no tendency for it to correct itself. As the speed increases, this possibility of error is increased. If the ratio is thirty-six to one (fairly common) there will be thirty-five positions that can be wrong and there will be no automatic correction. To guard against such a possibility, it is a common practice to parallel the high-ratio system with another of one to one. This is referred to as a two-speed system.

8.12. Synchro-capacitor

In the differential synchro and in the control transformer, the magnetizing current is supplied from synchro-generators. Because each apparatus is highly inductive, the current lags far behind the voltage, resulting in a low power factor. To overcome this, it is a customary practice to interpose, as shown in Figure 8 : 4, three stator capacitors

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connected in delta. As the current in a capacitor leads the voltage, it is possible by this arrangement to neutralize the lagging reactive component of the magnetizing current, and so reduce the total current from the synchro-generator. The capacitors, in groups of three, are hermetically sealed in metal containers. For best operation, the three capacitors (one in each arm of the stators) should be equal within one per cent. The connecting leads from the capacitors to the synchro units should be as short as possible.

8.13. Accuracy

When an error is mentioned, it refers to the measurement obtained from a synchro-generator of a given size driven by a synchro-motor of the same size. It is possible to estimate errors in advance from a unit known as the *torque gradient.*[4] The difference between the angular position of the shaft of a synchro-generator and the shaft of a synchro-motor determines the torque of the motor. When the angular positions or difference of the two shafts is small, the correcting torque will vary directly as the angular difference. If a torque of one inch-ounce displaces the shaft of a synchro-motor one degree from the position of the generator shaft, a torque of two inch-ounces will cause a displacement of two degrees. The torque of a synchro-motor that produces one degree of rotation is called the torque gradient. Knowing the torque gradient, the torque for any amount of rotation can be found by multiplying by the number of degrees the shaft turns.

8.14. Capacity of load in synchro-generator

As synchro-motors are added to a synchro-system, both the accuracy and the available torque are lessened. The permissible load varies with the rise in temperature of the synchro-generator rotor. The increase in temperature will depend on the size of the generator, on the size and number of the motors, and on the mechanical loads. It will also vary with the number of control transformers and differential synchros connected in the system.

8.15. Errors

Even though synchro-generators, control transformers, and differential generators, are driven units, they are subject to electrical errors. These are caused by variations in the windings and the magnetic structures that occur in the process of manufacture. In addition to

[4] For details, see Appendix.

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the inherent errors common to synchro-generators, synchro-motors also have errors due to the friction of the brushes and bearings.

Because of the presence of electrical errors, the dial of a synchro-motor may lead the readings of a synchro-generator at some of the sectors in the periphery of the dial. On the other hand, mechanical errors produced by friction, introduce a component of the total error that is lagging; that is, an error in the reverse direction.

8.16. Resolvers

In a synchro-system, we may look upon the synchro-generator as a *vector*[5] *resolver* and a synchro-motor as the *vector adder* (**8.17**). In a synchro-generator, the vector equals the amplitude of the rotor voltage and the relative angle between the stator and the rotor. This vector may be resolved into three components along the axes of the three stator windings. These are transmitted electrically to the stator of the synchro-motor where they are recombined to form vector components of the magnetic field of a given strength in a given direction. The magnetic field produced by the rotor excitation of the motor then aligns itself with the vector field produced by the rotation of the rotor.

Both operations just described are employed in data transmission systems, although either system, that is, a resolver or a combination process, may be used by itself. A resolver may be one of two kinds: a single-frequency system, or a multiple-frequency system.[6]

In the single frequency systems, the vectors are resolved into components; a single-phase sinusoidal voltage is applied to a single-phase rotor (as in Figure 8 : 5 (*a*)). The synchro resolves the vector into components that are perpendicular to the axes of the secondary windings. The output voltage is then used in different ways. These may be recombined in synchro-motors or in control transformers for use in synchros or servos (**8.24**). The voltages may be rectified and used to control the motion of an indicator (Figure 8 : 5 (*b*)). The secondary of the resolver is wound with two secondary coils perpendicular to each other. They are widely employed on problems of data fed to electronic

[5] A vector is a quantity that has both magnitude and direction. It may be expressed by a line of which the length indicates its magnitude and its angular relation to some reference plane or line, its direction. Velocity is a *vector* whereas speed is a *scalar*.

[6] If a 2-phase resolver is supplied with a saw tooth wave train, the sine- and cosine-modulated output of the resolver may be used to drive the deflecting system. If the tube is electrostatic, the output of the resolver should be saw tooth voltages feeding into a high impedance; if the tube is magnetic, saw tooth currents should feed into an inductive load.

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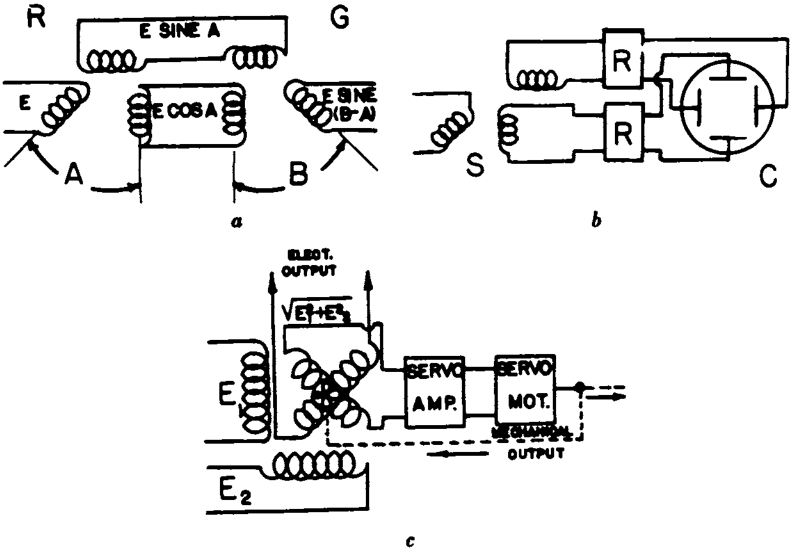

FIG. 8 : 5. DETAILS OF RESOLVERS

(*a*) Connections of resolver in single-frequency system R, resolver; G, combiner or integrator
(*b*) Rectified voltages from synchro resolver (S) applied to indicator (C); R,R, rectifiers
(*c*) Resolver connected for computer

computers. The secondary serves also as a coordinate transformer, for it transforms polar into rectangular coordinates.

8.17. Vector adders

By means of vector adders, we may obtain either an electrical or a mechanical output, or both. In a synchro-motor or transformer, the vector output is a magnetic field arising from the combined magnetomotive forces of the stator windings. In the synchro-motor, the rotor turns until the magnetic field due to the exciting current is antiparallel[7] to that generated in the stator winding. The mechanical output or corrective force owes its magnitude to the angular position of the rotor with respect to the stator. In the control transformer, the vector output is again the intensity of the stator magnetic field but the rotor windings are maintained perpendicular to the direction of the magnetic field by the servo amplifier (8.24) and driving motor.

[7] As applied to fields, anti-parallel means that the vectors representing the fields are parallel but opposite in direction.

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The data output is scalar[8] and consists of the angular displacement between the rotor and the stator.

In the accompanying diagram, Figure 8 : 5 (*c*) a resolver is shown connected for use in a computer. One winding of the rotor, which is connected to the servo-amplifier, drives the servo-motor and also acts as the rotor of the control transformer. The windings are kept perpendicular to the vectors of the magnetic field at all times. The second

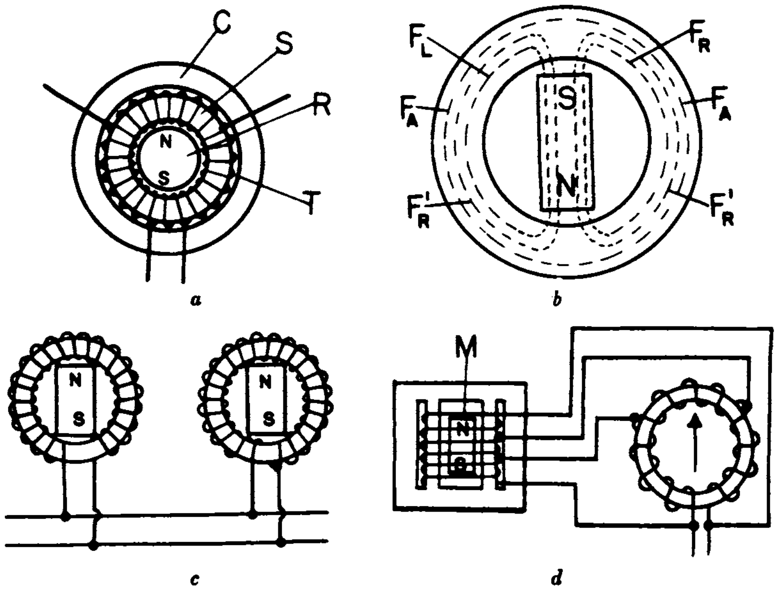

FIG. 8 : 6. DETAILS OF MAGNESYN
(*a*) Core of toroidal coil (S); rotor of permanent magnet (R); toroidal coil (T); cylindrical stack core (C)
(*b*) Magnetic fluxes (F) set up in magnesyn
(*c*) Two magnesyns connected for synchronous operation
(*d*) Linear magnesyns (M) connected to rotary magnesyn

rotor winding is perpendicular to the first and is always aligned with the stator field. The voltage induced in this winding is proportional to the amplitude of the magnetic field. The vector output obtained is the signal on the second rotor winding; the phase is given by the angle between the rotor and the stator. If the stator has two windings that are perpendicular, the resolver becomes a coordinating transformer which transforms rectangular coordinates into polar coordinates.

[8] A scalar is a quantity having only magnitude; e.g. temperature.

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8.18. Electrical characteristics

As the units operate at a fixed frequency, the response or a unit is not critical. Most synchros are built for operation at sixty or four hundred cycles. For high accuracy, the load on the synchro should be as light as possible. The reactive (inductive) component of the impedance should be kept low, for the error current is retarded in its application if it must pass through a high inductance. By applying a booster current through an amplifier, the effect of the out-of-phase component caused by the inductance can be overcome.

8.19. Magnesyns

A magnesyn is a rotary inductor consisting of a toroidal-wound coil and a permanent magnet, designed to give remote positive indications. It is never employed for the transmission of power but rather for very light loads, such as index pointers or compass cards. A magnesyn may be connected to a synchro through a matching device and the combination can then be employed as a data-input system for a servo mechanism. They are also made in linear forms. The commonest type consists of a stator with a permanent magnet as rotor. The core of the toroidal coil which is shaped like a doughnut, is made up of laminations of highly permeable material such as Pennalloy. Around the toroid is a cylindrical stack core made of laminations which serves to complete the magnetic path (Figure 8 : 6 (*a*)) when the Pennalloy becomes saturated by the A.C. exciting current. The rotor, mounted on bearings, consists of a permanent magnet in the form of a short stout cylinder. The bar magnet sets up a uniform magnetic field around the periphery of the toroid. At 120 and 240 degrees, taps are taken off at the ends of the coil (stator), thus yielding three equal voltages.

Magnesyns are normally built for use at 400 cycles and 28 volts. Two sizes are common, one for fifty milliamperes, and the other for one hundred milliamperes. In accuracy, they are a match for synchros in general; errors run to not more than one-quarter degree per unit.

8.20. Magnetic and electrical relations

Magnetomotive force (MMF) is set up in the circular core, as in Figure 8 : 6 (*b*). The magnet axis bisects the core. H_1 is the MMF. Because the material of the core is uniform and symmetrical, it presents the same magnetic reluctance in each path, thus making $H_1(F'_R)$[9]

[9] As the flux is proportional to the MMF, if the permeability is assumed to be constant, we may substitute one set of quantities for the other (F for H or H for F) without affecting the statements in the text.

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the same in each half of the path. The alternating current through the coil sets up an alternating MMF in the core, $H_2(F_A)$. As shown in the figure, the resulting MMF in the half of the coil, $H_L(F_L)$ is $F_A - F'_R$, and in the right half, $H_R(F_R)$ is $F_A - F'_R$. The density of the resulting flux caused by the total MMF consists of two parts: F_A which is common to both halves of the core; and a flux density caused by H_1 combined with H_2. Thus F_L equals F_A plus F'_R; F_R equals F_A minus F'_R.

If two units are joined as in Figure 8 : 6 (*c*), the same voltages will appear at the same taps. The voltages are balanced at all times. Because of a change in the position of the rotor, a change will occur in the second harmonic voltages. A difference in rotor positions will cause an unbalance in the voltage of the two units. Thus, a current will flow,

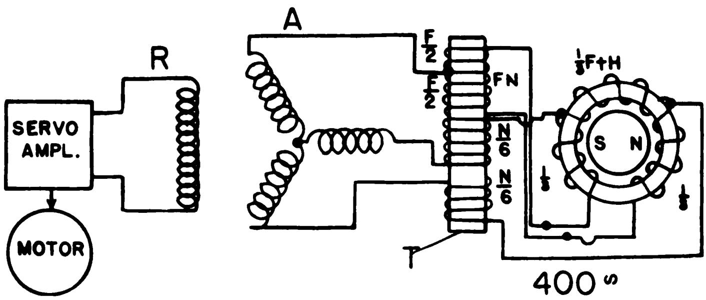

Fig. 8 : 7. Connections of Synchro and Magnesyn through Coupling Transformer
R, rotor; A, stator, T, coupling transformer

producing a magnetic flux which will set up a torque and bring the rotors back into alignment.

8.21. Linear magnesyns

The operation of a linear magnesyn is identical with that of a rotary magnesyn. The rectangular core (Figure 8 : 6 (*d*)) is made of Permalloy and the control leg is hollow. Within this a permanent magnet M can move lengthwise. Both the fundamental voltage and the second harmonic voltage vary with the position and motion of the permanent magnet, not differing in these respects from the operation of a rotary unit.

8.22. Joint operation of magnesyns and synchros

To operate magnesyns and synchros together, some method must be employed to cancel out the fundamental voltage, which must not appear in the synchro secondary. The synchro will operate very well on the second harmonic voltage. An easy way of removing the fundamental voltage is by employing a coupling transformer (Figure 8 : 7). The diagram of connections and the lettering scheme in the figure should make this clear.

8.23. D.C. selsyn

Figure 8 : 8 (*a*) shows the diagram of what is known as the *D.C. selsyn*. This operates on direct current of low intensity. A practical use is in gauges for fuel tanks to indicate the level of the fuel. The

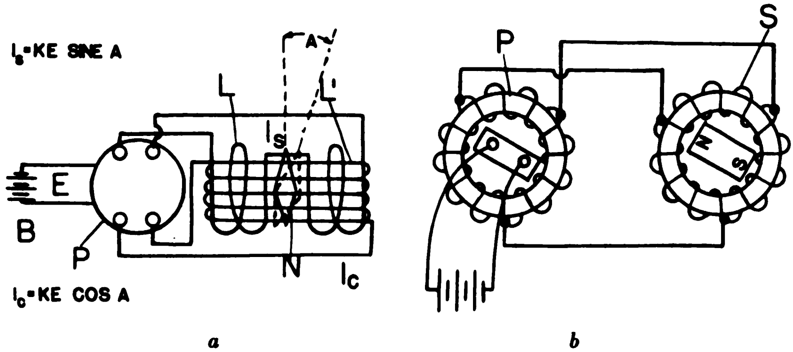

FIG. 8 : 8. CONNECTIONS OF A D.C. SELSYN
(*a*) Potentiometer (P); compass needle (N)
(*b*) Two 3-coil, 3-wire D.C. selsyns connected for joint operation: (P) potentiometer; S, synchro

design shown in the figure is a model made by the General Electric Company. The current for two coils, L and L′, is provided by the battery (B), through the sine-cosine potentiometer (**3.26**). The currents, I_C and I_S, are of the values shown. With identical coils of perpendicular axes, the magnetic field at the center will be constant, and the direction of the angle A is the referred direction, which is the angular position of the shaft of the potentiometer. The angle through which the needle of the compass rotates is matched by the angle through which the potentiometer shaft turns.

In the 3-wire 3-coil system, the transmitter is a potentiometer with a 360-degree winding tapped at 120 degree intervals and supplied with D.C. current from a battery, as shown in Figure 8 : 8 (*b*). The brushes on the potentiometer make contact at points on the winding 180° apart. If the three leads of the synchro-stator are connected to the

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three leads of the potentiometer taps, a steady magnetic field is set up in the stator, and the rotor will turn with the shaft of the potentiometer.

8.24. *Servos*

We would not expect a small transmitter selsyn to operate a huge receiver selsyn. Such an arrangement is illustrated by an antenna and a *gun director radar combination.* Here it would be necessary for the huge guns to follow the antenna as the latter is moved. Obviously, a small receiving selsyn motor could hardly be expected to move heavy guns that weigh many tons, yet the movement of the antenna should be accurately paralleled by the guns. Some form of amplifying device must be employed which will supply adequate power and yet preserve faithfully the accuracy of movement.

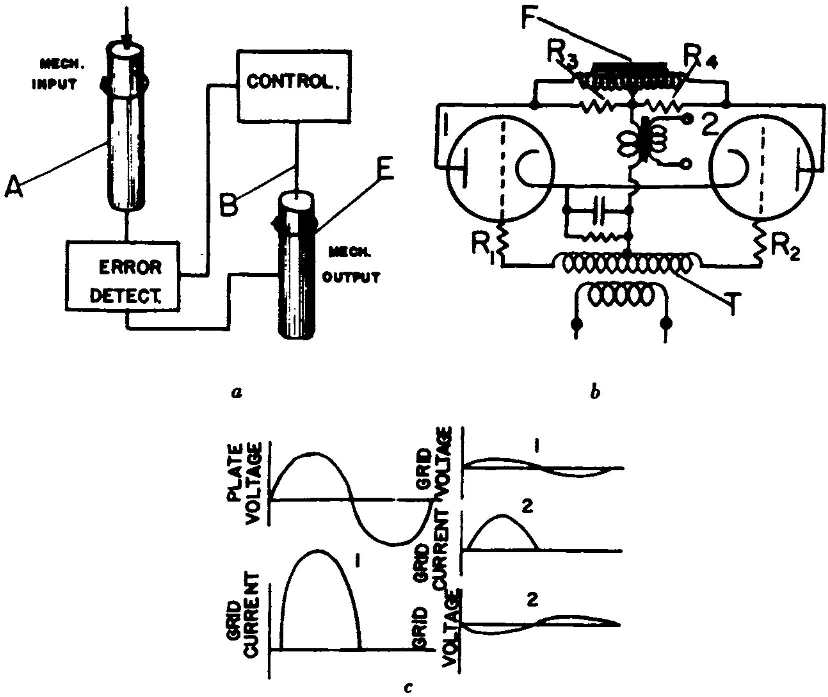

FIG. 8 : 9. DETAILS OF SERVO MECHANISMS
(*a*) Simple form: A, input; E, output; B, simplified control
(*b*) Circuit of connections of servo-amplifier for small D.C. motor: F, field of D.C. motor; T, control transformer
(*c*) Curves for voltages and currents in tubes of (*b*)

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An arrangement of selsyns and amplifiers is called a servo-mechanism or more often simply, *servo.* A method that might be used is shown in block form in Figure 8 : 9 (*a*). The current set up in the rotor of the receiving system is amplified and it supplies sufficient power to the motor to operate the guns. The purpose of the error-detector is to measure the lack of agreement between the input angle and the output angle (the angle between the direction in which the antenna points and the direction toward which the gun points), for this is the shift in displacement between the output and the input. The amplified power in the controller drives the output shaft to make the correction indicated by the error-detector.

8.25. *Synchro-control transformer as error-detector*

If the input (antenna paraboloid) and the output (anti-aircraft gun, for example) are widely separated—beyond the feasibility of employing belts or gears—the error-detector is a synchro-control transformer coupled to a synchro-generator. Commonly, the synchro-generator is mechanically coupled to the input (antenna), and the control transformer is connected to the output (gun), as in Figure 8 : 10.

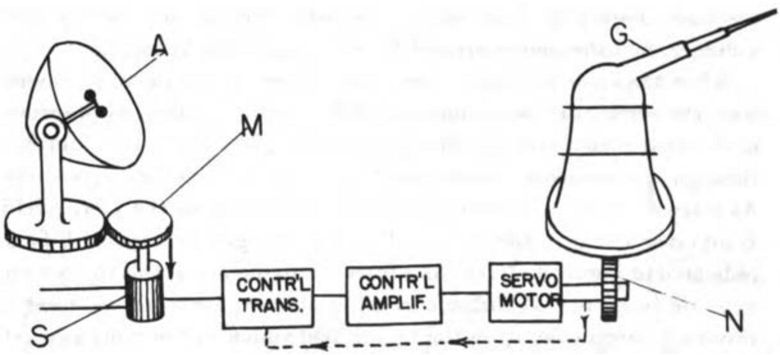

FIG. 8 : 10. BLOCK DIAGRAM OF CONNECTIONS OF SYNCHRO-CONTROL TRANSFORMER
A, antenna; M,N, gears; S, synchro-generator; G, gun

The output (gun) is rotated by the servo-motor which is a large powerful motor of many horse power. The operating power for this large motor comes from the control amplifier which is controlled by the error voltage obtained from the control transformer. The servo-motor

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may be A.C. or D.C. If the servo-motor is D.C., a rectifier must be applied to the output of the control amplifier in Figure 8 : 10.

8.26. Use of servo-amplifier with D.C. motor

The function of the servo-amplifier when employed with a D.C. motor is first to rectify the A.C. error voltage from the control transformer and then amplify it to the amount required for operating the motor. A necessary part of the servo-amplifier is the rectifier which must be phase-sensitive; if the phase of the control transformer voltage reverses, then the polarity of the rectifier output (D.C.) must also reverse.

In Figure 8 : 9 (*b*) is shown a circuit diagram of connections for a D.C. motor of small or moderate size. As can be seen, the triodes 1 and 2 are connected in push-pull arrangement and receive plate voltages from the A.C. supply line. As connected, both plate voltages are in phase (see 6 : 1). The synchro-control transformer supplies the grid voltages which are 180° out of phase (when one is maximum negative, the other is maximum positive). As both grids and plates derive their voltages from a common power supply, it follows that one grid must be in phase and one out of phase (by 180°) with the plate voltage at all times. Plate current can flow only when the plate voltages are positive. Figure 8 : 9 (*c*) shows the plate voltage supply, the grid voltages, and the plate currents for a specific error in voltage.

When the error voltage is zero (when there is no error to be corrected), the currents in both tubes, 1 and 2, will be the same. As the motor of the field is connected in the diagram, the plate currents would flow through in opposite directions and thus magnetize the field oppositely. As a result, there will be no magnetic field set up in the motor field. If an error voltage exists in one direction, the grid voltages will be as indicated in Figure 8 : 9 (*c*). As a direct consequence of this the current in 1 will be greater than the current in 2; thus, there will be a net or resultant current set up in the motor field which will become magnetized. Should the error voltage then reverse its polarity 2 would draw the greater current, and the resulting magnetic flux through the motor field would reverse. The purpose of resistors R_1 and R_2 is to prevent excessive grid currents from flowing when the angle of error is very large. Without them the terminal voltage of the transformer that supplies the grids might greatly exceed the grid bias, resulting in excessive grid current.

Because the inductance of the field winding of a motor is high, it is necessary here to shunt the field as shown with resistors R_3 and R_4.

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Were they omitted, little current would flow through the motor field because its high inductance would prevent rapid growth. The time allowed by the conduction period of tubes 1 and 2 is too brief. On the other hand, because of the presence of the resistors R_3 and R_4 the current increases in small stages during each conducting period; even in the cut-off period of the tubes, field currents will flow through the windings and resistors.

As a result of the foregoing, the field current will become steady and the variations with conduction and cut-off periods, slight. In addition to their function as described, R_3 and R_4 serve as buffers to shield the field coils from excessive voltages which would otherwise be induced in the winding by the sudden stoppage of current through tubes, 1 and 2.

What values shall we give to R_3 and R_4? As they are shunted across the field, it is evident that if they are too small, too much current will be shunted away from the motor field. If less current flows through the field winding, the inductive voltage across the field will be less and the field currents will become steadier. This advantage is counterbalanced by the fact that the delay in response to a change of error in voltage increases as R_3 and R_4 decrease. Because of the large inductance of the field, the currents through the field circuit require several cycles to attain a final value, whereas the currents through the resistors change immediately. The effect of an increased delay enhances the tendency of a servo-mechanism to *hunt*, or oscillate about a mean position.

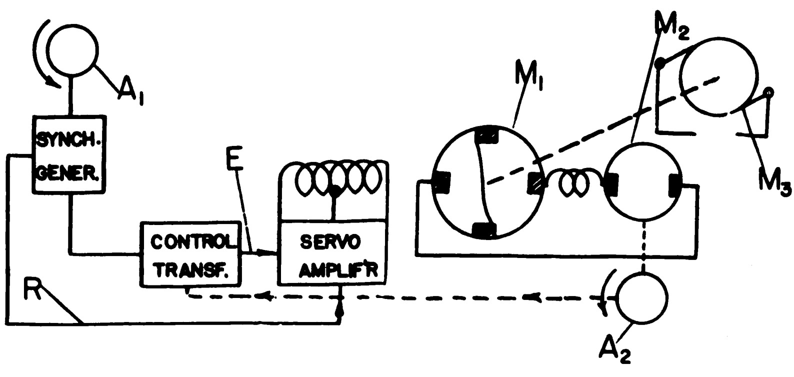

FIG. 8 : 11. BLOCK DIAGRAM OF CONNECTIONS OF AMPLIDYNE FOR SERVOS
A_1, angular input; A_2, angular output; E, error voltage; M_1, amplidyne; M_2, D.C. motor; M_3, constant-speed motor; R, reference voltage

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8.27. Servo employing an amplidyne

Figure 8 : 11 shows a circuit containing an *amplidyne* which is especially suited for servos. Figure 8 : 12 (*a*), shows an amplidyne in cross-section; Figure 8 : 12 (*b*) schematically represents its connections and magnetic relations.

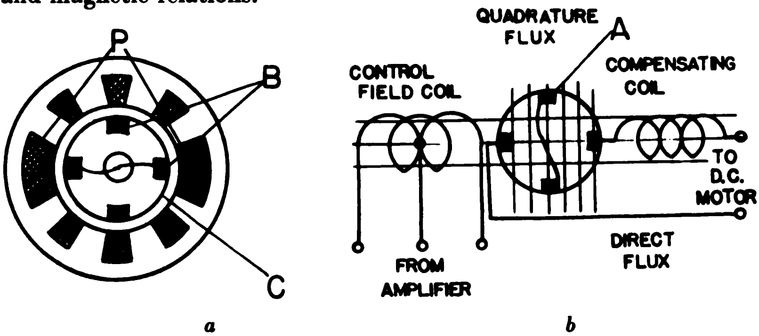

FIG. 8 : 12. DETAILS OF AMPLIDYNES
(*a*) Cross section: B, brushes; P, field poles; C, armature
(*b*) Connections and magnetic fluxes set up in amplidyne; A, armature

Externally, the amplidyne resembles an ordinary D.C. generator (or motor). Its field poles are short and wide and carry multiple windings. Two sets of brushes whose axes are perpendicular to each other make contact with the commutator. One set is placed as in any standard motor or generator but the brushes are short-circuited; the other set, perpendicular to the first, is the output brushes. The amplidyne is driven by a constant speed motor (such as an ordinary A.C. synchronous motor) and in order to minimize weight and bulk, its speed of rotation is high.

We may consider the amplidyne as two separate generators: one comprises the shorted brushes and the control winding; the other has for its output the current from the unshorted brushes. Current from the servo amplifier flows through the control winding and sets up a magnetic flux, as shown by the light horizontal lines in Figure 8 : 12 (*b*). As the armature conductors rotate, they cut this magnetic flux and the voltage induced in them produces the current that flows through the shorted brushes. Because of the short-circuit a very small control field is needed to generate a large current in the armature. The amplidyne is magnetized by the large armature current perpendicular to the magnetic field of the control winding. This field is shown by the parallel vertical light lines in Figure 8 : 12 (*b*). A very great quadrature

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flux is thus produced by the slight flux from the control field. As the quadrature flux is perpendicular to the control field flux, the armature voltage produced by its conductors cutting the quadrature flux is a voltage at the brushes perpendicular to the shorted brushes. The output brushes supply the necessary voltage to the servo load. It is common to find a ratio of 1 : 10,000 between the power of the control field and that of the output, and this is a measure of the amplification of the amplidyne.

Without the windings labeled "compensating", very little current could be drawn from the terminals of the amplidyne. The output current would magnetize the generator perpendicular to the quadrature axis, that is, along the direct axis but in opposition to it. Without the compensating coils, a little output current would be sufficient to reduce or wipe out the control field magnetic flux. To prevent this and to neutralize the armature reaction of the output current, the compensating coils are wound in slots in the faces of the poles and are connected with the output brushes in series. The magnetic flux of the compensating winding is just sufficient to cancel the flux produced by the output current, but it should not alter the magnetic flux produced by the shorted brushes.

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Chapter 9

TRANSMIT-RECEIVE DEVICES

9.1. Purpose of T-R switch

Because it is commonly desigued with a single antenna, a radar system incorporates special protective devices known as T-R (transmit-receive) *switches* which shield the receiver while the transmitter is operating; and also cut off any possible loss of power into the transmitter when the receiver is operating. A single antenna has the advantages of simplicity and minimum weight and there is no problem synchronizing directions, as with multiple antennas. Besides, the use of one large antenna, ensures greater directivity, as well as more efficient power transmission.

It is said that the relations between the minimum light that the human eye can see and the maximum that it can tolerate is as one to a hundred millions, or 1/100,000,000. Even so, it requires a long period of time for the eye to adapt itself to these extremes; in fact, several minutes for the ordinary eye.

The power in a radar transmitter during a pulse may easily be 1000 kilowatts (a million watts). The minimum power in an echo that the radar receiver may detect is often not more than a billionth of a billionth of this. The ratio of the extremes in radar are therefore one to a billion billion, or 1/1,000,000,000,000,000,000. Furthermore, when the radar is called upon to operate over very short distances, it may be severely taxed. Remembering that an electromagnetic wave travels 1000 feet approximately in a microsecond through air, a target 500 feet away will require a microsecond for the beam to travel out and for the echo produced by the reflection of the pulse to return. To state it

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otherwise, the transmitter must be turned on and off in a microsecond. Obviously, no mechanical switching arrangement in existence can function in so brief an interval.

9.2. How the T-R switch operates

By means of the T-R switch, the transfer of connections from the transmitter to the receiver is accomplished in a fraction of a millionth of a second. We saw (3.16) that by the use of metal septums and irises in wave guides, we can make the electric field in a wave guide very intense. By enclosing part of a wave guide with an iris in a glass envelope which contains argon and water vapor at reduced pressure (a partial vacuum), it is possible to cause a spark discharge with even a slight rise in voltage. A gap containing a spark discharge is the equivalent of a very low resistance, whereas an ordinary gap in a circuit represents an enormously high resistance.

If by means of the transmitter we can cause the vacuum gap to spark across the receiver during transmission, so that the effect is that of placing a short-circuit across the receiver, the latter will be protected from a large influx of energy. If the spark ceases after the transmitted pulse has passed, the short-circuit will be removed, and the receiver will function once more. It is also desirable to cut out the transmitter circuit so that none of the minute energy of the echo will be wasted in the transmitter, but all of it will find its way into the receiver. Bearing in mind that the receiver and the transmitter should each be matched to the transmission lines of the antenna and wave guide (so that no undesirable reflections and standing waves be set up) throughout all these operations, the practical arrangements for accomplishing these ends is a model of ingenuity.

9.3. Details of T-R switch

Figure 9 : 1 shows a T-R vacuum tube commonly used in radar systems of centimeter wave (microwave) lengths. S is the spark gap between cone-shaped terminals, PP are discs of copper fused into the glass and making metallic contact with the spark terminals. In use, the discs span the intense field of a resonant cavity and the high voltage is across them; the wire, W, is known as the "keep-alive" terminal. The gas in the tube is argon and water vapor at a few millimeters pressure. The wire (W) ends in a point which ionizes (makes conducting) the gas immediately around it because a fairly high voltage (about 1000 volts) is always connected to it. Because of the condition created by the keep-alive terminals, a slight increase in voltage between the

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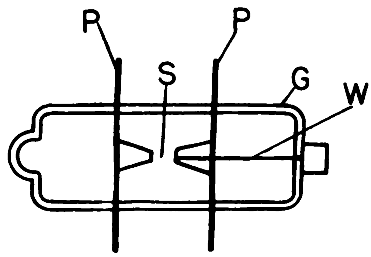
main spark terminals is sufficient to break down the gap with a spark discharge.

9.4. Character of the discharge

If an ordinary unenclosed spark gap were used, the voltage required to break it down would be extremely high (several thousand volts). Furthermore, the voltage necessary to maintain the keep-alive terminal active or in a state of preparedness would also be correspondingly



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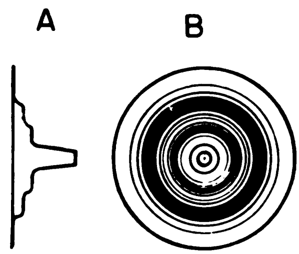

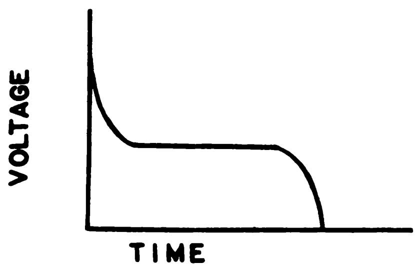

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FIG. 9 : 1. CROSS-SECTIONAL VIEW OF T-R VACUUM TUBE, SHOWING GLASS ENVELOPE (G)
FIG. 9 : 2. WARPS IN COPPER DISCS, AS SEEN IN CROSS SECTION (A) AND FRONT VIEW (B)
FIG. 9 : 3. GRAPH OF VOLTAGE ACROSS SPARK OF R-T TUBE

high at atmospheric pressure. As the keep-alive voltage is on even when the receiver is operating, it is necessary that its voltage be as low as possible to protect the sensitive part of the receiver (especially the crystal) from excessive current. So, by enclosing the gap in an atmosphere of gas at low pressure, both the breakdown voltage and the keep-alive voltage can be made as low as possible.

The discharge of a gap in a low-pressure gas is really diffuse and is called a "glow" discharge. Immediately following a discharge, there are great numbers of free electrons and ions in and around the gap. Until

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they have largely disappeared (which they do because of drift to the walls and recombination), the gas is partially conducting, and the receiving echo will waste part of its energy in the tube. It is therefore essential that the deionization, as it is called, be as fast as possible. The interval of time during which the ionization is reduced to a point where the power of the signal is half of what it would be were there no ions present is known as the *recovery time.*

9.5. Need for constancy in T-R switch

As a magnetron heats up its dimensions change, causing its operating frequency to shift. The magnetron is almost entirely of copper. The T-R tube is largely composed of copper and glass. Compared to copper, the temperature coefficient of glass is negligible; that is, its change of dimensions with a change of temperature is slight. As a result, the overall change in the dimensions of the composite tube is considerably different from that of one of solid copper. The T-R tube shields the sensitive crystal from the power pulses of the transmitter (maguetron). The T-R tube is adjusted to operate best at a fixed frequency, or wave length. To serve its function best, any change in the operating frequency of the magnetron should be matched by an equal change in the T-R tube. It is therefore desirable to adapt the T-R tube, despite its composite character, to behave as though it, too, were made of copper.

If the copper discs sealed into the glass cylinder were quite flat, an increase in temperature would cause the discs to expand and become bowed. The direction in which they move would be a matter of chance. If they expanded in the direction of the gap, the latter would decrease; if they expanded outwardly, the gap would increase. Such a random change would result in ineffective operation. The actual copper disc is not flat but has a decided warp or wrinkle and is bowed outward (Figure 9 : 2). This bias causes the discs *always* to move outward (away from the gap) on expanding with increases in temperature. In consequence, the cone terminals of the gap also move outward, and the cones themselves expand and move outward. The over-all effect of the warp or wrinkle in the discs is to cause the expansion of the chamber to simulate that of a chamber made entirely of copper.

9.6. Anti-transmit-receive switch (A-T-R)

The A-T-R or the anti-transmit-receive switch, also called the R-T switch, structurally resembles a T-R switch, but the keep-alive electrode is omitted. It has only one loop or iris by which energy passes in and out; the T-R tube has two loops or irises permitting energy to

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pass *through* the T-R chamber. The purpose of the A-T-R is to cut out the transmitter from the circuit when the receiver is operating, thus preventing any of the signal energy from being wasted in the transmitter.

9.7. *Cause of "spike" in discharge*

The T-R tube causes a discharge to take place across its gap terminals when the transmitter pulse is sent through from the magnetron to the antenna. The discharge acts as a low-resistance path or short circuit across the receiver. The voltage required to jump across the gap is much greater than the voltage required to sustain the arc, once it has started. In fact, the voltage between the gap terminals resembles the curve in Figure 9 : 3.

The time, T, the duration of the spike (5.13) is of the order of 3–6 $\times$ 10^{-9} seconds (3–6 billionths of a second). Even though short in duration, the energy in the spike may be sufficiently great to burn out the crystal. The purpose of the keep-alive electrode is to maintain an ionized region in the vicinity of the spark gap. The presence of ions here enables the spark discharge to occur at a lower voltage, thus making the energy of the spike lower. The lower the energy of the spike, the better will be the protection afforded to the crystal. In other words, the greater the number of ions in the gap (produced by the keep-alive ionization), the less will be the energy of the spike. There is an upper limit, however, to the number of ions to be introduced by the keep-alive electrode.

9.8. *Restoration time should be small*

As soon as the transmitter pulse has ceased, it is desirable to remove the short-circuit across the receiver so that it can receive the echoes without diminution of energy. Even though the spark discharge is extinguished, there will be ions in the spark gap, because they are sluggish. We must remove these ions before the echo reaches the receiver; otherwise, the ions will act as a partial short, or shunt, across the receiver. The time interval between the end of the transmitter pulse and the removal of the ions should be made as short as possible, that is, the restoration time (9.4) should be at the minimum.

The greater the number of ions present, the longer will be the restoration time. As the keep-alive terminal is active all the time, we see why the ions it produces should not be too numerous. They would shunt off and fritter away some of the energy of the receiver which is contained in the echoes.

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After the spark discharge, how are the ions in the gap removed? Some are removed by natural dispersion or diffusion, and travel to the walls and the metal parts of the chamber; some (but extremely few) recombine with electrons and form neutral atoms and molecules; most are removed by being captured by neutral atoms of the gas present in the tube.

9.9. Reason for gases in T-R switch

What determines the character of the gas in the T-R tube? At first thought, it would seem that only a partial vacuum should be required to facilitate a spark discharge. It is a common practice, nevertheless, to employ a mixture of either hydrogen (H) and water vapor (H_2O) or argon and water vapor which are stable and require low voltages. By the use of argon and hydrogen, the spike energy is kept low. Unfortunately, as these gases are poor deionizers, they have little value in capturing electrons and thus decreasing the restoration time. For this reason, the water vapor (H_2O) is added as this has pronounced advantages in removing or capturing electrons. The partial vacuum most favorable is a pressure of ten to thirty millimeters of mercury.

9.10. Life of T-R tube determined by gas clean-up

What determines or controls the length of life of a T-R tube? With continued use, the vacuum in the tube becomes higher and higher until the restoration time and the leakage current become excessive. In actual radars, the only reason why the T-R tubes have to be replaced is because their vacua have become too high and their protective function has accordingly diminished. Only one reason can account for the increase of the vacuum: the removal of the gases in the tube. This is known as gas clean-up. Part is due to a sputtering process, that is, the material of the electrodes evaporates and becomes deposited on the walls of the T-R tube. As this takes place, some of the gases are also trapped and removed from the chamber.

Another cause of the removal of gas is chemical action. The water vapor, H_2O, breaks up into HO and H. The oxygen combines with the material of the electrodes, forming a gradual crust upon them of copper oxide, and liberating still more hydrogen.

It has been determined that the rate of clean-up is directly related to the current in the keep-alive discharge. The larger this current is, the faster the gases disappear from the T-R tube, and the shorter is its life. So, for a long-lived T-R tube, the keep-alive voltage and current should be low.

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To decrease the chemical action in the tube, it has become a common practice to coat the spark terminals with some neutral substance such as a form of copper oxide, or to gold-plate them.

The energy of the spike varies with the length of the spark gap; by decreasing the length, we should minimize the energy of the spike. As the sparkgap is shortened, the resonant frequency (the period) of the T-R chamber is decreased, because the terminals of the spark gap behave like the condenser portion of the re-entrant resonant cavity (**3.26**).

9.11. Keep-alive terminal should be negative

The keep-alive terminal is made of tungsten, because this sputters very little; and it is kept at a negative voltage with respect to the cones —the gap terminals. By maintaining the keep-alive terminal negative, electrons (negative) are attracted to the spark gap terminals (positive) where they are needed. On the other hand, should the voltage be reversed, that is, if the keep-alive is made positive and the spark terminals, negative, the electrons would travel away from the spark gap and toward the keep-alive terminals. The effect of this would be to make the spike voltage and the energy very high.

9.12. Presence of radioactive material in T-R tube

In order to initiate a discharge of gas across a gap at a moderate voltage, *some* electrons or ions must be present. Where the gap is exposed or in the open, such free electrons will always be present, because they are always present in the atmosphere. These may be due to cosmic ray collisions, radioactive emissions from the surroundings, or other causes. In a T-R tube, surrounded by several metal chambers and shields, as in an actual radar installation, there may be few, if any, free electrons present in or near the T-R gap. In fact when a T-R tube has been idle for several days, it may require several minutes for a spark discharge to strike. With the keep-alive inactive, the crystal will receive no protection.

To ensure a readiness to function at all times, a slight amount of a radioactive substance is introduced into the T-R tube in the process of manufacture, just before it is sealed off. A drop of radioactive cobalt chloride solution is placed on the tip of a cone near the keep-alive electrode. The water of the drop evaporates off during the sealing process, leaving a solid deposit of radioactive cobalt chloride on the tip of the cone. This has a half-life of five years,[1] which means that for

[1] Its activity or emissive power will be reduced to half in five years; the half-life of radium chloride is about 1700 years.

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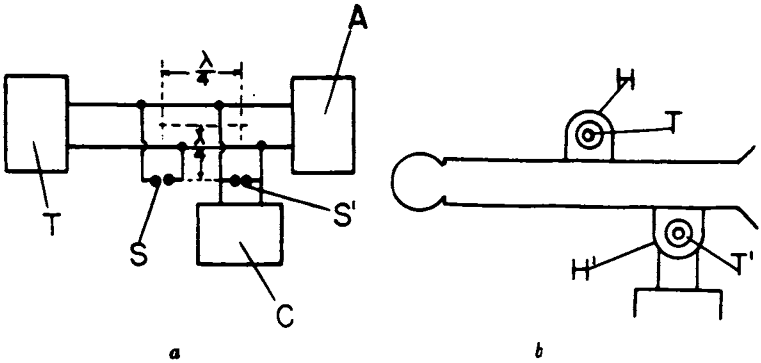

FIG. 9 : 4. DETAILS OF SWITCHING ACTION
(*a*) Low-frequency radar circuit: T, transmitter; S,S′, spark gaps; C, receiver; A, antenna
(*b*) High-frequency radar circuit: H,H′, resonant chambers; T,T′, T-R vacuum tubes

several years, there will be a natural emission of beta rays (electrons) in the vicinity of the spark gap. A T-R tube thus equipped or prepared will always start in less than five seconds.

9.13. T-R switches at low frequencies

Before illustrating the use of the T-R vacuum tube in wave guide circuits, it will be advantageous to describe the protective means at lower frequencies where transmission wires are employed. As vacuum tube mixers can be used at long wave-lengths in place of crystals, the receiving sets are more rugged. For such circuits, even an ordinary spark gap may prove adequate.

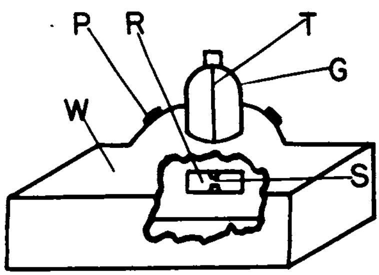

FIG. 9 : 5. T-R TUBE COUPLED TO WAVE GUIDE BY MEANS OF IRIS
W, wave guide; P, tuning plug; R, iris; S, spark gap; T, keep-alive conductor; G, glass envelope

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9.14. How switching action occurs

Figure 9 : 4 (*a*) shows the action of switching. During transmission of a pulse from T, both spark gaps, S and S′ are fired. This produces a short circuit at the gaps and an open circuit one-quarter wave-length away. Hence, so far as the transmitter goes, power is transferred without loss to the antenna because the open circuits prevent power from going into the stub lines. On the other hand, during reception, the gaps are naturally open, so at the end of the quarter-wave line from S, a short circuit will appear across the line. But this short circuit across the line is a quarter-wave from the stub line that leads to the receiver C; hence, all the echo from the antenna (A) will go into C, and none of its energy will be diverted or wasted. No energy from the echo can enter the transmitter, for the path to the latter is blocked by the open circuit across the transmission line that leads to the transmitter.

Figure 9 : 4 (*b*) shows a wave guide for microwaves similar in its layout to that in (*a*). In place of the resonant lumped circuits of (*a*), however, we have resonant chambers, H and H′. In place of the simple spark gaps at S and S′, we have the vacuum tubes, T and T′. The two circuits are identical in operation.

Figure 9 : 5 shows how the T-R tube is coupled to the wave guide by means of an iris aperture. The resonent chamber may be tuned by screw plugs whose movements in or out decrease or increase the volume of the chamber and alter the resonant frequency.

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Chapter 10

ANTENNAS

10.1. Directive antennas in radar

Of paramount importance is the method of radiating the pulses of the radar transmitter into space and receiving the echoes. We can not throw up any form of loose wire as in a household radio receiver. To economize on the power required, we must concentrate the energy in a specific direction. To the extent that we curb the radiation in unwanted directions, to that degree do we save in power. To insure the fact that all the energy is transmitted and not frittered away, the antenna should be matched to the receiver and the transmitter.

10.2. Antenna a transmission line of high radiation

The energy in a transmission line is wasted in its resistance and in radiation; the antenna may be looked upon as a transmission line where the radiation is at the maximum and the losses of heat are kept at the minimum. Suppose we had two wires of a transmission line carrying a high-frequency current, as in A, Figure 10 : 1 (*a*). The line terminates in an open circuit. Around each wire is a magnetic field due to the current; between the wires is an electric field ending on the surface of the wires. B, in the same figure shows an idealized diagram of the wires and of the magnetic and electric fields. The lines of magnetic flux are circles; the lines of electric flux are arcs everywhere at right angles to the magnetic lines.

All the energy sent into the transmission line is divided in three ways: (*a*) that wasted as heat in the wires; (*b*) that stored in the electric and magnetic fields; (*c*) that radiated out into space. The energy stored in the fields fluctuates or seesaws back and forth but it is not wasted. When the magnetic energy is at the maximum, the electric energy is least; when the electric energy is at the maximum, the magnetic energy is least.

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The electric and magnetic fields reach out farther and farther as the wires are separated. When the frequency is high, some of the energy in the fields breaks away and moves outward with the speed of light, 186,000 miles a second. This occurs as electric and magnetic waves that link each other. Together, they are known as *electromagnetic waves*. They are identical with waves of light except for their lengths. Visible light waves are extremely short, of the order of 50,000 to the

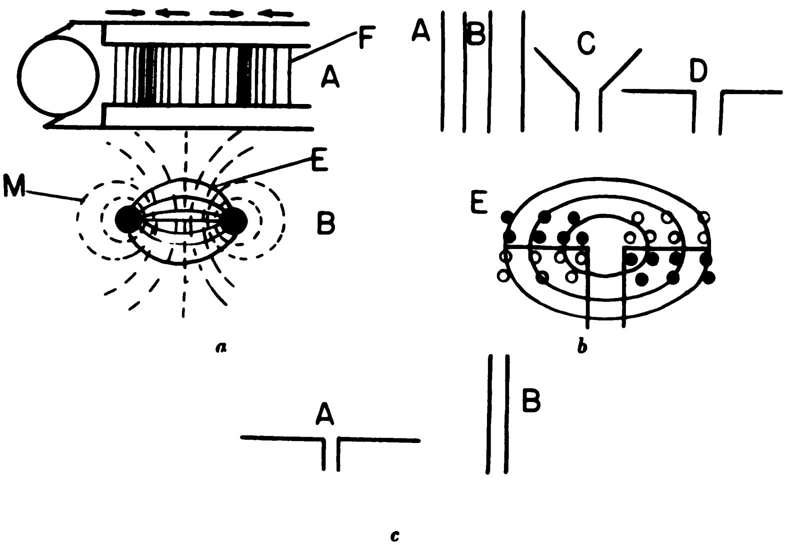

FIG. 10 : 1. ELECTRIC AND MAGNETIC FIELDS AROUND TRANSMISSION LINE
(*a*) Longitudinal view: (A): HF currents (arrows); F, lines of electric field; cross section (B): E, lines of electric field; M, lines of magnetic field
(*b*) Increase in radiation from transmission line in going from A to B: E, magnetic lines (solid) and electric lines (dotted) about antenna (D)
(*c*) Two radiators: A radiates more than 100 times as much as B

inch. Radio waves may be many feet in length; even the shortest of the microwaves used in radar are thousands of times longer than light waves.

By spreading the wires of the transmission lines, we increase their radiating qualities. If we separate the wires, as in A, B, and C of Figure 10 : 1 (*b*), we successively improve their radiation. Now let us fold the wires at right angles as in D. We have obtained the maximum possible separation and the greatest radiation. In E we show the character of the magnetic and electric fields surrounding D.

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It is interesting to observe how the radiated energy increases as the antenna arms or branches of a transmission line are spread apart until they finally extend in opposite directions. Thus, a dipole antenna, shown in A in Figure 10 : 1 (*c*), has a radiation resistance of 64 ohms. With the same current, the "antenna" in B has a radiation of only 0.5 ohm. In other words, as a radiator, A is more than one hundred times more effective than B.

10.3. *Oscillating energy of antenna*

The most popular form of antenna is the half-wave length, commonly called a *dipole antenna*. In Figure 10 : 2 (*a*), from L to M is roughly a

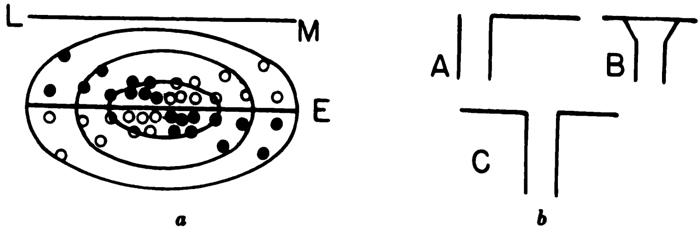

FIG. 10 : 2. EFFECTS IN HALF-WAVE LENGTH ANTENNA
(*a*) Electric (solid lines) and magnetic fields (dots) close to antenna, L-M
(*b*) Three half-wave antennas with different feeds; impedance increases in passing from A to B to C

half-wave in length. In the diagram of E, the electric and magnetic fields are those close to the antenna. When the antenna is resonant, that is, when the inductance and capacitance are equal and opposite, the total energy in the antenna remains constant. At one moment it is all magnetic (stored in the magnetic field), at another time, a quarter-cycle away, it is all electrical (stored in the electric field), but at any given instant the total energy stored—the sum of the two—does not vary.

10.4. *Large radiation resistance of antenna*

The method of feeding energy into an antenna is important. In Figure 10 : 2 (*b*) are shown three half-wave antennas fed as indicated. The total electrical impedance that each presents to the feeding lines varies from high to low in going from left to right, A, B and C.

The physical sizes of the antenna wires—their diameters—are important. The heavier they are, that is, the larger their diameters, the less sensitive they are to slight changes in frequency. Because this is

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important in radar (and in television), such antennas are not simple wires, but tubes whose thickness usually exceeds five per cent of the wave length.

The total resistance of an antenna, measured at its center, is made up of two parts: the effective resistance which depends on the material, its length, and its cross-section; and the radiation resistance. As the antennas used in radar are thick in cross-section, the effective resistance is negligible; only the radiation resistance is in appreciable amount.

10.5. *Impedance of antenna at resonance*

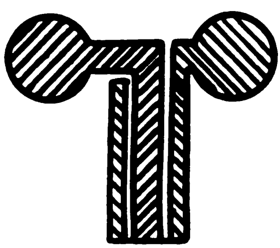
From elementary electricity, we know that the power wasted in a conductor of resistance, R, having a current, I, passing through it is

$$P = I^2R.$$

We can define the radiation resistance of an antenna as the ratio of the power radiated to the current squared, or

$$R_r = P/I^2.$$

The electrical impedance of any circuit is made up of its resistance and reactance. At resonance, the inductance and capacitance neutralize each other, and the impedance becomes a pure resistance. This applies to a half-wave antenna at the resonant frequency.



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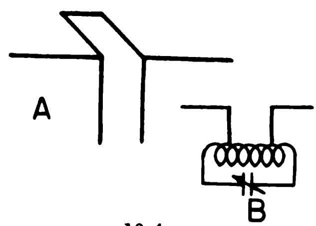

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Fig. 10 : 3. Cross Section of Stubby Antenna Dipole Used for Large Radiation and Small Corona Effects
Fig. 10 : 4. Stub Connection for Producing Resonance (A), and Equivalent Effect in Wiring (B)

When the antenna is stubby, as are radar antennas, the actual physical length is perceptibly less than the half-wave length. A common form of an antenna dipole is shown in Figure 10 : 3. This is useful where a large amount of power is radiated and corona effects—the

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discharge produced by points at high voltage—must be prevented.[1] The actual length may be twenty per cent less than the physical length for the required wave-length.

10.6. How antenna is made resonant

It was remarked (10.3) that, at resonance, the stored energy remains steady, and the antenna presents resistance only to its source of power. If, however, the antenna is less than a half-wave, it reacts to the source of power as a capacity. If the antenna is more than a half-wave, it reacts to the source of power as an inductance. In either case, the antenna may be made resonant by the use of a stub, as shown in Figure 10 : 4. The effect of the stub is shown by B. By varying either the length of the stub or the length of the antenna, resonance can be attained.

10.7. Character of fields around antennas

Figure 10 : 2 (*a*) showed the appearance of the electric and magnetic fields in the immediate neighborhood of the antenna. This is known as the *induction field*. As we move farther away, the induction field disappears and only the radiation field is perceptible.

Figure 10 : 5 (*a*) shows the apperance of the radiation field around a half-wave antenna for one moment of time.[2] The electric and magnetic fields are still perpendicular to each other. The closed arcs represent the electric field. The open and filled dots represent the magnetic fields viewed end on. These are circles whose centers are on the axis of the antenna. The filled dots represent the magnetic field going into the page; the open dots represent the magnetic field coming out of the page. At half-wave length intervals, measured radially from the center of the antenna, the fields reverse. This applies to both the electric and the magnetic fields which are everywhere perpendicular to each other and dependent upon each other. With such an antenna, the fields are strongest on a line perpendicular to the antenna at its center; they are weakest along a line running axially through the antenna. At any point in space, the change of field strength of either kind generates or produces the other. It is impossible to produce one field without setting up the other.

[1] It will be observed that the outer conductor in Fig. 10 : 3 is connected directly to one of the halves of the dipole; to prevent radiation by the outer conductor of the coaxial cable at this point, a quarter-wave decoupling choke, a sleeve one-quarter-wave in length, surrounds the outer conductor and effectively stops radiation. The sleeve choke has received the name "bazooka". Further details in Appendix.

[2] For details, see Appendix.

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The strength of the electric field about a simple half-wave antenna, is shown in Figure 10 : 5 (*b*). Observe that it is greatest along A-A and dwindles to zero in line with the axis of the antenna (D). The distance from the center to the circumference is a measure of intensity of the power in the direction shown by the arrow. This diagram shows the intensities in only one plane. To demonstrate how they appear in three dimensions or space, we rotate the figure about the antenna; the figure generated will be shaped like a doughnut (toroid).

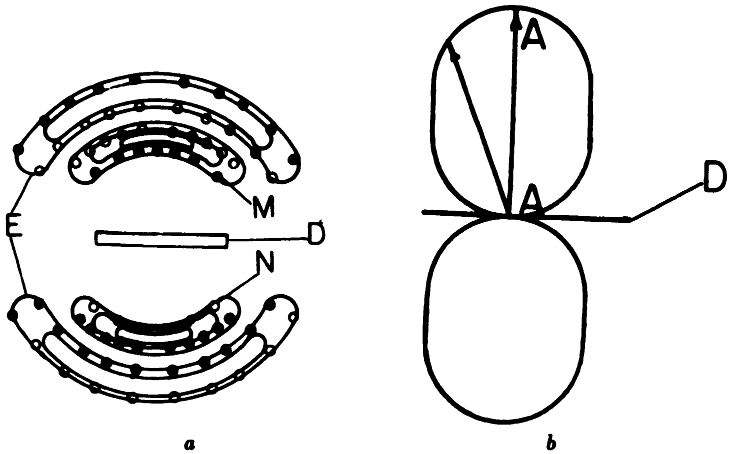

FIG. 10 : 5. FIELD OF RADIATION ABOUT HALF-WAVE ANTENNA
(*a*) Appearance of field at considerable distance: E, electric field; D, antenna; M,N, magnetic lines viewed perpendiculraly to electric
(*b*) Strength of electric field: D, antenna; A-A, intensity perpendicular to antenna at mid-point

10.8. Directivity increased by arrays

In order to obtain more directive effects, we may employ a group of antennas. These are known as *arrays*.

Figure 10 : 6 (*a*) shows the pattern of power intensity of four half-wave antennas in a row; each two adjacent antennas are separated by a half wave-length. All are fed by a transmission line in exactly the same manner, that is, all currents in the various antennas are in phase. This array, known as a *broadside* receives and transmits symmetrically with the major axis on a line perpendicular to the line that joins the centers of the four antennas. The small loops, called *minor lobes*, show the directive effects in the directions indicated.[3]

[3] For further discussion, see Appendix.

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Figure 10 : 6 (*b*) shows a group of eight half-wave antennas (not drawn to scale) with a quarter-wave separation between adjacent ones. The over-all length of the group has remained unchanged, but the number of antennas has doubled. As the effect on the pattern is hardly noticeable, we may infer that it is the over-all length, rather than the number of the antennas, that affects the pattern.

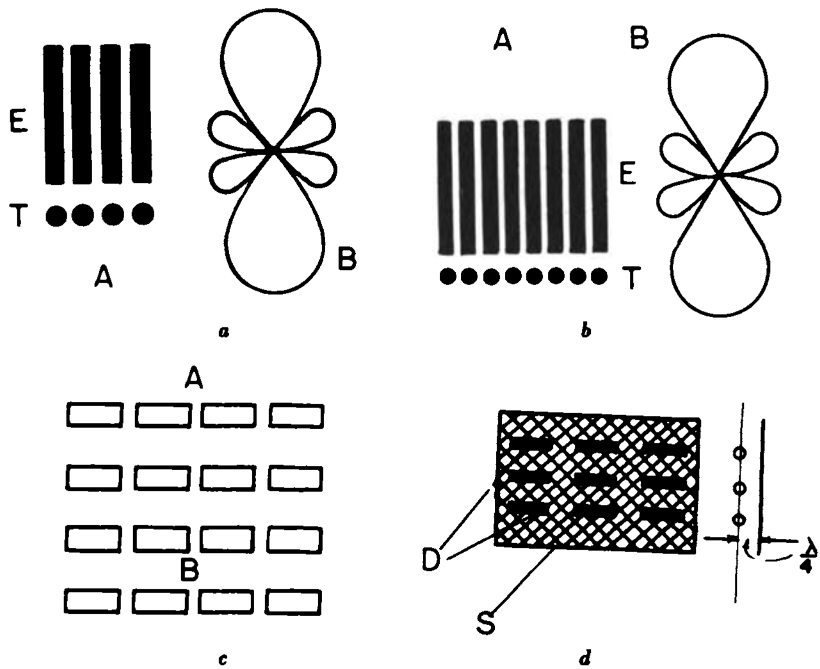

Fig. 10 : 6. Various Arrays of Antennas
(*a*) Four half-waves (A): T, top view; E, elevation; pattern of power intensity
(*b*) Eight half-waves (A)
(*c*) Broadside curtain: A, elevation; B, top view
(*d*) Array with reflector of heavy mesh screen: D, antennas; S, screen

10.9. Use of reflectors with antennas

By disposing the group of antennas in rows and columns all in one plane, as in Figure 10 : 6 (*c*), we may obtain special effects. The principal radiation is still at right angles to the plane in which the antennas lie. The directive effect is altered by varying the over-all width. By changing the height of the array, the pattern in the vertical direction is modified.

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The form of array shown in (*c*) is known as a *broadside curtain*. It transmits or receives equally well, fore and aft. In radio, such a two-way characteristic may be desirable; in radar, one direction only should be effective. A way to accomplish this is to place a reflector behind the array about a quarter-wave length away. A simple sheet of metal would function well. Where the array is large, such a sheet might not prove practical because of its weight, its wind resistance (it would act like a sail), and its opacity where visibility is essential. By way of a workable compromise, it is customary to employ a screen made of heavy wire mesh, as shown in Figure 10 : 6 (*b*). By this means, the radiation to the rear is suppressed and the radiation forward is increased by the reflection.

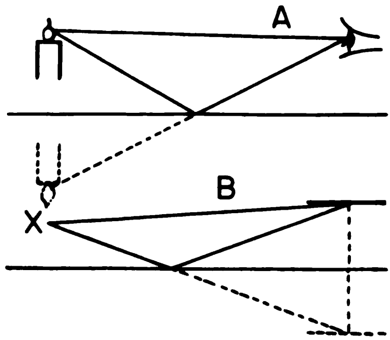

FIG. 10 : 7. SIMILARITY OF BEAM OF LIGHT (A) AND RADIO BEAM (B) IN RELATION TO REFLECTING MEDIUMS

Let us examine a single half-wave antenna with a reflector such as is used in television. At any point X in Figure 10 : 7, the actual and the reflecting antennas behave as though a light were placed before a mirror, as in A. In B, we show the antennas and their effect at a point, *x*, which receives both the direct ray and the reflected ray. Just as with the candle, the reflected ray appears as though it came from the image of the antenna, which is as far behind the reflector (mirror) as the real antenna (candle) is in front. Because the real antenna is a quarter-wave ahead of the reflector, the image of the antenna is a quarter-wave behind the reflector, making the real antenna and its image a half-wave, or 180°, out of phase with each other. In the forward direction, therefore, the effect is as though there were two antennas radiating, separated by a half-wave and excited in opposite phases. For best results, the reflector should be slightly larger than the antenna supplied with power (called the *driven antenna*).

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10.10. *Folded dipole antenna*

In the ordinary half-wave antenna or dipole, the characteristic input resistance at the center where it is fed is 73.5 ohms. If we double the length of the dipole and fold it over so that it appears as in B of Figure 10 : 8 (*a*), we have what is known as the *folded dipole.* The characteristic resistance of such an antenna is four times that of a simple half-wave antenna.

10.11. *Paraboloid antennas and horns*

We have already observed that short waves, such as are used in microwave radar (centimeter wave lengths), behave in many respects like light waves. In Figure 10 : 8 (*b*) is shown a dish-like reflector

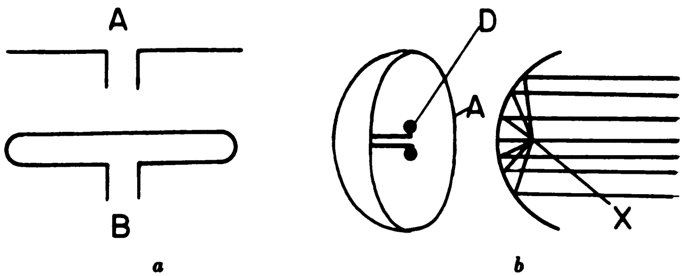

Fig. 10 : 8. Dipole Antennas
(*a*) Ordinary dipole (A); folded dipole (B)
(*b*) Paraboloid antennas: A, dish; D, dipole

known as a *paraboloid* (made by rotating a parabola). It has a central point, X, which is the focus of the paraboloid. If a light source of small dimensions (theoretically, a point) is placed at the focus of such a dish, all the reflected light is emitted in a parallel beam. If a radiating dipole is placed at the focus of a paraboloid, the electromagnetic beam is almost parallel, and the dispersion or spread of the beam is slight. As the dipole is not a point, however, but a surface, the direct beam from the focus will not come from a point. The larger the dish is in respect to the dipole, the more nearly parallel will be the beam that issues from the reflector. If the diameter of the mouth of the paraboloid is many times larger than the wave length, the beam can be made to approximate an ideal one with no dispersion.

Horns may be employed effectively as antennas or radiators of electromagnetic waves. Their principal disadvantages is the fact that they require relatively great space. On land, there is little or no bar to their

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use. There is little practical choice between square or conical metallic horns so far as results are concerned. The most favorable angle of flare (taper of the horn) is 50°. If the horn is very large, this angle will be slightly decreased. The beam can be made as narrow as desired; it is exceptionally free from spurious or undesirable lobes. In practical horns, the material of the horn can be quite cheap, viz., sheet iron. As the maximum length is short, the attenuation is low, and hence the character of the walls is of little consequence.

When an array of horns is employed with parallel axes, the amount of interaction between horns is remarkably slight. As a result, a receiving and a transmitting horn can be fixed side by side with little or no interference.

10.12. *Cosecant square antenna*

An interesting form of antenna that has been widely used is the *cosecant square* dish, shown in Figure 10 : 9 (*a*). It owes its name to the fact that the intensity of the signal transmitted by it varies as the

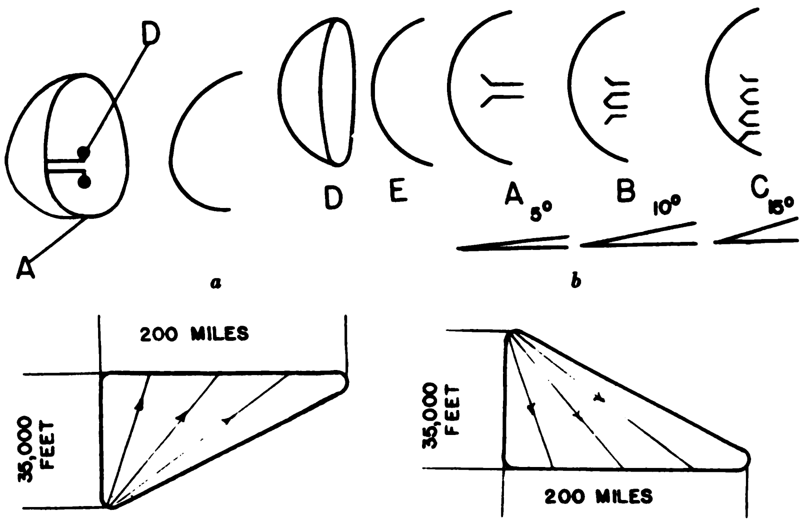

Fig. 10 : 9. Cosecant Square Antennas

(*a*) A, dish; D, dipole

(*b*) Operation of cosecant square antenna: D, paraboloid E, cross section of dish; dish with (A) one, (B) two, (C) three horn feeds. Angles below indicate coverage

(*c*) Plot of ground radar employing cosecant square antenna

(*d*) Plot of air-borne radar employing cosecant square antenna

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square of the cosecant of the angle between the horizontal and the line of the target. The following illustration should make this clear.

Suppose we had an antenna reflector, elliptical in outline, parabolic in section, and of the dimensions shown in Figure 10 : 9 (*b*) at D and E. It is fed by the horn at the focus, and produces a beam of five degrees from the horizon, vertically. Now let us add a second horn feed below the first, as in B. The second horn spreads the beam from five to ten degrees above the horizon. Similiarly, by adding still a third horn feed below the second, as in C, we spread the beam to fifteen degrees above the horizon. Why do we do this?

We may desire to employ a radar for long-range detection of airplanes, as far out as two hundred miles and as high up as 35,000 feet. We grade the power sent into each feed, giving the uppermost horn, with the lowest beam, sufficient power to reach the full extent of two hundred miles. The center horn should emit enough power to reach one hundred miles, and the lowest horn, sixty miles.

Each horn is so graded that a target first detected at the extreme range of two hundred miles and 35,000 feet will be least visible until it has passed at the elevation of fifteen degrees.

Instead of multiple feeds and the complication resulting therefrom, we can employ a single feed, but the reflecting dish must then be shaped to give the desired range contours. This is what the cosecant square dish accomplishes.

Figure 10 : 9 (*c*) shows a plot of the ground radar employing a cosecant square antenna. In an airborne radar, as the least energy is required for the closest ground siguals, the radiation from the cosecant square is in a downward direction, as shown in Figure 10 : 9 (*d*).

10.13. How antennas are fed

The method by which the transmitted power is supplied or fed to the paraboloid is important. It may be fed from the front or from the rear; it may be supplied by a wave guide or by a coaxial transmission line. In Figure 10 : 10 (*a*), A shows a front feed, and B and C, rear feeds. The feeds terminate the transmission line and should match perfectly; in addition, the termination should cover or spray the reflector surface entirely with the wave energy. The focus of a paraboloid may be short and deep, as in A of Figure 10 : 10 (*b*); or long and shallow, as in B.

In the former, the termination of the feed will lie well within the dish, with the result that only a part of the dish receiving energy from the feed is effective; in the latter, the termination may lie well in

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advance of the dish and though the entire surface may be sprayed with energy, much of the energy will fall outside of the reflector and be wasted. Instead of a paraboloid, the reflector may consist of a section of a paraboloid, as in A of Figure 10 : 10 (*c*); or it may be a cylindrical segment as in B. Such antennas have the features of a parabola along only one axis. They emit narrow beams in one direction and broad beams at right angles.

A coaxial feed terminates in a half-wave dipole. This must be matched to the coaxial transmission line to avoid standing waves caused by the reflection. The transmitted energy from the dipole is returned to the main reflector by means of a small second reflector placed a quarter-wave length from the dipole which, in turn, should be placed at the focus of the paraboloid.

In Figure 10 : 10 (*d*), the termination of the feed to the wave guide is a horn. The flare and length of the horn are adjusted until the entire reflector is sprayed with energy. Here, the termination of the horn

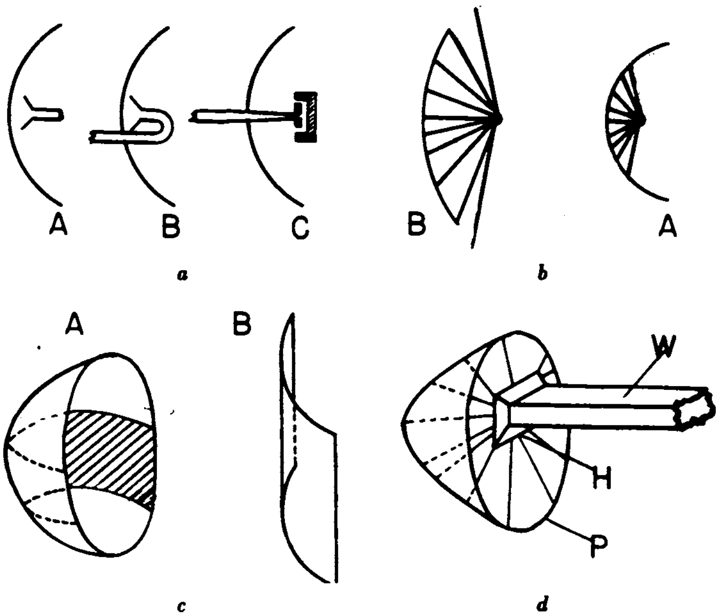

FIG. 10 : 10. PARABOLOIDAL DISHES

(*a*) Methods of feeding: A, front feed horn; B, rear feed horn; C, rear feed Cutler radiator
(*b*) Short focus (A); long focus (B)
(*c*) Reflector consisting of section of paraboloid (A); cylindrical segment (B)
(*d*) Horn termination of wave guide illuminating paraboloidal dish

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feeds into space. To obtain a perfect match, the horn must match the impedance of space.[4]

10.14. Dielectric antenna, or polyrod

There is no reason why a wave guide cannot consist entirely of a dielectric. Such a wave guide could transmit power. Practically, the losses in the ordinary dielectric would make this type of wave guide inefficient. Still more serious, any inequality or irregularity in the guide would cause energy to be radiated out into space. This very defect has been transformed into a virtue: Antennas known as *polyrods* are built of dielectrics, chiefly polystyrene. If the diameter of the dielectric rod is large compared to the wave length, and the dielectric constant is high, most of the electromagnetic field is confined to the interior of the dielectric.

If by some means, such as coupling a dielectric rod to a wave guide or a coaxial cable, the waves are introduced into the dielectric, they will travel along it to its termination, where there will be an abundance of radiation. By suitable tapering such a polyrod, that is, decreasing its diameter gradually, more of the electromagnetic energy is forced out as radiant energy. Using an array of polyrods, either end fire or broadside (**10.8**), a directional gain as high as one hundred (20 decibels) has been obtained in practice.[5]

10.15. Energy paths from antenna

If the antenna of a radar were isolated in space away from the earth and other bodies, it would simplify calculations. Because we are bound to the earth, we must consider a number of features that affect our calculations. An antenna sends out electromagnetic energy. Some of it is transmitted directly, some is reflected from the earth's surface; some is reflected from a conducting layer of air known as the *ionosphere* (also known as the Kennelly-Heaviside layer), and some energy follows the contour of the earth.[6]

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[4] If the horn is not matched, electromagnetic energy will be reflected instead of being entirely radiated out, and standing waves will be set up in the wave guide.

[5] The performance is affected by its nearness to objects, and whether they are conducting or insulating. Metal rods will not be effective unless they are brought nearer than a wave length from the polyrod. Dielectric sheets can be brought even closer without perceptible effect. For gains not exceeding 100 (20 db), polyrod arrays are very compact and quite mobile. Such an array has found important use by the Navy in fire control.

[6] The ionosphere consists of a series of layers, which extend above the earth from 30 to 250 miles. The lowest layer is named *D*, highest, *F*. They are largely composed of ions, due to the sun, cosmic rays, etc; at microwave frequencies, they are of very little consequence.

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In Figure 10 : 11 (*a*), we show the paths taken by the direct and reflected waves. What is known as the surface wave dies out quickly and assumes importance only at short range—a mile or two. The wave reflected from the ionosphere is extremely important in commercial radio and broadcasting. For radar (at least for microwaves), the ionosphere is transparent and does not reflect. Such waves travel in straight lines along the line of sight. The practical limit of transmission is set by the intervening hump of the curvature of the earth (Figure 10 : 11 (*b*)).

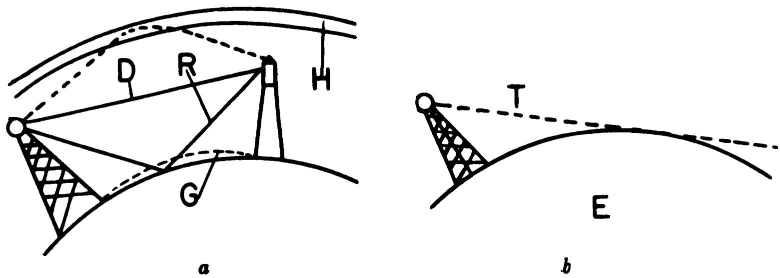

FIG. 10 : 11. PATHS OF RADIATION
(*a*) Direct (D) and reflected (R) beam; G, ground wave; H, ionization layer
(*b*) Limit of beam from transmitter (T) set by curvature of earth (E)

10.16. Effect of Earth on transmission

The ground wave reflected by the earth's surface is important. The effect of reflection from the ground when coupled with the direct beam from a transmitter is to enhance greatly the intensity of the field in some directions, where the directed and reflected beams aid each other, and to neutralize completely the fields in intermediate directions, where the direct and reflected beams are entirely opposed. As a result, instead of two broad lobes representing the field of radiation in isolated space from a dipole, this field consists of a series of lobes as shown in Figure 10 : 12 (*a*).

For purposes of calculation, the surface of the earth is considered a perfect reflecting plane, just as though it were a sheet of metal. If we treat the surface as a level boundary, the apperance of the direct and reflected rays would be as shown in Figure 10 : 12 (*b*). With a perfect reflector, all the energy that strikes the reflecting surface leaves it again. When the angle is favorable, the electromagnetic energy[7] striking the target is actually doubled because of the reflection. This

[7] See Appendix.

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means that the energy returning in the echo is doubled; or, to state it otherwise, the same energy from an echo would be returned from a target twice the distance away because of the enhancement by the reflecting surface.

We saw (2.4) that to double the distance of detection by a radar transmitter requires an increase of power that varies as the fourth power of the distance. To transmit to, and detect, a target twice as far, requires 2^4 or $2 \times 2 \times 2 \times 2$ times as much power, or a sixteen-fold increase. So, at favorable angles, the increase in range due to the earth's reflecting surface is equivalent to a sixteen-fold increase in transmitting power.

Where the distance or range is great, we cannot ignore the curvature of the earth. The reflecting surface is no longer considered a flat plane. C, in Figure 10 : 12 (*c*), shows a beam reflected by the surface, as from a nearby target. As a radar beam is a bundle of rays, not just a line, it has appreciable thickness. The outermost lines shown represent the boundary lines of the beam. The angles of incidence are always equal to the angles of reflection. When the transmitter and the target are close, the earth may be considered a flat surface. If we took a cross-section of the beams at A-A and B-B, they would appear as circles of equal area, as in D, and we say that the reflected beam has suffered no dispersion or spread.

Now let us consider the effect of increasing the distance almost to the limit of the transmitting range. The angles of reflection of the rays are still equal to the angles of incidence. Because of the perceptible curvature of the earth's surface, the rays of the reflected beam will spread. A cross-section now of the direct and reflected beams at A-A and B-B, respectively, will appear as in D of Figure 10 : 12 (*c*). The reflected beam is being dispersed or spread, and the reenforcement of the direct beam to the target is diminishing. Finally, at the extreme range of the target, which is the same as the line of sight range, only the direct beam strikes the target; there is no reenforcement from reflection. This is readily seen in E.

10.17. Radar line of sight

We have mentioned the line of sight limitation. As a matter of fact, the visual line of sight is different from the radar line of sight. In physics, we discuss the phenomenon known as *mirages*. Because of the differences in the refracting powers of the layers of air the speed of light through these layers will differ. In travelling over a hot desert, the air

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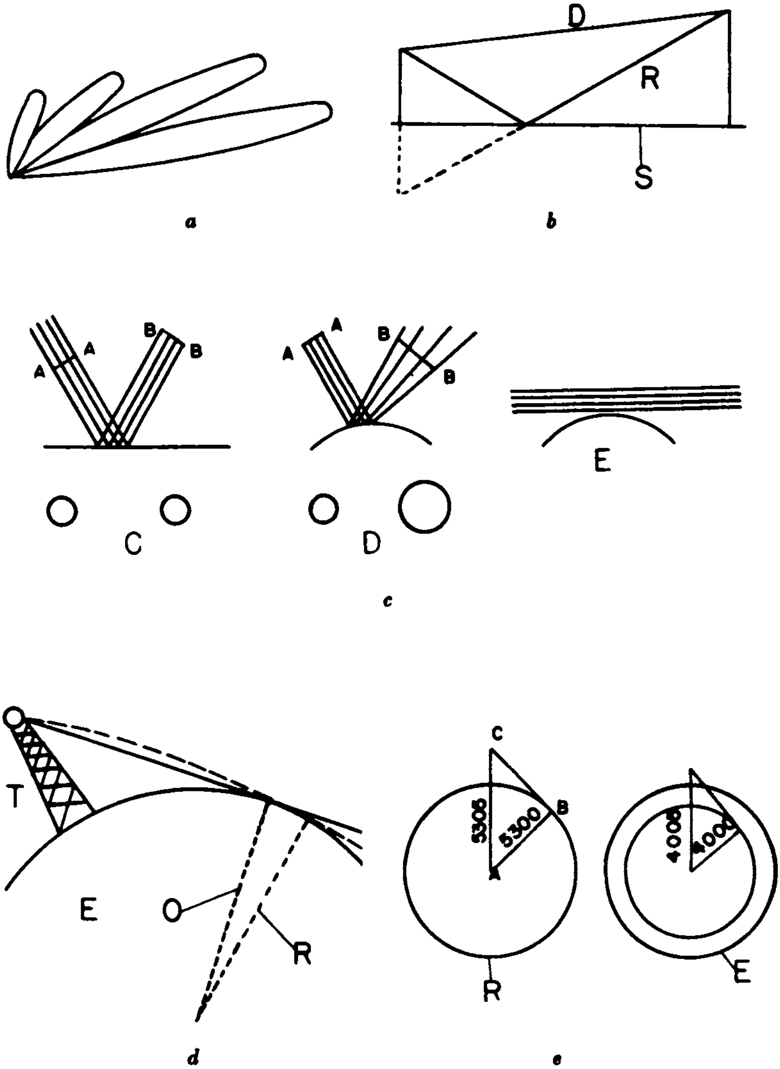

FIG. 10 : 12. EFFECTS OF EARTH ON TRANSMISSION
(*a*) Field of radiation from dipole antenna
(*b*) Behavior of direct (D) and reflected (R) beam from earth's surface (S)
(*c*) Scattering of reflected beam caused by curvature of earth: C, from flat, D, from curved surface; E, grazing angle
(*d*) Visual lines and radar lines of sight from transmitting tower to earth; O, visual, R, radar radius
(*e*) Comparison of radar earth (R) with actual earth (E)

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immediately over the desert may often be hotter and therefore less dense than the air farther up in the atmosphere. This is a reversal of what we consider normal conditions. That is, that the higher we go, the rarer is the atmosphere. Because of this freakish condition in the air, the visual line of sight is refracted or bent and we have mirages. Our optical horizon, normally set by the hump or curvature of the earth at about twenty miles, may be greatly increased.

Because the layers of air are not uniform, because the atmospheric pressure and temperature drop as we rise, and because of its water content, we have a medium of varying refractive powers for radar waves. As we ascend, the refractive index of air decreases and the electromagnetic velocity increases (being at the maximum in a perfect vacuum); that is, the radar waves move faster in the upper atmosphere than near the earth's surface. The radar waves are thus bent toward the earth.[8]

In Figure 10 : 12 (*d*), we show the ordinary visual line of sight and the radar of sight. The effect is the same as though we had a larger earth and straightened out the radial line of sight to a tangent. Investigation shows that for the atmosphere under standard conditions, we should multiply the radius of the earth by 4/3 to obtain a fictitious "radar earth" where the radar lines of sight would then be straight lines. If the radius of the actual earth is 4000 miles, the radius of the radar earth is $4/3 \times 4000$ or approximately 5300 miles. When the engineer desires to calculate the maximum range of a radar transmitter, he therefore employs this radius of 5300 miles and computes the length of the tangent to this fictitious sphere.

In Figure 10 : 12 (*e*), we desire to find the radar horizon of an airplane five miles up. In the right triangle, ABC, we must determine the length of the side BC. From simple geometry, BC is $\sqrt{(5305)^2 - (5300)^2}$ or 230 miles, approximately. The actual optical line of sight would be the length of the tangent to the actual earth whose radius is taken at 4000 miles. This comes out 200 miles, approximately. Thus, because of the curvature of the radar vision, our horizon is extended thirty miles.[9] This horizon is well beyond the transmission limit of the power of an ordinary airborne transmitter.

10.18. Metal lens antenna

A form of microwave antenna adapted for ground or stationary use is the so-called *metal lens*. Two views of this antenna are shown in

[8] See Appendix.

[9] See Appendix.

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Figure 10 : 13 (*a*). Microwaves, like light waves, can be refracted or bent; this is another way of saying that they can be focused. The assembled wave guides that comprise the lens have the contour (in the axial cross-section) of a plano-concave lens. The amount of refraction or bending depends upon the depth of the cells in the wave guide from front to back, just as the amount of bending produced by an optical lens depends upon the thickness through the glass.[10]

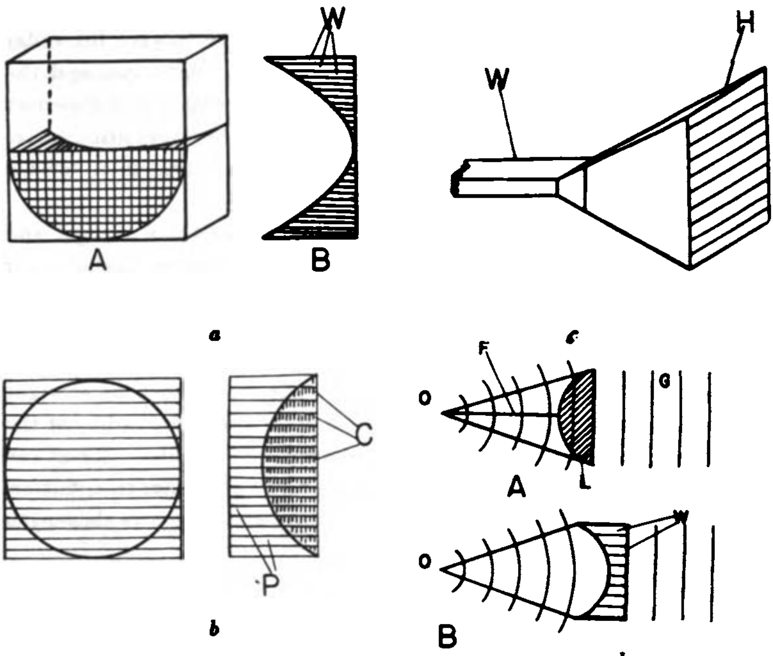

FIG. 10 : 13. METAL LENSES

(*a*) Front view (A) showing cells of wave guide; B, side section, showing contour of wave guides (W)
(*b*) Use of metal strips (C) embedded in slabs of polystyrene foam (P)
(*c*) Practical form of metal lens: wave guide (W) terminates in pyramidal horn containing lens (H)
(*d*) Similarity of optical lens and radar lens: A, plane-convex glass lens (L); B, equivalent plano-convex radar lens; (W) wave guides

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[10] In passing through wave guides whose cross sections are close to cut-off, the phase velocity is increased beyond the velocity of the wave in free space (3.10); hence, the longer the wave guide, the greater is the shift in phase. In this respect, a wave guide lens is the inverse of an optical lens. If the contour of a wave guide lens is convex, it behaves toward electromagnetic waves as a concave lens does to light; if the contour is concave, it behaves like an optical convex lens toward light.

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Theoretically, it is quite possible to make a lens of some transparent dielectric that can focus microwaves, as a glass lens focuses light waves. For a seven-centimeter wave (employed in actual relay transmission today), a ten-foot lens would be necessary. The weight, unwieldiness, and expense of such a huge mass makes it wholly impracticable. Instead, the metal lens has been adopted. This is composed of extremely thin strips of copper foil, which is laid in slots cut in a very light substance such as polystyrene foam as shown in Figure 10 : 13 (*b*).

From our knowledge of physics, we know that all glass has a refractive index *greater* than unity. A convex lens causes a *convergence* of light rays; a concave lens causes a *divergence* of light rays. The metal lens shown in (*a*) employed for microwaves has a refractive index *less* than unity; hence, a *concave* metal lens causes a *convergence* of the microwaves. The metal lens is being used for microwave relay stations at present. A practical form consists of a ten-foot frame to hold the lens which is fed by a wave guide, that terminates in a pyramidal horn, seen in Figure 10 : 13 (*c*). An important advantage of the metal lens over a paraboloid (see **10.11**) of comparable size is the greater tolerance it permits in construction and deformity. A reason for this is obvious from the fact that the energy from the horn feeds *through* the lens; in a paraboloid, the energy is fed against the paraboloidal surface from which it is *reflected*. Errors due to irregularities are multiplied by two. The similarity between an optical lens focusing ordinary light waves and a metal lens focusing microwaves is easily seen in Figure 10 : 13 (*d*).

In A, a point source of light is placed at the focus of the lens O. All the rays striking the lens at an angle are bent or refracted; only the ray F on the exact center, which strikes the lens surface exactly perpendicularly, passes through unaffected. The extent of the refraction depends upon two factors: the obliquity of the striking rays and the thickness of materials in the lens. The farther we go from the center of the lens, the thinner is the cross-section of the lens. The rays are retarded less as we leave the center, the effect of the obliquity of the light rays is compensated by the smaller bending or refraction, and in consequence, the rays emerge on the far side in parallel beams.

We may consider the metal lens in B as an assemblage of wave guides of varying lengths. A wave passing through the outermost cells is retarded *least*, because of the *greater* distance covered in the wave guide; a wave passing through the center is retarded *most*. This is the

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reverse of conditions in the optical lens because the index of refraction is *less* than unity for the lens of a wave guide.

The disadvantage of a wave guide lens is its bulkiness as compared, for instance, to a paraboloidal dish. The individual cells of a wave guide should be larger than a half-wave length so that they will exceed the cutoff wave length and not increase the attenuation excessively.

The advantage of a metal lens over that of a paraboloid is in the greater tolerance allowable in the former. For microwaves, the greatest permissible variation in a paraboloid is a few hundredths of an inch. A metal lens may be distorted as much as a quarter-wave length. Because the waves suffer attenuation, the individual cells or wave guides of the metal lens should not be smaller than a half-wave length in order to keep the attenuation low.

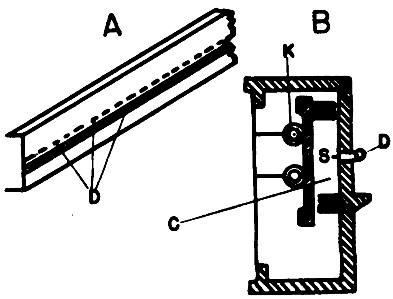

Fig. 10 : 14. Antenna consisting of Linear Array of Dipoles Fed from Wave Guides
A, external front view; B, cross section of assembly; D, dipoles; K, roller cams; C, variable wave guide space; S, stubs terminating dipoles

10.19. Multiple dipole array

Figure 10 : 14 A shows a linear array of dipoles spaced a half-wave apart. What is particularly deserving of attention is the manner in which they are fed, and the means employed for directing the beam. This form of antenna is important for use in peacetime; it is now employed widely in the GCA (ground control approach) method (14·1) of guiding airplanes to a landing.

Each of the dipoles projects into the channel of a wave guide, shown in section B of Figure 10 : 14. By means of cams, actuated by a driving motor, the width of the section of the wave guide can be varied over appreciable limits, and the phase of the individual feeds varied. The

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effect of variation in the width of the wave guide is to cause the combined wave front to shift from side to side over an angle of 60°. In the radar known as AN/APQ 7, operating at three centimeters, the antenna is composed of 250 dipoles; the width of the beam is only 0.4 of a degree; the total length of the antenna is 16.5 feet, and its weight is 180 pounds.

The relation between the angle (α) of the azimuth beam, the width (w) of the guide, the spacing of the dipoles (s), and the wave length in free space (λ_f) is given by the formula

$$\sin \alpha = \sqrt{1 - \left(\frac{\lambda_f}{2w}\right)^2} - \frac{\lambda_f}{2s}$$

Spacing between centers of adjacent dipoles is equal to half of the width of the guide, when this is 1.2 inches. The adjacent dipoles are reversed so that actually they are all in phase. The side lobes are only two to five per cent of the main beam. An entire assembly weighs 412 pounds.

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Chapter 11

OBSERVATIONS ON RADAR SYSTEMS

11.1. Simple radar in block form

We have examined and studied vital components of radar and described their essentials and characteristics. Now let us see the organism as a whole in the light of what we have learned.

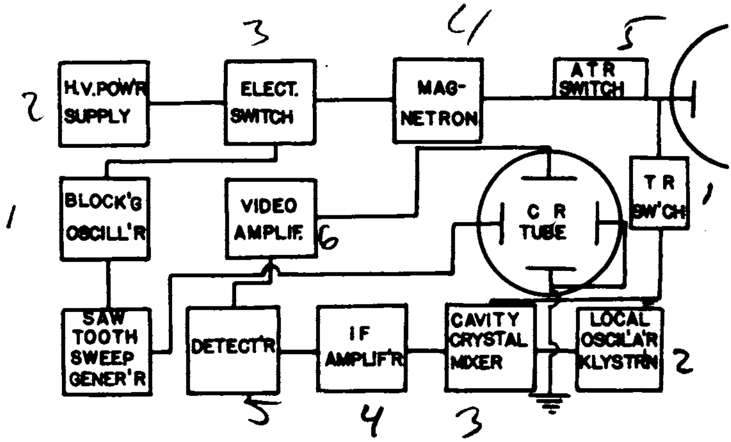

Fig. 11 : 1. Radar System in Block Form

Figure 11 : 1 shows an entire radar system in block form. We have already studied the various components; it should therefore not be difficult to follow the operation of the connected units.

Let us begin with the blocking oscillator (6.14) which could just as easily be a multivibrator (6.10). The oscillator generates a series of

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sharp pulses of one microsecond duration, for example, and at the rate of 1000 per second; this means that it produces a pulse every 1000 microseconds (1/1000 of a second).

The pulse from the blocking oscillator triggers (sets off) the saw tooth generator (6.6) which, in turn, supplies the saw tooth voltage to the horizontal plates of the cathode ray tube and produce the saw tooth sweep. Note, also, that the blocking oscillator is connected to the switch, which is triggered or closed by the pulse 1000 times a second. Thus, 1000 times a second, a high voltage from the high voltage supply is applied to the magnetron, which oscillates for a microsecond at an amplitude of 24,000 volts (for example). The microwave oscillations are fed by the magnetron into the antenna from which they are sent out toward the target.

The T-R switch (9.1) will prevent any appreciable quantity of this enormous energy from entering and probably ruining the crystal mixer. Some microseconds later (it cannot be more than 1000 microseconds because this is the present rate of repetition), depending on the distance of the target, some of the energy echoed from the target will return to the same antenna. Now, the A-T-R (9.6) switch will prevent the energy of the echo from entering the circuit of the magnetron or transmitter; practically all of the energy from the echo will pass through the T-R switch into the crystal mixer (or converter). Here it will combine or beat (5.12), with the oscillations from the local oscillator, a reflex klystron (4.9). The beat or difference in frequency (usually 30 or 60 megacycles in radar will feed into the IF amplifier (5.5) where it is increased and then detected. From the detector (5.6), in the form of video frequency signals, it passes to the vertical plates of the cathode ray tube.

The start of the linear sweep of the cathode ray tube is synchronized with the high-frequency pulses leaving the magnetron by the triggers from the blocking oscillator and hence, the transmitting antenna. The occurrence of an echo pip along the sweep of the cathode ray tube will depend upon the elapsed time from the transmitter to the target and back from the target to the receiver. As the horizontal trace of the screen of the cathode ray tube represents distance, it is usually calibrated in miles. If we note the location of the echo pip on the screen, we will obtain on a type A screen the distance of only the target. To get the angle of elevation of the target—an airplane, for instance—and its bearing, we must simultaneously observe the angular elevation and the azimuth of the antenna beam.

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A numerical illustration should make the previous statements clearer. We will assume that we have spotted an airplane twenty miles away. Pulses are being sent out by the transmitter at 1000 a second, or one every 1000 microseconds. As the duration of the pulse is one microsecond, each pulse is followed by a period of silence of 999 microseconds in which the transmitter is cut off. As the radar energy covers 1000 feet in a microsecond, the time of travel to the target and back, forty miles, will be 40×5280 divided by 1000 or 211 microseconds. If the saw tooth sweep is designed for 400 microseconds, that is, if the range (7.7) is adapted for a full sweep across the cathode ray tube in 400 microseconds, the echo pip at 211 microseconds will appear slightly past the center of the screen. The height of the plane above ground (angular elevation) and the direction with respect to the radar (azimuth) will be given by the direction the mobile antenna is facing.

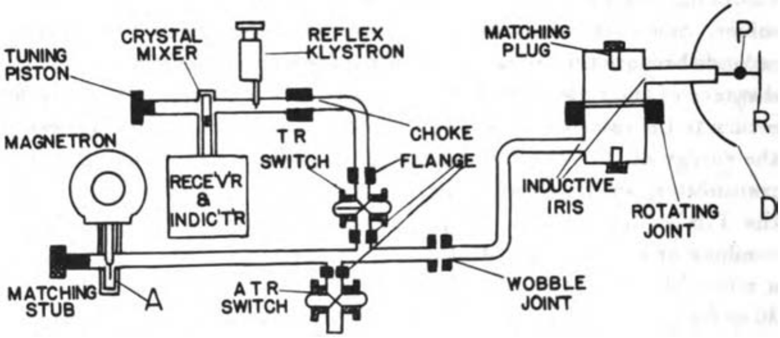

FIG. 11 : 2. RADIO FREQUENCY ASSEMBLY OF 3-CENTIMETER RADAR
A, coupling of magnetron with wave guide; D, antenna dish; P, dipole; R, reflecting disc

11.2. *A three-centimeter radar system*

In Figure 11 : 2 is shown the radio-frequency setup of a three-centimeter radar. Note that the magnetron is coupled to the wave guide by a stub that crosses the entire width of the narrow dimension of the wave guide. This stub serves as a local antenna feeding into the wave guide that it excites. The wave guide, which is rectangular, contains an $H_{0,1}$ mode ($TE_{0,1}$). The stub or probe of the magnetron is parallel to the electric field in the wave guide that it excites. At the extreme lower end is a choke plunger which prevents the escape of the electromagnetic energy and helps to match the guide to the stub of the magnetron.

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The magnetron coaxial stub is sealed into a glass tube. The metal block of the maguetron serves as the anode; the outside of the glass seal is copper-plated and it makes contact with the anode. As the central conductor must be connected to the central conductor of the coaxial cable that feeds into the antenna, special precautions are taken to prevent the glass seal from being cracked or broken because of mechanical strains. The projecting stub of the magnetron fits into a long recess in the end of the coaxial cable but makes no physical contact with it. As the recess is a quarter-wave long, it and the stub of the magnetron make up a coaxial line that is open-ended. At point A, therefore, the impedance of the magnetron stub and the coaxial extremity is very low (3.27). It is equivalent, in fact, to a metal joint; yet the lack of physical contact prevents any stresses being transferred to the glass of the seal.

The joint of the choke flange permits continuity of the wave guide without a mismatch. The choke joint (3.32) prevents leakage and acts like a short-circuit across the gap between the two lengths of abutting wave guide. The joint, called a "wobble", separates physically the sections of the wave guide by an actual air space so that no vibration or stresses occurring in the antenna portion are communicated to the remainder of the radar set. Because of the quarter-wave choke incorporated, even a separation of several millimeters (3.32) produces no electrical discontinuity or mismatch.

For matching the rectangular wave guide to the circular wave guide, an inductive iris (3.31) is interposed. The circular rotating joint is equipped with a quarter-wave choke and the screw plugs at the top and bottom serve to match both this choke with the antenna wave guide and the main wave guide to the transmitter. The wave guide pierces the center of the paraboloidal dish and ends with a small dipole which is parasitical (4.2). It is fed inductively and backed by a metallic disc which helps to reflect energy over the entire surface of the paraboloidal dish.

The receiving part of the circuit is connected to the main wave guide by means of a series joint along the broad face. The T-R (9.1) and the anti-T-R (9.6) switches are the series types, coupled to the wide dimensions of the wave guide. The anti-T-R switch is coupled to the main wave guide by a choke joint to prevent a mismatch. The T-R switch, because it must afford a through passage to the receiver, requires two choke joints, one on each side. Both switches are tuned (their resonant cavities) by screw plugs (9.3). The RF energy is fed into the crystal

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mixer which spans the narrow dimension of the wave guide. The local oscillator, a reflex klystron (4.19), also feeds into the crystal mixer and is coupled to the wave guide by a partially entering probe. The oscillator is matched to the crystal by means of the adjustable tuning plugs (3.24). Similarly, the wave guide beyond the crystal is carefully terminated by a tuning piston containing a quarter-wave choke plunger.

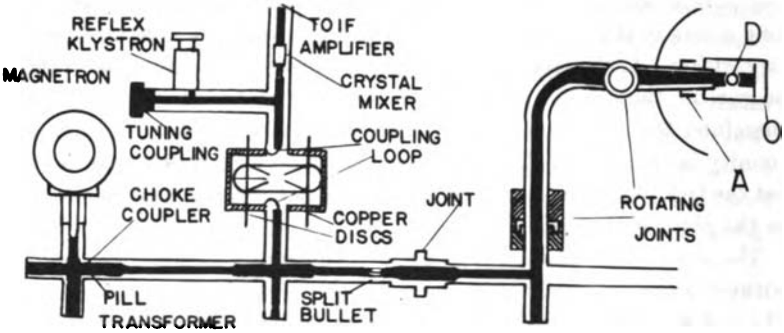

FIG. 11 : 3. RADIO FREQUENCY ASSEMBLY OF 10-CENTIMETER RADAR A, quarter-wave bazooka or coupler; D, dipole, O; transparent polystyrene housing

11.3. *A ten-centimeter radar system*

Figure 11 : 3 shows the RF constituents of a common type of ten-centimeter radar employing coaxial connections (3000 megacycles makes this permissible). The oscillator is a magnetron, coupled to the coaxial line through a choke coupler (3.32). This employs the rigid coaxial transmission line whose rigid center conductor is supported on quarter-wave stubs (3.27). The outer conductor or external piping is connected in lengths by means of bolted flanges; the central conductors are connected by means of hollow-socket and split-bullet plugs. The transmission line between the magnetron and the T junction has no means of adjustment; when once installed, it is permanently fixed. To facilitate matching the magnetron to the transmission line, a "pill" transformer[1] box is employed, a quarter-wave length of enlarged diameter. To prevent a mismatch with the antenna, a double-stub tuner (3.28) is inserted.

Because of the two capacitive joints (3.32), the antenna, which is a paraboloidal dish, may be rotated completely in azimuth, and it may

[1] Name is derived from its resemblance to a pill box.

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be swung vertically through a large angle (60°). The paraboloid is fed from the rear by means of the coaxial conductor which terminates, through a junction (bullet-and-socket), in a direct-feed dipole. The disc reflector is supported on a stub, and the entire dipole and disc are enclosed in a transparent polystyrene container. The coaxial cable is connected directly to the dipole, the inner conductor to one half of it, and the outer conductor to the other half. For this reason, it is necessary to interpose the quarter-wave decoupling choke called a "bazooka" (10.5) to prevent the outer conductor of the coaxial cable from becoming a radiator.

The connection from the T-junction to the T-R switch is made through a coupling loop that engages the field in the chamber made by the copper disc terminals (9.3) of the T-R tube. The outgoing loop of the cavity feeds the echo pulse into a crystal mixer, which is also supplied through another arm with the output of the local oscillator, a reflex klystron. The beat product from the mixer (the IF output) is fed into the IF amplifier. By means of a screw head, the beating oscillator may vary its coupling and control its intensity.

11.4. Relation between pulse and range

In the light of the foregoing pages, let us examine the pulses of a radar more carefully. A pulse travels with the speed of light, 186,000 miles a second. In a microsecond (millionth of a second), therefore, it will move 186,000 × 5280/1,000,000, or approximately 1000 feet; and cover a mile in approximately five microseconds. To detect a target one mile off, the pulse and echo must travel a total of ten microseconds. A target fifty miles distant, will require 50 × 10 or 500 microseconds for its detection.

11.5. Relation between size of target and width of beam

If the sweep across the screen of a cathode ray tube is five inches for the fifty mile range, and we employ a pulse of one microsecond (which covers a range of one thousand feet), this will represent 1/250 of the full width of the screen of the cathode ray tube (for a type A indicator). The breadth of the pulse on the screen should be 1/250 of 5, or 1/50 of an inch. But the diameter of the beam of a cathode ray tube when well-focused is about one millimeter (7.4), so the minimum diameter of a target that can be detected will be one millimeter, which is 1/25 of an inch. Thus, the minimum limit in size of the smallest target visible on the screen will be 4/100 of an inch, and this is set by the diameter of

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the beam focused by the cathode ray tube. To employ an analogy, if we were painting lines with a brush, obviously the width of a line could not be narrower than the thickness of the brush. A house painter's brush is unfit to perform the function of an artist's camel's hair brush.

11.6. Relation between width of pulse and range of resolution

As one antenna serves for both receiving and transmitting, reception will not be possible during the transmission of the pulse. The duration of the pulse thus sets a lower limit to the range. As a pulse of one microsecond corresponds to 1000 feet of distance, 500 feet would then be the minimum range on a radar with such a pulse (for the outgoing and echo pulses cover a total distance of 1000 feet).

The accuracy or precision of range measurements is controlled by our ability to measure time with precision. If the error must not exceed three yards, the error in time must not exceed a hundred-millionth of a second (a hundredth of a microsecond). If this is the fact, then the error will not exceed three yards whether the range be a thousand yards or 50,000 yards. In other words, the error in range is absolute.

We have observed that the pulse (4.14) of a radar transmitter covers a band of frequencies rather than a single frequency. The width of the band is inversely related to the width of the pulse; that is, the narrower the pulse, the greater must be the width of the band. Thus, if a pulse of one microsecond requires a bandwidth of two megacycles, a pulse of half a microsecond will require a bandwidth of four megacycles. The ability of a radar beam to reveal two targets directly in line will depend on the width of the pulse and the separation of the targets. This ability is called the *range resolution*. The shorter the pulse, the better the range resolution; that is, the closer will be the targets that can be shown separately. There is a definite relationship between the width of a pulse and the range resolution. The minimum distance between two targets is half the width of the pulse. Thus, a pulse of five microseconds would have a length of 5000 feet. Therefore, two targets would be shown separately only if they were 5000/2—at least 2500—feet apart.[2]

[2] As a target reflects energy for the duration of the pulse, a one-microsecond pulse will show a width of approximately 500 feet—the minimum in range resolution. With such a pulse, an object 500 feet in extent, or a sheet of metal one hundredth of an inch thick will appear as a single pip; or, if two objects are separated by less than 500 feet in range, they will appear as one on the screen of the cathode ray tube.

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The reason for this should become clear as we study the diagrams in Figure 11 : 4 (*a*). A shows a series of 5000-foot pulses leaving a transmitter. At 1 and 2, in B, are shown two targets, 2500 feet apart. The forward edge of the pulse has just reached target 1. This means that echoes are returning to the radar receiver. At C, the advancing pulse has reached target 2, and target 1 is at the center of the 5000 foot pulse. The radar has been receiving echoes continuously. At D, the lagging edge of the pulse has reached target 1, and target 2 is at the center of the pulse. At E, the lagging edge of the pulse has reached target 2. The echo will now cease. The radar has been receiving echoes continuously from B to E and the two targets appear as part of one echo on the screen of the cathode ray tube.

11.7. Relation between width of beam and resolution in azimuth

How accurately can we measure the angular direction of a target? In other words, what is the resolution in azimuth?[3]

Here, the width of the beam plays an important part. In A of Figure 11 : 4 (*b*), is a lighthouse, five miles from a radar, on which it appears to the eye as a point source. The scanning beam of the radar is 10° in width and is moving in the direction of the arrow. In B is shown the appearance of the indicator tube during the scan. It is clear that when the beam first strikes the target, the echo will appear on the screen, and it will continue to produce an effect on the screen during the sweep of the beam across the target. As the target is a point source, the echo will cause an image equal to the width of the beam, 10°. In effect, the smallest object that appears on the screen will cover the minimum arc equal to the width of the scanning beam.

Suppose that the target is now a torpedo boat destroyer viewed in its full width as in Figure 11 : 4 (*c*). We shall assume that the target is relatively near and covers or subtends an arc of 5° as at A. As the beam sweeps upward and touches the target, the echo will be received. The echo will be sent back throughout the sweep of the beam; that is, for the full width of the beam plus the angular width of the target, or a total of 15°.

11.8. Resolution in range greater than in azimuth

Radar detectors are far more accurate or precise in range resolution than they are in azimuth or angular bearing. With a one-microsecond

[3] Where it is possible to employ visual measurements, optical data on bearing (azimuth) are more accurate than radar.

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pulse, the distance between the forward and rear parts of the pulse is approximately 1000 feet (the distance traveled by the edge of the pulse in one microsecond). As the minimum resolution is one-half the pulse, or 500 feet, it is obvious that for extreme ranges this may be a very small variation. With the pulse unchanged the resolution would be the same whether the range is 10 or 100 miles. A measurement in azimuth is good if it does not exceed 1/10 of the width of the beam.

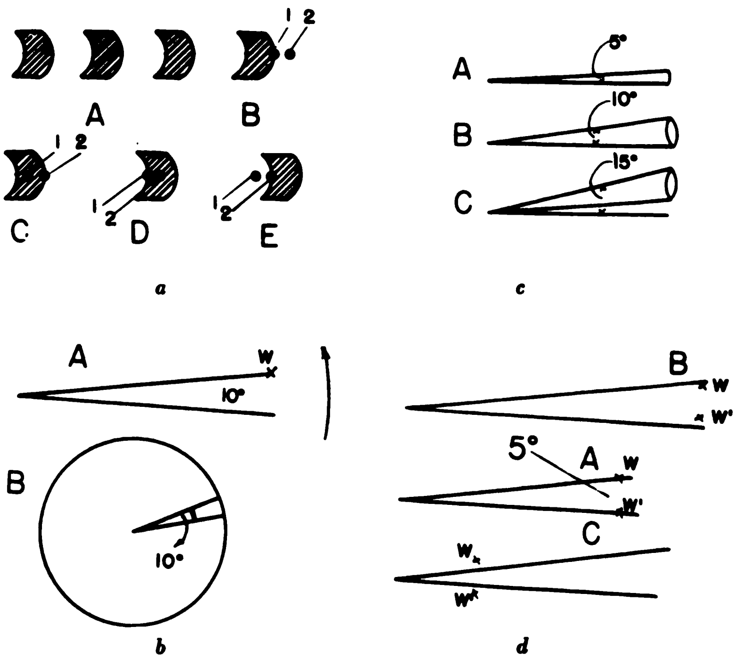

FIG. 11 : 4. RELATIONSHIPS OF WIDTH OF PULSE, BEAM, AND RESOLUTION
(*a*) Width of pulse and resolution of distance
(*b*) Width of beam and resolution of azimuth
(*c*) Width of beam, size of target, and azimuth
(*d*) Effect of distance on width of beam and resolution of azimuth

Using a beam 10° wide, our accuracy would be 1°. At 60 miles, the accuracy in bearing or azimuth would be about a mile. With a one-microsecond pulse, the range resolution would be 500 feet, from which we may infer that our radars are more accurate in range than in bearing.

How wide a beam shall we employ? This is controlled by the aperture (for a paraboloid) of the reflector, which, in turn, will depend upon

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the wave length. In A of Figure 11 : 4 (*d*), are shown two lighthouses so spaced that they just span an angle equal to the width of the beam. In other words, as the width of the beam is 5°, so is the spacing at the distance shown between the lighthouses. If we view the lighthouses at a greater distance, as in B, they will appear as one, because the angular aperture will have decreased. Correspondingly, if we view (with the radar) the lighthouses at a shorter distance, as in C, the angular aperture will have increased beyond the width of the beam and we shall see them separately. In any event, the limit of resolution of two objects in azimuth is the angular width of the beam.

11.9. Aperture of paraboloid related to width of beam

Using a paraboloidal dish reflector, the relation between the diameter of its aperture and the width of its angular beam is given by the formula,

$$\text{angle} = 1.2\ L/D,$$

where D is the diameter of the aperture and L is the wave length (twice the length of the dipole).

For a ten-centimeter wave length, an aperture of 75 cm (30 inches—a fairly common dimension), the width of the angular beam is $1.2 \times 10/75 = 0.16$ radians;[4] or, in degrees, approximately 9.6°.

11.10. Relation between power and frequency of repetition

We have already observed that the maximum range resolution depends on the length of the pulse; and that the length of the pulse is inversely related to the bandwidth (4.14). We can improve the range resolution by decreasing the length of the pulse, which means increasing the bandwidth and, unfortunately, increasing the noise that accompanies increase of bandwidth (5.3). The minimum signal we can see varies directly with noise and inversely with pulse. If we lengthen the pulse, we decrease the range resolution. Other things being the same, the average power of the transmitter will determine the power in the pulse. As we increase the length of the pulse we increase the power in the pulse, so, to keep the average unaltered, we must decrease the number of pulses in a unit of time. This is another way of saying that to maimtain average power, we must decrease the rate of repetition if we increase the duration of the pulse.

[4] A *radian* is 180 divided by π.

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11.11. Relation between range and frequency

As the wave length is decreased, the concentration or directivity of the transmitted beam is improved. This means that the range will be increased because the beam is spread over a smaller area; hence, azimuth or angular resolution is improved. On the other hand, as the wave length decreases (frequency increases), the available power of the transmitter decreases. Beam widths depend upon the radiating antennas. In an antenna producing a narrow beam, fewer pulses will hit the target than in an antenna producing a wide beam.

11.12. Relation between rate of repetition and strength of signal

If we direct a stationary beam against a target, the brilliance of the echo (on a PPI screen) will be greater than if we employ a fast scanning beam. Obviously, a steady beam will be more sensitive and have a greater range than a scanning beam. In fact, the faster the beam scans, the shorter will be the time the target is exposed to the beam; hence, the fewer will be the number of echoes received back by the receiver. Thus, the minimum detectible signal will be lessened by increasing the rate of repetition, because this, in turn, will increase the number of pulses that strike the target in each scan, and therefore increase the number of echoes returned. Experiments show that if we quadruple the rate of repetition (multiply by 4), the minimum signal that can be detected will be reduced not by four but by the square root of 4, or 2.

11.13. Relation between rate of repetition and average power

When a pulse is sent out, it must be cut off so that the echo will have enough time to return without being obscured by the next pulse. Stated otherwise, the time interval between pulses should be sufficient to permit the pulse to hit the target and return before a new pulse is sent out. It is evident that this will depend on the distance to the target, or range. As the distance increases, the time for the pulse to travel out and back will increase. As the power of the transmitter is in the pulses, the rate of repetition will control the average power required.

11.14. Relation between time of scan and strength of signal

Let us assume that an antenna rotates in azimuth (horizontally) sixty times a minute, or once a second. The angle covered in a second

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is 360°. If the width of the beam is 10°, a point target that, itself, has no angular spread will be swept in 10/360 or 1/36 second. It has been found that the minimum detectible signal varies as $(8/S)^{1/2}$ where S is the time in seconds during which the target is swept in each scan. Substituting 1/36 for S, we obtain $(8/1/36)^{1/2} = 16.8$. In other words, the minimum strength of the signal has to be increased by 16.8 in order that we may detect over the same range as that of a stationary beam. To keep the loss low, therefore, a narrow beam should scan or sweep slowly.

11.15. Factors determining range of radar

On what does the overall range of a radar depend? The obvious factors are the power of the transmitter, the sensitivity of the receiver, the reflecting area of the target, and the gain of the antenna.

Even though the pulse power may be relatively enormous—1000 KW not being a rare output—because it is employed in very short bursts with long intervals between, the *average* requirement of power may be small. Yet the pulse determines the range. Thus, suppose the pulse is one microsecond and the repetition frequency is 500; then the power will be transmitted for a total of 500 microseconds in a period of one second. This "on" period is 500/1,000,000 or 1/2000 of the total time; therefore, the average energy need be only 1/2000 of 1000 KW or 0.5 KW (500 watts). In other words, with a pulse of one microsecond and a repetition frequency of 500, we can obtain 1000 KW power with only an average energy of 500 watts. So much for power requirements.

An antenna that radiates power uniformly in *all* directions would be almost an impossibility, as well as excessively wasteful. Such an antenna would be "isotropic". The commonly used paraboloidal dish reflector concentrates the beam in a narrow area. The increase in power resulting from this concentration compared to the power radiated in the required direction from an isotropic radiator is the *gain* of the antenna.

11.16. Strength of echo dependent on many factors

The reflective quality of the target will determine the magnitude of the echo. This will depend upon the size of the target, its shape, and its aspect. If the target is stationary, its echo should remain steady. On the other hand, airplanes in swift motion and battleships in manoeuvres will present changing aspects to the radar beam, as well as rapidly shifting echoes. Objects on land will vary less, yet even a tree or a

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forest, especially in a wind, will show fluctuating images. Clouds appear vague because of their contours, and, in addition, their movements will produce fluctuating echoes. So also will the surface of a body of water which is variable yet characteristic.

It is customary to define the cross-section of a target as the cross-section of a sphere which will produce an echo of the same strength at the same range. A study of the range equation tells us that we can double the range by increasing the power by sixteen times, or by increasing the sensitivity of the receiver sixteen times. We can gain the same advantage by quadrupling the area of the antenna, or correspondingly reducing the wave length to one fourth.

11.17. Visibility may depend on operator

The visibility of a target in the clear sky or in open space is limited only by the power of the radar transmitter. On the other hand, when a target sends back an echo along with a background of echoes, the question of visibility is determined by the ability of the radar operator to distinguish the target from the background.

11.18. Methods of decreasing visibility of targets

Just as we practised visual camouflage in war and by protective coloration rendered objects less visible, so it is possible to apply substances that will absorb radar beams and send back no echoes. In one type of absorber, the reflection from the front surface is canceled by the reflection from the back layer, producing destructive interference. This is known as an *interference absorber.*

In another kind of absorber, the front face produces no reflection. As the wave progresses through the material, it is attenuated and gradually extinguished. Such absorbers were planned by the Germans for use on U-boats but they were never put into practical use.

In one form of absorber, metal particles such as iron filings are distributed through a non-conducting matrix or material. Another kind of absorber employed by the Germans was composed of a series of layers whose conductivity varied with the depth or thickness. Such layers, when separated by a dielectric consisting of plastics in foam structure, effected remarkable absorption when employed in layers up to 13 centimeters in thickness. Using a device of this composition 2.5 inches in thickness, ensured complete absorption.

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Chapter 12

MEASUREMENTS AND TESTING

12.1. Measurements of fields important in radar

It has been said that we would have no science if we had no measurements. This applies to any of the specialized sciences and to their technical applications.

In the measurements of power, voltage, current, and frequency, at low frequencies and direct currents, no special problems are encountered. For such purposes, wattmeters, voltmeters, ammeters, frequency meters, exist by the score in convenient form.

We have seen that at the very high frequencies involving microwave circuits we can no longer employ coils and condensers in the forms with which we have become familiar. Hence, instruments involving coils and solenoids, condensers, and resistors also lose their usefulness and we must resort to new devices. We must be able to measure standing wave ratios, power, radiations, wave lengths, and frequencies in the ultra-high region, and other quantities that are important in radar.

We have already studied resonant chambers (3.21). Properly constructed, the resonant chamber easily measures Q in excess of 10,000. Such a chamber can be used to measure wave length, and frequencies; it may serve as an echo box, reveal the power spectrum of a magnetron or high frequency oscillator, measure the power factor of a dielectric, and also its reciprocal, its Q.

12.2. Wave meters

Wave meters are of two types: transmission and absorption. In the transmission wave meter, when the frequency is far off resonance, no

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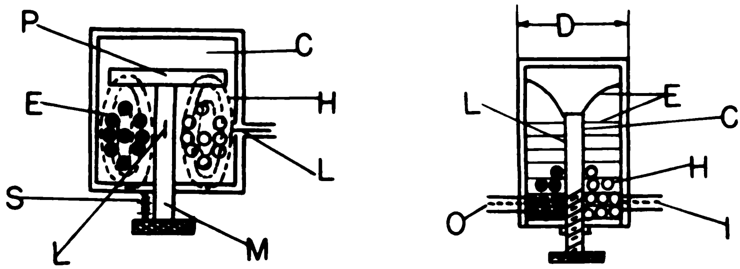
power is transmitted. As a cavity is tuned to resonance, power is transmitted to the load. In the absorption wave meter, as the cavity is tuned through the generator frequency, the power of the load changes. Commonly, the power-measuring load is a crystal-and-meter combination, called a bolometer.

As a wave meter of high precision, a brass or copper cylinder, silver-plated on its interior surface, has its length accurately varied by means of a plunger, as in Figure 12 : 1 (*a*). A micrometer screw equipped with



a *b*

FIG. 12 : 1. TYPES OF WAVE METERS
(*a*) Resonant chamber: M, micrometer screw; S, measuring scale; P, piston; L, loops; C, cavity; E, electric field; H, magnetic field
(*b*) Coaxial form: C, central conductor; D, diameter of outer conductor; L, length of inner conductor; I, input; O, output; E, electric field, M, magnetic field

a measuring scale serves as a means for moving the piston. Note particularly, that the piston does not touch the walls or circumference. The power is fed in by a loop placed near the center of the wall, and withdrawn by a similar loop, spaced 90° away. The cavity is excited by an $H_{0,1,1}$ (3.9) wave as shown.

At resonance, the meter (microammeter) shunted across the crystal rectifier will give the maximum indication, denoting that the wave length of the source is the same as that of the resonant chamber. As the length of the chamber is decreased, the resonant wave length diminishes; as the length of the chamber increases, its wave length increases. The scale on the screw can be calibrated to read directly in wave lengths. The reason why the plunger is kept away from the walls of the chamber is to prevent the excitation of other forms or modes.

Observe the directions of the maguetic and electric fields. The currents flow circumferentially in the surface; hence, the gap between the plunger and the walls does not intercept or affect the currents. It is

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only in the modes known as $H_{0,1,1}$ (and its family, $H_{0,m,n}$) that currents flow in such a manner. Any other mode requires a flow across the ends; hence, the gap at the piston suppresses all modes but this.

An effective method of measuring wave length by the employment of a coaxial chamber is shown in Figure 12 : 1 (*b*). Here, the diameter D of the outer conductor of the coaxial cable is considerably smaller than half the length of the wave to be measured. The center conductor (C) is movable by means of the knob and threaded portion. The wave to be measured is fed in at I through a coupling loop. The indicator is a crystal rectifier and a microammeter coupled at O. As C advances into the chamber, resonance will be set up when L is slightly under a quarter-wave in length (it would be exactly a quarter-wave but for the constant capacity effect between the end of C and the chamber walls). Resonance will be set up (shown by the meter readings) as successive half-wave lengths of rod are moved in. The distance on the rod between two successive resonance readings gives us the wave length.

12.3. *Measuring spectrum of magnetron*

The power of the pulse of a magnetron does not occur at a single frequency but is spread over a band. With the aid of the previous resonant chamber we can ascertain the spectrum of the magnetron. This reveals the relation between the power and the frequency components throughout the band. The output from the magnetron is fed into the resonator through its coupling loop. The wave length (frequency) and the output are measured on the microammeter. Then the wave length is varied to a new reading and the microammeter again read. Thus, step by step, it is possible to plot or chart the entire band of frequencies and power, and reveal the full spectrum of the magnetron.

12.4. *Echo box*

It often becomes necessary to ascertain whether a radar transmitter is operating properly, and yet there may be no means of obtaining an echo at the moment. An *echo box* has been provided and incorporated in radar units to supply the necessary information. This device is simplicity itself: a metallic chamber with silvered walls, a resonant chamber of very high Q.

Suppose we desire to measure the force with which a bell is struck. We may place the bell in a chamber whose walls do not absorb sound

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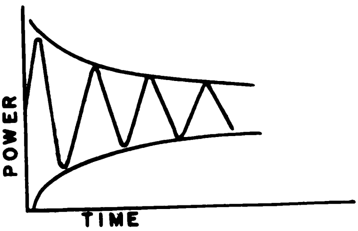
(high reverberation). We strike the bell and note the reverberations, that is, how long we can continue to hear the sound. If we strike the bell with greater force, we shall hear the sound for a longer interval. The interval of time becomes a measure of the magnitude of the striking force. We might call the period of reverberation the "ringing" time.

In comparing the ringing times of different radars employing the same echo box, care should be exercised that the conditions of test are identical. Otherwise, the relative measurements will be erroneous. The dipole of the echo box should bear the same relation to the radar antenna in the various tests; the RF cable connection between echo box and the dipole should remain fixed; the measurements should be taken at the same temperature.

Let us feed a slight part of the radar output, taken from the antenna radiator by means of a coaxial cable, into a resonant chamber. If the chamber has a very high Q (very low loss), it will resonate for a long time after the pulse has been applied. The time during which the oscillations are noticeable is called the "ringing" time. The greater the power output of the radar, the greater will be the ringing time which then becomes a measure of the power. Actually, the oscillations in the



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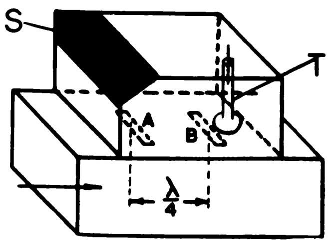

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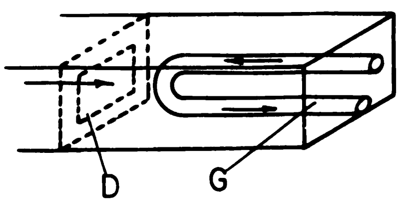

12:4

Fig. 12 : 2. Exponential Decay of Oscillation
Fig. 12 : 3. Directional Coupler
Fig. 12 : 4. Method of Measuring Large RF Power
D, adjustable diaphragm; G, glass tube calorimeter

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resonant chamber will decrease very slowly and exponentially. Figure 12 : 2 shows such an exponential decay much exaggerated. In reality, at ten centimeter operation, which means 3000 megacycles in frequency, we may have a ringing time of fifty microseconds. This would mean there would be 3000×50 or 150,000 oscillations present in this time. On the face of the cathode ray tube screen of the indicator, instead of a pip, we would see a high level plateau[1] gradually dying out to the "grass" or noise level. The length of the plateau is the ringing time, or measure of the output of power.

12.5. *Measurement of low power with thermistor*

It sometimes becomes necessary to measure the power passing through or along a wave guide. When the total power is small in amount, we must employ relatively sensitive indicators. When the power is huge, our measuring device may be more rugged. For small power, a resistance element, recently discovered, has gained widespread use. This is known as a *thermistor* (meaning a thermally sensitive resistor). It is composed of a mixture of metallic oxides in which oxide of manganese is predominant. Its valuable property is the fact that its resistance changes enormously with variations in temperature. It is made up in various forms, such as beads, discs, and wafers. For a change of 100° F, it is not unusual for the resistance of a thermistor to change by 1000. It has become the basis for very sensitive measurements. In one form, it can indicate the change of temperature of a millionth of a degree centigrade. By use of it, the heat of a man a mile distant will register its presence.

The thermistor employed in radar measurements consists of a tiny bead, about five mils (0.005 inch) in diameter composed of a mixture of oxides of manganese, cobalt, nickel, an copper. It has an extremely high negative temperature coefficient (as the temperature coefficient increases, the resistance drops). Thermistors are highly sensitive and require no amplifying devices. Their reactance compared to their resistance is negligible. There is no appreciable difference in measurement, whether they are employed at D.C. or at high frequency. Furthermore, they are not sensitive to burnout.

The bead is enclosed in a glass tube containing two slender wires that are connected to the bead. For the measurement of power in a wave

[1] The plateau is really the envelope of the train of oscillations. The individual oscillations are so rapid that they do not appear on the screen of the scope, which simply displays the averaging effect.

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guide, the bead thermistor is placed across the narrow dimension of the guide, spanning the broad faces at their centers. The thermistor is then carefully matched to the guide so that there are no reflections. When the guide is so terminated, all the power of the wave guide will appear in the thermistor as heat. We need but measure the resulting change of resistance to find the power. To do this, we connect the bead in one arm of a Wheatstone Bridge. With the power of the wave guide turned off, we balance the bridge until the meter registers zero. We then turn on the power in the wave guide and again balance the bridge. This is necessary, for the flow of current through the thermistor has changed its resistance. The change of resistance of the thermistor is a measure of the heat change, and hence of the power. We may calibrate the meter so that instead of re-balancing the bridge, we can use the readings of the meter directly to measure the change of resistance.

The foregoing method, although it is practical, will not ensure the greatest precision. A change in the external temperature of the surroundings will cause a change in the resistance of the thermistor, even though no power is flowing in the wave guide. We might protect the thermistor by surrounding it and the wave guide with temperature-insulating materials.

By diverting a small part of the energy of a wave guide into a directional coupler, the thermistor may be employed to measure large power. In Figure 12 : 3, power is passing down a wave guide as shown by the large arrow. Across the upper wide face of the guide are two narrow slots, spaced a quarter of a wave length apart; S is an absorbing substance such as wood and T is the thermistor. Electromagnetic energy will pass through the slots from the lower wave guide into the upper one. In the forward direction from A to B, the waves will add and pass down to the thermistor. In the direction from B to A, the waves will be a half-wave length apart and will cancel. Therefore, the thermistor will measure power moving in the forward direction. The amount of power coupled into the auxiliary guide will depend upon the width of the guide slots. S is an absorbing substance that will absorb any energy passing in the reverse direction.

12.6. *Measurement of high power*

An effective method of measuring the *full* power of large amount in a wave guide is to convert the energy into heat and measure the quantity of the heat change. Figure 12 : 4 shows a wave guide along

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which a magnetron is transmitting power. D is an adjustable diaphragm or iris to ensure a perfect match without reflection. When such a condition prevails, all the energy in the wave guide will be absorbed in the glass tube calorimeter at the end of the wave guide. We must know the temperature of the water at both the inlet and the outlet and also the rate of flow of the water. Knowing this, we can measure the quantity of heat liberated in a given time and this is a direct measure of the energy flow down the guide from the magnetron.

12.7. Attenuators

Attenuators may be of two types, cut-off, and resistance. A wave guide beyond cut-off may serve as an attenuator, for the field introduced into it decays exponentially.

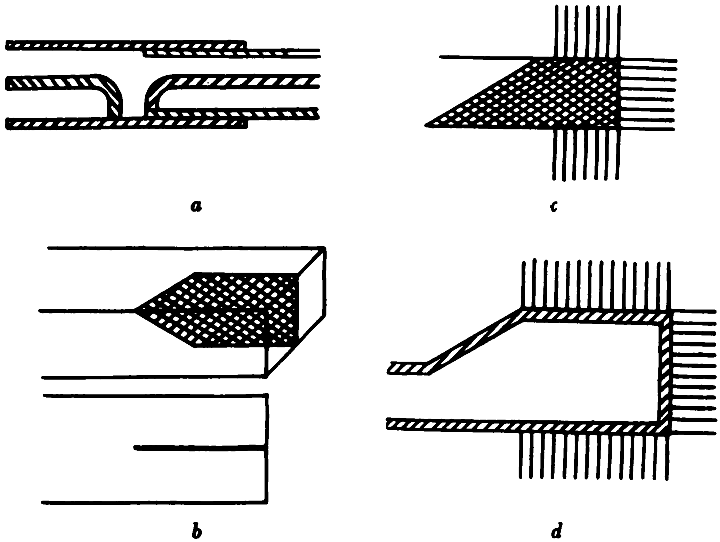

FIG. 12 : 5. TYPES OF ATTENUATORS
(*a*) Based on frequency cut-off
(*b*) Based on losses in resistance
(*c*) High-power equipped with cooling fins
(*d*) High-power with resistance walls and cooling fins

For practical purposes, an arrangement shown in Figure 12 : 5 (*a*) should prove effective. This consists of two coaxial cables. The external diameter of the smaller is just sufficient to slide easily in the larger. The center conductor of each cable is short-circuited as shown in (*a*). The attenuation is varied from the minimum amount when the

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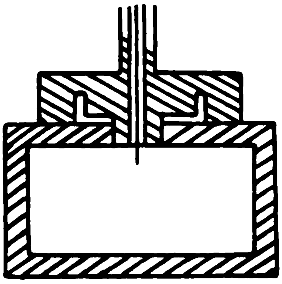
loops are in contact to the maximum when their separation is greatest.

In the resistance attenuators, attenuation is produced by the insertion of a resistive material that uses up the excess energy.

For handling small power, dielectric sheets are coated with carbon or aquadag and inserted into the wave guide as in Figure 12 : 5 (*b*). To keep the standing wave ratio very low, the resistive strip is tapered as indicated, minimizing reflection. Glass strips and rods on which extremely thin (a few molecules in thickness) layers of high resistance metal have been deposited by evaporation are extremely effective.



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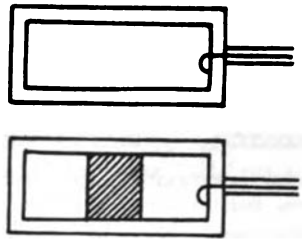

12:7

FIG. 12 : 6. METHOD OF MEASURING DIELECTRIC LOSSES IN RESONANCE CHAMBER

FIG. 12 : 7. CROSS SECTION OF PRECISION PROBE

For attenuators of high power, provision must be made for the dissipation of heat. A common method is to equip the wave guide that contains the absorbent materials with metallic radiating vanes or fins, as shown in Figure 12 : 5 (*c*). Materials frequently used for high power are water, sand coated with graphite or Aquadag, and silicon cast in porcelain. Better than the foregoing in many respects are wave guides whose walls are made of poor conductors, shown in 12 : 5 (*d*). Such an arrangement suffers less on high power from voltage breakdown and offers effective means for removing heat. By suitably tapering the wave guide, a good match in impedance may be effected and the standing wave ratio kept desirably low. A mixture of graphite and cement has been employed effectively for the walls of such wave guides.

12.8. Measuring loss in dielectrics

There is no such thing as a perfect insulator. All, even the best, lose or waste energy. It becomes necessary, at times, to measure the

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power factor of a dielectric when it is placed in an alternating or oscillating electric field. The ratio or fraction of the power wasted to the peak power of the electric field during a cycle is called the power factor of the dielectric. Remembering that the Q of a resonant cavity (3.26) is the ratio of the power stored in the cavity (multiplied by a constant) to the power lost or dissipated, we first measure the Q of the cavity when it is empty. Then we insert the dielectric[2] as shown in Fignre 12 : 6 and measure the Q with the dielectric present. The difference in Q's is due to the loss in dielectric.

Without the dielectric, the power (P_W) is lost in the wall of the chamber. When the dielectric is present,

$$Q = \omega W / P_W + \mathrm{P}_D$$

wherein $\omega = 2\pi f$ and W is the maximum energy stored.

When no dielectric is present,

$$Q_W = \omega W / P_W$$

If we take the reciprocal, we obtain

$$1/Q = P_W/\omega W + P_D/\omega W$$

We find that

$$Q_D = \omega W / P_D$$

hence, $1/Q = 1/Q_W + 1/Q_D$; $1/Q = Kf$ where K is a constant. K is determined from the geometry of the dielectric, the position it occupies in the field of the chamber, and the mode of oscillation employed.

12.9 *Precision probes*

An ideal probe should exercise no effect upon the field in the wave guide. Being ideal, no such probe exists. For this reason, in making standing wave measurements, we are always faced with a compromise. If the probe is very small, the coupling coefficient will be very small and a highly sensitive indicator will be required; on the other hand, by making the probe large and the coupling coefficient similarly large, the coupling coefficient will produce really serious errors because of the major effect of its presence on the field of the wave guide. Which compromise we shall adopt will depend upon circumstances, such as the accuracy required, the sensitiveness needed, and the power available.

It is very important that the probe be perfectly symmetrical about its axis and in relation to the guide and slot. It is equally essential that there be no variation in the penetration of the probe as it travels

[2] For details, see Appendix.

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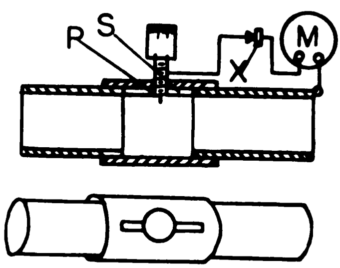
along the slot; in other words, the depth of penetration should be as constant as possible. By surrounding the probe with a shield as shown in Figure 12 : 7 slot waves (waves of energy lost through slot) caused by lack of symmetry are largely prevented.

The reactance of a probe is largely controlled by the amount of penetration.

12.10. Checking fields in wave guides

We have shown or described the character of the electric and magnetic fields (modes) in hollow wave guides. These can be checked or plotted experimentally. Figure 12 : 8 presents an arrangement that



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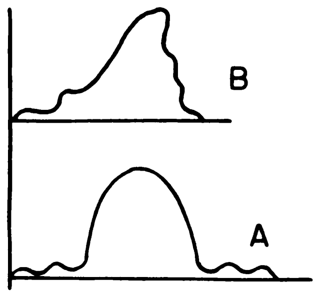

12:9

FIG. 12 : 8. ARRANGEMENT FOR MEASURING AND PLOTTING FIELDS IN WAVE GUIDE

P, probe; S, slot; X, crystal, M, microammeter

FIG. 12 : 9. CURVE SHOWING SPECTRUM OF MAGNETRON

A, correct form; B, poor spectrum

incorporates a crystal and a probe for measuring and plotting such fields. The probe is placed in a slotted wave guide so that it can be moved backward and forward. If the wave guide is circular in cross-section, the slotted part may be connected with two adjoining wave guides in a sliding fit. Thereupon, it will be possible to rotate the probe around the axis of the wave guide and also move the probe lengthwise. Thus, all parts of the wave guide may be tapped. The readings on the microammeter will show the flow of current after it is rectified by the crystal.

12.11. Care and measurements of magnetrons

In magnetrons employed on airplanes or in airborne radars, the magnetic field is obtained from permanent magnets made of Alnico V. These should be kept away from contact with magnetizable substances.

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Even a momentary contact with a wrench (iron) or screw driver may be sufficient to weaken the magnet by several gausses.

Despite the fact that a magnetron appears sturdy and substantial, except for its glass seal, it should be handled as though it were extremely fragile. A slight bending of the RF lead, far less than sufficient to break the glass seal, will radically change the characteristics of the tube.

In those magnetrons in which the magnetic field is produced by electromagnets, as in ship-borne and ground installations, precautions should be observed never to apply the pulsing voltage unless the magnetic field is of full strength. With no magnetic field, or with a weak one, the current through the magnetron will become excessive, not only damaging the magnetron but even the tubes of the modulator.

If the pulse of the magnetron is correct, its spectrum will be symmetrical as in A of Figure 12 : 9, showing the high maximum in the center of the band and low points on each side. Its shape may be easily determined by means of a wave meter (11.18). On the other hand, if the spectrum is poor, as in B, and it is spread over a band that is wider than the bandwidth of the receiver, much of the power will be wasted. A bad spectrum of this type may be caused by very low voltage, improper strength of magnetic field, or even a poorly adjusted RF system. This would mean that we should check the modulator, the magnetic field, and the tuning of the radio-frequency system.

The magnetron offers a good example for illustrating the character of measurements we should be able to gauge or appraise. The strength of the magnetic field is easily measured by a flux-meter; a coil with a known number of turns placed in the air gap and removed will cause a deflection of the flux-meter which is proportional to the intensity of the magnetic field. Peak voltage may be measured by a peak voltmeter or by the use of an oscilloscope in which a known fraction of the voltage may be measured on its screen. Peak current may be measured by passing a known fraction through a known resistance and measuring the peak voltage across it. The duration of the pulse may be measured on an oscilloscope by using a calibrated sweep. The rate of recurrence of the pulse—the frequency at which the voltage pulse is applied—can be obtained from comparison with a calibrated oscilloscope. "Duty cycle", which means the fraction of the time during which the magnetron operates, can be expressed by a ratio of the average current to the peak D.C. current; or it can be indicated as a product of the duration of the pulse times its rate of recurrence.

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Peak input power is represented by the product of the peak D.C. voltage and the peak D.C. current; from which it follows that the average input power is the peak power input multiplied by the duty cycle. The average power output is what the magnetron delivers to a load. It might be measured by using a water column as an absorber (see 12.4). Knowing the rate of flow and the rise in temperature, it is easy to calculate the power. Again, the peak output power is easily determined by dividing the average power output by the duty cycle. If we know the peak output and the peak input, the over-all efficiency is obtained by dividing the former by the latter; this is the same as the ratio of the average output to the average input. The frequency of oscillation of a magnetron is readily obtained by feeding a small amount of its RF power into a resonant calibrated cavity of high Q. Then, (by means of a combined detector, crystal, and meter), we need only observe the frequency where the cavity suddenly absorbs or passes power.

These are a few typical simple measurements; they are by no means exhaustive.

12.12. Precautions in handling crystals

Crystals employed in the mixer of receivers are especially delicate components. It is always advisable to have on hand a number of fresh crystals, each enclosed in a metallic foil wrapper. In dry clear weather, the static charge on the body passing through a crystal from the operator handling it may impair or ruin it. Before handling the crystal, one should touch some grounded metallic object to remove any accumulated static charge on the person. As a rough indication of the sensitivity of a crystal, the ratio of the resistance from front to back and back to front should be at least ten to one for a good crystal. Regardless of what it may be, if the ratio decreases by more than one-half, the crystal should be discarded.

12.13. Visual detection of change in T-R gas tube

The life of the T-R gas tube is limited, even that of the cold-discharge variety. As in many sealed tubes in which discharges of gas take place, the vacuum grows higher because gas is absorbed by the metals in the tube. Even chemical combination between the materials of the electrode and the gases[3] in the tube will produce a similar phenomenon. The glow discharge which is turned on for long periods is responsible for much of this failing; hence, it becomes necessary to employ a "keep-

[3] The atmospheric gases—argon, helium, krypton, neon, and xenon—are inert.

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alive" voltage as low as good operation will allow (9.3). By a sputtering process the metal of the electrodes is deposited on the inside of the glass with use, and the gradual darkening of the tube is a measure of this process. Though the operation of the tube as a protective device is not affected by this deposit it does, however, affect efficiency by absorbing energy from the echo and thus decreasing the receiver's range or sensitivity.

12.14. Details important in radar

In dealing with microwave circuits, what would be trifling dimensions in other low-frequency phenomena may become critical and of paramount importance. One inch of number 20 (B & S gauge) copper wire has a reactance of eight (8) ohms at a frequency of 60 megacycles—the IF frequency in airborne radars.

In a three-centimeter wave guide measuring one inch by one-half inch, a hole 0.04 inch in diameter in the narrow wall causes an attenuation of 20 db at 10,000 megacycles; that is, such a hole at this frequency permits one per cent of the energy to leak out.

The seemingly harmless projection of a condenser shaft from a cabinet may be fraught with serious consequences: that anything projects externally may serve as an antenna to radiant energy and feed into the cabinet, or it may radiate energy out of the cabinet. This might be corrected by an insulated shaft (dielectric materials instead of metal) or in a metallic shaft that is grounded externally.

12.15. Shielding and its effect on Q

It goes without saying that at microwave frequencies shielding becomes crucial and indispensable. The necessity for shielding the RF circuit from the IF, or the local oscillator circuit in the presence of the RF circuit, are matters too obvious to require explanation.

To shield components from one another electrostatically, any good conducting material, such as copper or aluminum, is effective, if it is introduced as separating barriers or partitioning walls. At extremely high (microwave) frequencies the barriers are also effective as magnetic shields. The high-frequency currents set up in the barriers create a magnetic field which opposes or neutralizes the magnetic field impressed. All shields should be well-grounded. As a shield creates its own opposing field by means of eddying currents caused by an impressed high-frequency field, the Q of the shielded circuit is lowered by the shield. This is to be expected, because the currents in the shield represent wasted power (3.26).

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12.16. *Attenuation of coupling in IF amplifier*

It will be recalled that the fundamental mode in a rectangular wave guide (**3.20**) has a cut-off wave length equal to twice the width of the wave guide. If, for example, the width of the wave guide is half a meter, the cut-off wave length is one meter. It is interesting to observe the consequences if we view the metal cabinet that houses a radar unit as a wave guide, itself, and consider the electromagnetic fields present inside the cabinet. If the frequency is very much less than the critical frequency, the wave guide cuts off transmission. It has been found that when this condition prevails, the attenuation is about 27 decibels in going a distance equal to the width of the wave guide (Figure 12 : 10). In other words, the power shrinks to 0.002 (which is the loss

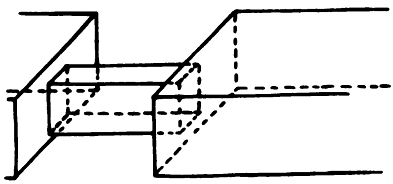

FIG. 12 : 10. WAVE GUIDE ATTENUATOR MUCH BELOW CUT-OFF

equivalent to 27 db) in traveling a distance equal to the width of the wave guide. Let us examine the effect of coupling an IF amplifier in a cabinet on the electromagnetic field in the cabinet. If the IF is sixty megacycles, the wave length is five meters. The width of the cabinet would have to be 2.5 meters for cut-off, or approximately eight feet. As the ordinary metal cabinet housing the IF amplifier is only a small fraction of this in width, the attenuation of the field within the cabinet is apparently very large.

Let us consider an actual IF amplifier, consisting of many stages and mounted in its metal cabinet, and examine the effect of coupling the circuits of the amplifier and the field of the wave guide of the cabinet. The attenuation of the field of the wave guide is 27 db. It is possible for the energy coupled back between the output and the input of the amplifier actually to exceed the signal energy that is directly impressed upon the input stage of the amplifier; if it does, the amplifier may oscillate. This may be prevented by increasing the spacing between the IF stages so as to increase the attenuation of the wave guide; such an increase, however, would be undesirable for other reasons.

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We may also decrease the width of the cabinet and by thus narrowing the wave guide, increase the attenuation. Here we are limited by the minimum dimensions required to accommodate the equipment in the cabinet. A practical solution is to place a metal partition between the wall of the cabinet and the outside of the IF amplifier. This, in effect, would place the IF amplifier in its own wave guide of narrow dimensions and very high attenuation, and thereby reduce the coupling field between the output and the input stages to a negligible amount.

12.17. Microwave signal generator

A microwave signal generator is a source of electrical power. It is an oscillator whose frequency and output can be varied accurately and measured. Among its most useful functions is the testing of receivers by supplying signals of known characteristics. In the microwave range, the accuracy of a signal generator is not so great as at radio frequencies. Furthermore, the flexibility of such a signal generator is quite limited and usually restricted to a range of 10 per cent.

It is of the utmost importance that a signal generator be well shielded. As the power of an oscillator is greater than the signals detected, minute leaks may introduce into a receiver being tested oscillations equal to, or greater than, the signal intensities to be measured.

It is therefore of interest to be able to measure the leakage of a signal generator. A simple practical method is to employ a calibrated receiver, such as a superheterodyne. A small horn termination at the end of a flexible transmission line, connected to the receiver, is employed to explore the space around the signal generator. The smaller the signals that are to be detected, the greater will be the effect of leakage.

Leaks of microwave energy will occur at poor junctions of wave guides, at small apertures and cracks, at flange couplings, and at attenuator openings. Joints should be grounded and faced so that abutting surfaces fit practically perfectly; holes, slots, and apertures should be shielded thoroughly. The material known as Polyiron[4] has a very high attenuation for microwaves; hence, it should be effective in absorbing power lost through leakage. By surrounding slots, apertures, and attenuator openings with Polyiron, as well as bushings through which insulated leads pass, the leakage of power can be rendered inappreciable. The power lost through openings, slots, etc., is absorbed by the Polyiron where it is harmlessly converted into heat and does not play havoc by coupling with the circuit components.

[4] Molded sections of powdered iron imbedded in a neutral matrix.

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Chapter 13

PROPERTIES OF FUNDAMENTAL COMPONENTS IN RADAR

13.1. Parameters at low and high frequencies

At low frequencies, and those used for commercial power, inductances, resistances, and capacitances present no unusual problems because each is relatively *pure*. That is, when we speak of the inductance of a coil, we mean that the other parameters such as resistance and capacitance are inappreciable and may be ignored. At extremely high frequencies such as those employed in radar, what would be insignificant at commercial frequencies may actually become controlling.

13.2. Comparison of composition and wire-wound resistors

The resistors employed in radar are either wire-wound or molded of various compositions.[1] The advantages of molded resistors are cheapness and compactness but these are offset by unfavorable properties such as lack of precision and of stability. Wire-wound resistors show appreciable reactance; when the frequency is extremely high, the reactance; when the frequency is extremely high, the reactance may actually exceed the resistance. As an illustration, #20 (AWG) copper wire has a resistance of 0.0008 ohms per inch (at 60° F). At 60 megacycles, its reactance is 8 ohms (10,000 times as much). If for any reason, the resistance should change, it will not be restored to its former value, when the apparent cause is removed.

[1] Lampblack or graphite mixed with porcelain or clay or resin and baked would be an example of a composition resistor.

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Molded resistors are inherently noisy. Wire-wound resistors are relatively quiet. Molded resistors are seldom required to operate in excess of two watts, though they can tolerate appreciably higher temperatures than wire-wound resistors can.

If precision is desirable, it is well to remember that molded resistors have a maximum accuracy of 5 per cent whereas the wire-wound can ordinarily be procured with an accuracy of 0.25 per cent and for special purposes as low as 0.05 per cent.

13.3. Equivalent circuits of molded resistors at high frequency

Because of the significance of the parameters at high frequencies, a composition resistor can be considered as the equivalent of a parallel circuit made up of resistance and capacitance. Figure 13 : 1 (*a*) is the equivalent diagram of a composition resistor at high frequency.

At extremely high frequencies Figure 13 : 1 (*b*) is more representative.

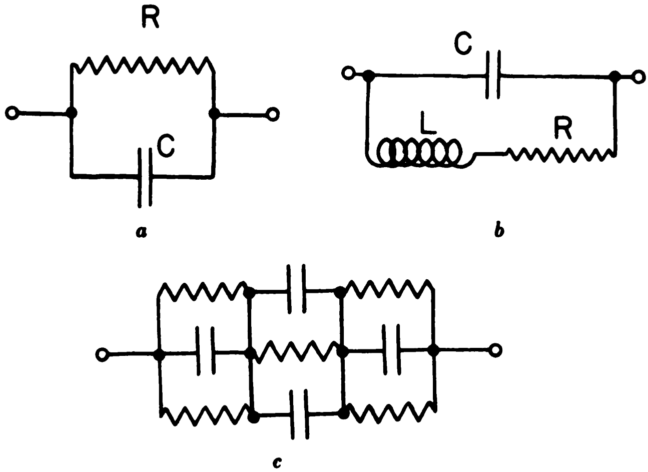

FIG. 13 : 1. EQUIVALENT CIRCUITS OF RESISTORS
(*a*) Molded resistor at high frequency
(*b*) Molded resistor at extremely high frequency
(*c*) Wire-wound resistor at high frequency

13.4. Factors affecting qualities of a resistor

Even the location of a resistor will affect its capacitance. Thus, the distance of a resistor from a grounded chassis will affect its capacitance and hence its impedance. Even the humidity of the atmosphere may

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considerably alter the resistance of a composition material. Changes as high as 3 per cent have been observed in composition resistors because of moisture in the air. Such resistors may dry out in prolonged use and then show a lower resistance.

13.5. *Materials and construction of wire-wound resistors*

The best wire-wound resistors are sealed in moisture-proof containers such as tubes of porcelain, pyrex, glass, or quartz. Thus protected, wire-wound resistors exhibit high stability. The common forms of such resistors consist of wire wound upon tubes of ceramic materials. The wires are usually alloys of nickel and chromium (Nichrome) or of copper and manganese (Advance). The wire is coated with some form of vitreous enamel or cement which is hardened by baking. Nichrome wire has a resistance of 600 ohms per circular mil foot. Its temperature coefficient is very high. The wire known as "Advance" has a resistance of 300 ohms per circular mil foot; its temperature coefficient is much lower. Even very slight changes in the percentage composition of the alloy will produce substantial changes in resistance and in temperature coefficient.

Wire resistors are usually wound with bare wire running as small as a mil (0.001 inch) in diameter. In order to decrease the inductance of wire resistors, they are wound non-inductively; that is, in pairs of wires, so that currents flow in each in opposite directions. To minimize capacity, the spacing of turns and coils is made large. Nevertheless, with all precautions taken, a 1000-ohm wire-wound resistor at ten megacycles (10,000,000), will still have a time constant ($R \times C$) of 0.1 microsecond.

The material of the coatings should have a coefficient of expansion approximately equal to that of the wire. Substances like vitreous enamel can tolerate temperatures up to 275°C. On the other hand, organic coatings such as the phenolic resins (Bakelite, for instance) can be used only at lower temperatures (about 60°C); the new silicone varnishes are usable up to 500°C. Customarily, wire-wound coils are made in single layers, but where high resistances are wanted in compact space, multiple layers are employed. An obvious disadvantage to multiple-layer coils is the fact that less heat can be dissipated, for each layer shields the underlying layer from radiating heat into space.

Wire-wound resistors employed at high frequencies may be represented by the circuit shown in Figure 13 : 1 (c). Even so, this is an

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inadequate representation when the frequency attains extremely high values. At frequencies of such high range, the inductance (L) may be less than the capacitance (C). At 40 Mc (40,000,000 cycles) a wire-wound resistor may have ten times its D.C. resistance.

Where extreme precision is necessary, the resistance wire is wound on forms or bobbins of molded plastics or ceramics. Usually the wires are placed in slots and the direction of winding in successive slots is reversed, thus reducing the inductive effect at low frequencies.

For use at low or moderate temperatures, enamel insulation is adequate for resistors; alternative insulating materials are Formex and Forminvar. Where the rise in temperature does not exceed 40°C, manganin wire as small as 0.8 mil is in use. This wire also has a low temperature coefficient; that is, its change of resistance with change of temperature is slight.

Following the winding process, resistors are impregnated with materials to exclude moisture, and for mechanical protection from shocks and abrasions. As already stated, the best protective covering is the hermetically sealed container of glass, porcelain, or quartz. Where extreme accuracy is desired, the resistors should be placed in a temperature-controlled container. The method of attaching connecting leads for precision resistors is also important.

13.6. Variation of resistance with change of frequency

Because of the close proximity of wires in slot-wound resistors, the distributed capacity may be significant at high frequencies. Consequently, to offset the capacitance, wire resistors are wound on flat mica cards at extremely high frequencies. For example, a coil type resistor of 1000 ohms at D.C. values may have an effective resistance of 4700 ohms at one megacycle (1,000,000 cycles) and an effective reactance of —278 ohms. By raising the frequency to ten megacycles (10,000,000 cycles), the effective resistance becomes only 13 ohms and the effective reactance, —390 ohms.

13.7. Construction of very large resistors

Resistors of extremely high values are molded. These are not accurate (tolerance up to 15 per cent) but they are extremely compact. They are manufactured in ranges up to 20,000 megohms (20,000,000,000 ohms). A convenient and common method of making such resistors is to coat a porcelain or ceramic tube with resistant materials, and then to cut a spiral groove, creating a very long spiral of extremely high

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resistance. For protection and stability, these resistors should be sealed in moisture-proof containers. Such resistors can be produced with resistance of a million megohms (10^{12}—1,000,000,000,000 ohms).

Still another form of an extremely high and relatively stable resistor is made by coating a film of metal on an insulating cylinder. Metallic alloys such as platinum-iridium or silver-palladium may be sputtered[2] on threaded insulating cylinders. The edge of the thread is then ground away, producing thereby a long spiral of metal. This resistor is not only stable, but also highly accurate.

13.8. *Varistors and thermistors*

There are special types of resistors whose resistance qualities vary in a peculiar manner. Among these may be mentioned *varistors* and *thermistors*. A *Varistor* is a resistor that changes substantially with temperature. If the temperature coefficient is very large and negative, the device is known as a *thermistor*.

For ordinary pure metals, the thermal coefficient is between 0.003 and 0.006 per degree C. An exception to this is iron which departs notably from this range at or near red heat. Thermistors are made of metallic oxides or mixtures of metallic oxides (**12.3**). The coefficients are not only negative (like carbon) but also range between three and five per cent per degree C. The resistance of a thermistor may easily double if the temperature drops only 20°C. Thermistors are made in many forms (**12.3**).

13.9. *Uses of thermistors*

In the forms of rods and discs thermistors are employed unmounted. Beads are usually enclosed in glass containers. As much care and attention is required in mounting thermistors as in manufacturing them.

The uses of thermistors are steadily increasing. They are especially suited for measuring extremely small changes in external temperature. They find wide use in bolometric measurements to gauge radiant energy (**12.3**). They also find extensive use in the measurement of microwave power. Compared to a platinum thermometer, the thermistor is at least ten times more sensitive, but it is not so accurate. Because thermistors are made in very small forms (small mass), their thermal capacity is correspondingly slight—a great advantage in measuring temperature. For the same reason, their time constants ($R \times C$) are short. When used in conjunction with coils, their negative

[2] A process of coating objects with metal by exposing them to the metal suddenly rendered fluid by the use of high temperatures.

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temperature coefficients can compensate for the positive temperature coefficient of the coils, and thus maintain a constant resistance, independent of changes in temperature.

Among the many uses of thermistors should be mentioned their combination with relays to introduce delays in time. These may range from a millisecond (one thousandth of a second) to several minutes. If the current through a thermistor is increased slowly so that sufficient time elapses for the thermistor to reach equilibrium, the drop in voltage across the thermistor will reach the maximum and then begin to decline as the current continues to increase. If the current continues to increase, the slope or coefficient will become positive.

The action of the thermistor is similar to that of a dynatron, that is, it can be used as an oscillator. The range over which such an oscillator can function is limited because the thermal capacity of the thermistor is minute. Nevertheless, as an oscillator, it is fairly effective in the lower ranges, especially at audio frequencies. It follows from the foregoing that thermistors may be used as amplifiers and even as switches. Placed in an oscillator circuit, a thermistor may be used as a stabilizer; together with a constant series or shunt resistor, it may be employed as a voltage regulator.

13.10. Varistors without symmetry

An unsymmetrical resistor is one whose resistance is a function of the magnitude and direction of the applied voltage. Because its resistance is measurably different in different directions, this type of resistor can be employed as a rectifier. Ordinary silicon and germanium detector crystals illustrate this type of resistor; also in the same class is the dry disc rectifier used for charging batteries. The dry disc rectifier may be copper oxide on copper, or selenium on iron or aluminum. Such rectifiers, which are highly efficient, are widely used on meters because they are insensitive and can tolerate overloads with impunity. Even better than copper oxide in this respect is copper sulfide which can stand considerably higher temperatures. For rectification at high voltages, selenium is especially suitable but it can tolerate only moderate rises in temperature. These are used up to 4000 volts.

In many respects, germanium crystals are better than silicon as their forward resistance is particularly low. The current through a crystal may vary between one and 300 milliamperes. The selenium rectifier may be used as a limiter. Connected back to back, a pair of crystals may be employed below one volt as a supplement to Thyrite.

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13.11. Symmetrical Varistors—Thyrite

Thyrite is a specially treated silicon carbide mixed with a ceramic binder and baked at 1200°C. The final product depends upon the heat treatment to which it is very sensitive.

Unlike silicon and germanium, Thyrite conducts uniformly in all directions and its conductivity increases rapidly with the applied voltage. This composite material may be considered as an aggregate of minute crystals or granules, separated by minute spacers of insulation which are films of silicon dioxide. The higher the potential gradient (voltage per unit distance), the greater the number of gaps that break down and become conducting. An advantage of Thyrite is the fact that the insulation reforms immediately after the discharge. To prevent absorption of moisture the Thyrite is impregnated with porcelain or other ceramics. Moderate overloads will not harm it. Thyrite can be obtained as rods 1/4 inch in diameter and 1-1/8 to 2-1/4 inches in length; as discs, from 1/2 to 6 inches in diameter, and up to several inches in thickness. Contacts with small rods and discs are made through "pigtails";[3] large units are held by clamps.

The range of voltage and currents over which Thyrite units may be employed is very great—voltages from 0.1 to 10,000, and currents from 10^{-7} ampere (one ten-millionth ampere) to hundreds of amperes. For protection against lightning and for surges of high voltages, Thyrite is an ideal substance.

13.12. Practical forms of resistors

At high frequencies, i.e., radio frequencies, the ordinary wire-wound resistor has an excessive inductance and capacitance. By winding the wire on a mica sheet and sealing it in gas-filled containers, the resistor can be made effective even at high frequencies. If the terminals of the resistor are connected to the bases of vacuum tubes they can be inserted or removed from circuits with negligible delay and inconvenience. In one type of such resistor, manufactured by the Ward Leonard company, the winding is zig-zag on a flat vitreous enamel form. Even for use up to one megacycle the inductance is negligible, and the capacitance is still inappreciable up to five megacycles.

A very useful form of resistance is made up as a cloth which can be employed up to several megacycles. This cloth is composed of an asbestos fiber woven with resistance wire. It has a particularly low inductance and capacitance, and it is well suited for dummy loads for

[3] Flexible conductors permanently attached.

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transmitters. As this cloth is entirely exposed, it dissipates heat particularly well. If cooled artificially by air blasts, oil, or cooling coils, such cloth is usable even on high power.

13.13. Resistors for high frequencies

For high frequencies both the over-all capacity and the end-to-end capacity must be low. The change in resistance with a change of frequency should be slight; this requires that the inductance be negligible. Up to 100 megacycles, the capacity is important in resistors exceeding 500 ohms; for resistors below 50 ohms, the inductance should be slight.

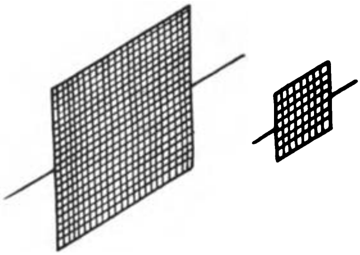
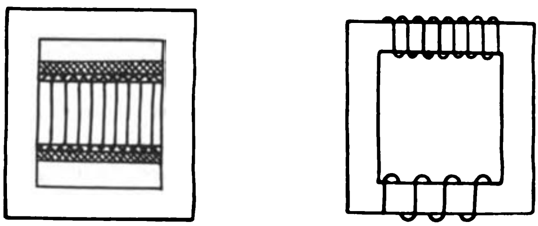


FIG. 13 : 2. SQUARES OF FABRIC OF IDENTICAL RESISTANCE



a *b*

FIG. 13 : 3. TYPES OF CORES IN TRANSFORMERS
(*a*) Shell type; (*b*) Core type

13.14. Resistors at extremely high frequencies

The reactance of resistors used at extremely high frequencies must be extremely small. A common form of resistor is a disc; equally popular is a sheet of low-loss plastic coated with the resistant fabric. Measured from side to side, a square of such fabric has the same resistance, regardless of size (Figure 13 : 2). Such cloth is rated as so many ohms per square. It may be obtained in resistances ranging up to 600 ohms per square. To make suitable connections with it, a metallic border is

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painted or coated on the edges. The discs mentioned above find their greatest use as shunt resistors in coaxial cables.

13.15. *Inductors*

The transmission of high power is accomplished more effectively by three-phase lines than by single-phase lines. The three-phase is much lighter than the single phase for the same amount of power. Transformers, similarly, built for three-phase use are also lighter and more economical. As much of the weight of a transformer lies in its iron, the disposition of the iron material is important. By using a shell-type core as shown in Figure 13 : 3 (*a*), which is built up of E or I laminations in groups the weight can be considerably reduced.

In the core type of transformer, shown in Figure 13 : 3 (*b*), the primary and secondary coils are symmetrically placed. In a transformer, maximum efficiency is attained when the losses in the iron core equal the losses in the copper coils. This requires that the mean length of the magnetic circuit be equal to the mean length of the copper; furthermore, the over-all area of the iron section of the core should equal the over-all area of the window of the core. The smaller the radial thickness (layers) of the coils, the better is the outward flow of heat.

A broad-band transformer will give the same performance over a broad band of frequencies, but to attain this result great care must be exercised. The distributed capacity,[4] the interwinding capacity,[5] the leakage, and the resistance must all be reduced to the practical minimum. In some respects, the factors participating in such transformers are conflicting. At the low-frequency end of the band, the output voltage is limited by the primary inductance of the transformer, which is finite; unlike a power transformer, primary inductance is much more critical because of the character of the power feeding into the primary. The impedance of the source of power feeding into a power transformer is practically zero. As a result of the low primary inductance the exciting current is increased, but this means little if it does not cause overheating. A broad-band transformer is fed by a source of high-output impedance; a decrease in the primary impedance will produce a corresponding decrease in the primary voltage, and hence, in the output voltage.

Suppose we double the number of primary turns. If the output is

[4] Capacity arising from the fact that a length of conductor has capacity in a measurable amount as the frequency rises to very high values, i.e., the megacycle range.

[5] As each layer of winding forms a condenser with the other layers of the transformer, the capacity effect at megacycle range of frequencies is very large.

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to remain unchanged, we must also double the number of turns in the secondary coil, which should double the secondary inductance. As a consequence, the leakage inductance[6] will be increased, and the high-frequency response will fall off.

The high-frequency response decreases because *leakage inductance* and the shunt capacitance both increase. The point of reasonance between the inductance and the capacitance will change.

The core of the transformer and the number of turns in the primary coil will largely determine the low-frequency response. In a broad band transformer losses of power and heating are of no practical consequence; on the other hand weight and size are very important.

Eddy currents in transformers can be reduced by using very thin laminations. A result of this is a decrease in the cross-section of the conductive (magnetic) path because more of the core consists of insulation. In very large transformers where the windings are massive, even the eddy currents set up in the conductors themselves will be large. It is not unusual to employ multiple conductors woven into strands in order to lessen eddy currents. By interleaving the windings or coils the leakage inductance can be reduced. It is important that the number of turns, when they are divided, remains the same in the aggregate. If they are not exactly equal a circulating current will be generated which will wipe out the leakage flux and force more of the total flux to pass through the core. If the turns are not carefully equalized, the result obtained is just the reverse of that intended, and the leakage flux is enhanced.

Distributed capacity can be reduced by subdividing the windings. The capacity between primary and secondary coils (the interwinding capacity) can be entirely eliminated by inserting a copper shield between the windings and connecting it to the ground. Placed around the core, a heavy copper sheet is highly effective as a shield (**13.20**). One precaution must be observed in the use of copper as a shield: if the sheet closes upon itself completely, it would serve as a short-circuited single-turn coil and enormous currents would flow through it. For this reason the copper sheet is insulated at its extremities forming a lap joint. Such a shield does not obstruct the chief magnetic field through the core of the transformer. Any component of the magnetic field, by its variations, induces eddy currents in the shield which themselves set

[6] The inductance created by the magnetic flux that leaks between the coils and does not embrace all the coils.

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up magnetic fields opposing the flux of the eddy currents. This kind of shielding is particularly well suited for long thin cores.

Another way to reduce capacity is to be sure to select insulation with a low dielectric constant. Among practical materials, those having a styrene base are effective as dielectrics of low values and low losses.

13.16. Materials and construction of cores

To make better transformers we must select better materials. For cores, Hypersil and Alleghany 4750 are used extensively. Hypersil (high-permeability silicon steel) is a grain-oriented silicon steel[7] which can be obtained in completely assembled cores. One common type of core is made up of two "C" sections, as shown in Figure 13 : 4 (*a*).

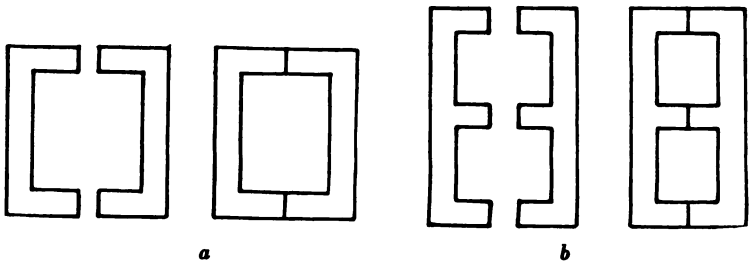

FIG. 13 : 4. TYPES OF CORES IN TRANSFORMERS
(*a*) "C" sections, forming single window
(*b*) "E" sections, forming double window

For greatest efficiency, the laminations of the core should be in the form of double windows, as shown in Figure 13 : 4 (*b*). When the loss of copper equals the loss in the core maximum efficiency is attained. A decreased loss of iron requires a decreased loss of copper. This is another way of saying that such a transformer will operate with less heating or that it can be run with a smaller core and the same rise in temperature.

13.17. Materials and properties of coils

The materials and properties of coils have been much improved in recent years because of the introduction of many new insulating materials. Especially good is polyvinyl acetal insulation for wire, Forminvar, or G. E. Formex. Enamel is too sensitive to abrasion and

[7] It has been ascertained that the magnetic qualities of many alloys depend upon the arrangements of their granular structures. In sheets of silicon steel, the grains appear as fibres. If the sheet of steel is rolled in the direction of its fibres, the magnetic properties sought are most favorable.

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to attack by chemicals. Forminvar resembles enamel electrically, but it withstands friction and mechanical abrasion much better; in addition, it is chemically inert and tolerates higher temperatures of operation.

Phenols, cresols, and certain mixtures of solvents in alcohols and aromatic hydrocarbons will attack Forminvar. In coating wire with enamel, the wire is drawn through a bath of enamel and then through a die which draws the film of enamel down to the desired thickness. It is then hardened by passing through an oven. The manufacture of enamel wire is delayed because time is required to evaporate off the solvent and to bake the enamel. Because the process of making enamel wire is slow, it is relatively costly. Furthermore, because of changes in viscosity (thickness of the liquid—its readiness to flow) and in composition, the final baked coating is uneven. This lack of uniformity is usually of slight importance, but for the use of precision potentiometers, even slight changes in thickness may become critical.

Compared to enamel, Forminvar has many advantages. It can be extruded on to a bare wire in a manner not unlike the extrusion of lead on heavy cables, and coating formed is tough, even, and tenacious.

13.18. Insulation between layers

The most common material used as insulation between layers is paper. As the quality of paper has risen and as the impregnating liquids have improved, paper insulation as a whole has benefited. Fiberglas is superior to paper in many respects, and in the form of cloth, string, or tape it is highly useful. It is very strong, it resists heat especially well, and it is chemically inert. It does not, however, withstand friction and abrasion as do many of the organic insulators, nor is it easily worked or handled. When Fiberglas is impregnated with silicone varnish, it becomes highly effective. Rayon is widely used in place of silk as an insulator. It is better than varnished cambric and more flexible; it is also considerably stronger. Nylon is not so effective because it cannot withstand high temperatures.

In order to feed power into a transformer, or extract power from it, leads are required for connections. If the wires on the transformer is heavy, they will serve as leads. When, however, a transformer is wound with fine wire, it is customary to solder slightly heavier wire to the fine wire; then very heavy wire is soldered to the intermediate wire.

Paper insulation is most commonly used on small coils and transformers. If the wire employed is very fine, it is wound on the cores or

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spools at random until the required number of turns is obtained. The number of layers is disregarded and the only insulation used is that on the wire itself. As this type of winding is not formed or shaped (the coil is not self-supporting), it requires a confining form or spool. Fine bare wire is sometimes employed, but for insulating purposes it has to be spaced by winding a string in a long helix around the bare wire.

For use at high power or on very high voltages, what is known as "pie" winding is often utilized.[8] Especially adapted for such winding is a ribbon-like conductor made of copper. For very large power and correspondingly large currents, the wire or conductor is often square or rectangular in section. This permits a better space factor, i.e., more copper in a given space.

Though coils are wound with wires as fine as 50 AWG gauge, it is common practice to avoid wires smaller than number #40 AWG gauge. The diameter of #50 wire is 0.001 inch; the thickness of enamel insulation is about one-tenth of this. It is extremely delicate, and a tension of fourteen grams (half an ounce, approximately) is sufficient to break it. It runs fifty-one miles to the pound.

13.19. *Treatment of coils*

As moisture, especially, raises havoc with insulation of coils, it is usual to treat coils for the removal of moisture and seal them against moisture re-entering. A quick and inexpensive method of accomplishing this objective is to immerse the coils in molten wax. This is a common but by no means good method. After immersion in the liquid wax, the coils remain until bubbling stops. This indicates that the air has been driven out. Thereafter, the coils are withdrawn and allowed to drain. For best results with this method, the wax should not cool below 110°C (above the boiling point of water) during the early stages of immersion. Even though the moisture in the coil is converted into steam, the pressure of the steam is not sufficient to force out the moisture against the pressure of the liquid wax.

Far superior to this method, though more costly, is what is known as the vacuum method. The coils are placed in a vacuum chamber where they are heated to expel moisture. Still in the vacuum chamber, the coils are impregnated with a wax varnish which is introduced into the vacuum container.[9] Because of the external pressure of the

[8] Coils wound as flat helices or discs are said to be "pie-wound".

[9] A good wax varnish consists of resin, shellac, and beeswax; the resin is readily soluble in alcohol.

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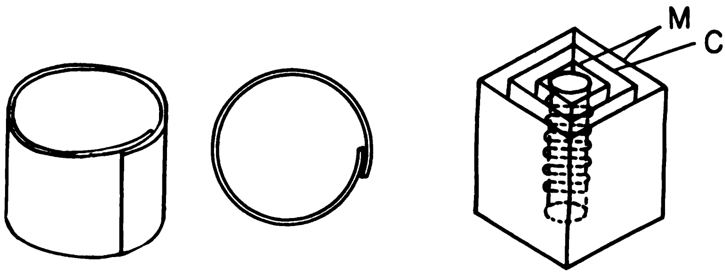
atmosphere, the insulating liquid is forced into the voids or spaces in the coil. This method is excellent but expensive and slow. It requires a long time to drive out the contained moisture thoroughly. This is an absolute essential; otherwise, the impregnation is only partial. The presence of moisture is gauged by measuring the degree of vacuum existing at any time. When the impregnation is complete, the entire mass of the coil and the insulation forms a solid block.

Inexpensive coils and transformers are insulated with a material consisting of a mixture of beeswax and paraffin, or beeswax and rosin. These are not so effective as the wax varnish already described.



a *b*

FIG. 13 : 5. TYPES OF SHIELDS
(*a*) Electrostatic shield of metal with insulated lap
(*b*) Magnetic shields for high frequencies; nested cans of Mumetal (M) and copper (C)

For coils and transformers used on voltages up to 10,000 volts, varnish is a safe insulator. For voltages in excess of this, the coils should be immersed in oil. It is well to remember that rubber insulation is attacked by oils and is soon decomposed and ruined. If it is necessary to employ a dry form of insulation, varnished cambric is excellent for high voltages; recently, an acetate rayon insulation has found wide acceptance. As the voltage mounts, the spacing between coils must be increased, even though immersion in oil is employed.

13.20. Methods of anti-electrostatic shielding

Shielding against both magnetism and electrostatic charges is often a necessity. As already noted (13.15), a sheet of copper inserted between windings is an effective electrostatic shield. Such a sheet should be wound with a large lap joint which is insulated in the region of the overlap so that it does not form a short-circuited winding; see Figure 13 : 5 (*a*). It is common practice to ground (connect to the earth) the

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shield. On the other hand, no shielding will be necessary if there is a grounded winding already between the windings to be shielded. When placed between the primary and secondary of a high-voltage power transformer, the shield suppresses radio-frequency noises in the supply lines, and prevents them from entering the output by means of the capacity between the primary and secondary evils. The higher the operating frequency, the greater is the need of shielding. Thus, at 60 cycles, grounding the shield (connecting to the core) at one point will usually suffice. At 400 cycles, it may be necessary to ground the shield at two points. As a protection from external electrostatic fields, an ordinary metal can placed around the coil or transformer to be shielded is often sufficient.

13.21. *Methods of anti-magnetic shielding*

Shielding against magnetism poses a very serious problem. The greatest protection is afforded by employing materials of very high permeability. Cans of Peramalloy or Mumetal are best. A reduction of 10 db (one-tenth) will be obtained by using a can of Mumetal of only ten mils (0.01 inch) gauge. At high frequencies, excellent shielding will result by arranging several cans concentrically (like a Chinese nest) alternating cans of copper and Mumetal. This is shown in Figure 13 : 5 (*b*). One pair of these cans (copper and Mumetal) will yield a reduction of 30 db (reduction 0.001); that is, they will cut down the field to 1/1000. Three pairs of such concentric cans will produce almost a perfect shield.

There is a strong impression, particularly among laymen that a heavy cast-iron container is a good and effective shield. Tests made on commercial transformers show a reduction of less than 6 db (reduction 1/4), demonstrating how inadequate such shielding is. Even containers of drawn steel offer little additional protection.

13.22. *Provisions for heat expansion*

On transformers and coils insulated with oil, leaks must naturally be avoided. Also, some arrangement must be set up to accommodate expansion due to heat. In small transformers, this is easily effected by leaving the flat surfaces on the ends of the transformers thin and flexible. If no such provision is made it may become necessary to incorporate a contrivance for expansion, such as the metal bellows shown in Figure 13 : 6.

A good method of reducing the changes of volume of oil due to temperature changes is to decrease the amount of oil used. This is done

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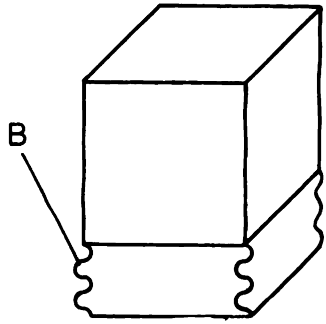
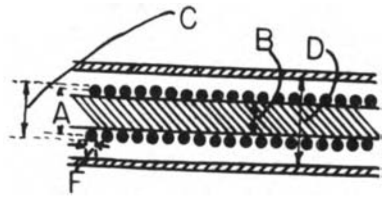
by filling part of the space with clean sand or glass beads, both of which are excellent insulators. One evident drawback to this is the fact that the weight is increased because sand is several times heavier than oil.



13 : 6



13 : 7

FIG. 13 : 6. METAL BELLOWS (B) IN BASE OF TRANSFORMER CASE TO ACCOMMODATE EXPANSION

FIG. 13 : 7. SECTION OF HIGH-IMPEDANCE COAXIAL CABLE WITH COIL SURROUNDING INNER CONDUCTOR

13.23. Impedance of transmission lines in practice

Cables of high impedance and up to 100 feet may be used to transmit video signals. The impedance of common coaxial cables runs from fifty to one hundred ohms per foot, and a capacity of ten to thirty *mmf* (micromicrofarads) per foot. By inserting a cable, both the peak voltage of the output and the gain from the amplifier tube are lowered. By employing a cable with a high characteristic impedance (also called *surge impedance*) we can obtain superior results. Remember that

$$Z_c = \sqrt{L/C}$$

where Z_c is the characteristic impedance; L is the inductance; C is the capacitance per unit of length; and T is the delay per unit of length. We can obtain a high characteristic impedance by making L large or C small. For this reason, high-impedance coaxial cables have inner conductors consisting of a close-wound coil instead of a simple wire; see Figure 13 : 7.

When F is very much smaller than A, A is approximately equal to C, and the maximum impedance is obtained when

$$D/A = \sqrt{e}^{\,10}, = \pm 1.65$$

[10] e or ϵ is symbol for base of Napierian logarithms value; 2.718.

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The delay per unit of length rises rapidly with the diameter of the cable. The effect of increased delay is to increase the intervals between echoes. The losses in transmission are proportional to C.

Loss through eddy currents will occur in the outer conductor because of the changing magnetic flux in the inner conductor. This can be minimized by increasing the spacing between the inner and the outer conductors. A practical method of decreasing eddy currents is to use for the outer conductor a strand composed of insulated fine wires.

13.24. *Q and accuracy of crystals high*

The Q of quartz crystals is very high and very stable. Extreme accuracy at the outset is easily ensured. How the crystal reacts to vibrations, humidity, and shocks will depend upon the character of the mountings and the enclosing containers.

13.25. *Piezo-electric crystals*

The so-called 15-megacycle crystal employed as a standard must resonate at a frequency of 15 Mc $\pm$ 0.15 Mc when unmounted. As there is appreciable damping due to mounting in a cartridge, the frequency may drop to 14.75 Mc. Great care must be exercised that the line of the axis is perpendicular to the faces of the crystal within one degree. This is readily checked by means of X-rays. The plane surfaces of the crystal are ground to the approximate thickness and then etched to the exact thickness required. Thereupon, the prepared crystal is gold-plated by sputtering and baked for one hour. By the use of gold, corrosion is minimized.

13.26. *Electromagnetic delay lines*

The interval of time between the formation of a pulse and its appearance in a circuit where it is to perform a specific function is the *pulse delay*. It is necessary to interpose some device or circuit arrangement to *effect the delay*.

Pulse delays of great precision are absolutely essential in radar practice. Two methods are commonly employed for attaining pulse delays: by one, the signal is stored in a tank and reproduced at some later time; in the other, a signal is fed into one end of a long transmission line and then fed out at the other end. The delay is equal to the time for the signal to pass through the transmission line. Which method is used is determined by the amount of the required delay. For delays not exceeding microseconds, the electromagnetic lines will suffice. Delays

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running in the millisecond range may employ acoustic methods, and delays up to a second may be effected through the use of storage tubes.

Signals are attenuated and distorted in delay lines as they are in networks in general because of losses in transmission, distortion in phase, and mismatch.

In an electromagnetic delay line

$$Z_c = \sqrt{L/C},$$

where impedance is Z_c, L is in henrys, and C is in farads. The time delay, T, in seconds equals $\sqrt{LC}$.

For a set impedance, Z_c, and a fixed time delay, T,

$$L = TZ_c \text{ and } C = T/Z_c.$$

By the use of a delay line, we have a compact device for obtaining the required inductance and capacitance. The delay time for a coaxial cable is easily computed from the formula

$$T = 1/3 \times 10^{-10} \times L\sqrt{K}$$

where L is in centimeters and T is in seconds. K is the dielectric constant of the material between the inner and the outer conductors.

For polyethylene, K is 2.25. Employing the foregoing formula, a length of 200 meters of polyethylene will introduce a delay of one microsecond (10^{-6} second). Transmission lines used for delay purposes are of two kinds: those with distributed parameters and those with lumped parameters.

13.27. *Lines with distributed parameters*

For use in the range between 200–3000 ohms (characteristic impedance), lines with distributed parameters are effective. In order to obtain a high inductance, the central conductor is a tightly-wound coil. As the inductance (L) is increased both the impedance (Z_c) and the delay are increased. By keeping the clearance between the center and the outer conductors small, the capacity (C) is also increased. Even though the delay is increased the impedance is decreased. The inductance of a long thin coil may be expressed by a simple formula,

$$L = 10^{-9} \times \pi^2 \times d^2/p$$

where L is expressed in henrys per cm, d is the average diameter in cms, and p is the pitch of the winding.

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This formula is strictly applicable at low frequencies only. At very high frequencies, the current and the magnetic field are linked, but the difference in phase is large. There is a steady drop in the inductance of the winding as the frequency climbs into the ultra-high frequency range. The capacity between conductors does not vary much with a change of frequency. Because the inductance decreases as the frequency increases, the delay time of the transmission (delay) line varies with the frequency. Unfortunately, a decrease in the delay time appears as a distortion in phase which, in turn, changes the shape of the transmitted pulses.

The attenuation of the delay line also distorts the signals. Only if all frequencies were equally attenuated would there be no distortion; the higher the frequency, the greater the attenuation. For this reason, a square wave pulse, which consists of a great number of harmonics (frequencies), becomes perceptibly rounded in passing through the delay line.

Attenuation in delay lines arises from two causes: the losses due to reactance in the conductors, and the dielectric losses in the insulation between conductors. Because of the skin effect (3.4) the resistance increases with the frequency. The dielectric losses are more serious. These occur in the space that separates the conductors and the turns of the coiled conductors. Obviously, the losses between conductors can be minimized by the use of low-loss material for the dielectric or insulation. Formex, though satisfactory at relatively low frequencies, is inadequate at very high frequencies.

Attenuation of the higher harmonics (frequencies) is due to the mismatch at the ends of the terminated line. If the line is matched accurately at low frequency, all power at this frequency is transmitted to the load. It follows, then, that high-frequency components will not be matched and that part of the power will be reflected from the ends of the line. Consequently, power reflected at the input will appear at the output after a delay of twice the length of the line.

There is still another cause for mismatch in coaxial lines which arises within the line before the termination. In a long coil, the inductance of a turn at the middle of its length is greater than that of a turn at the end because its magnetic field is coupled with a larger number of turns. Hence, the inductance per unit length of line varies, the impedance also varies, and a mismatch results. By increasing the diameter of turns as the ends are approached, this variation in inductance can be avoided.

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13.28. Methods of varying delay in lines

Delay lines, which can be varied somewhat resemble potentiometers in which the moving arm makes contact with the exposed coil. By employing coils for both the inner and the outer conductors, the characteristic impedance can be made larger. Ordinary delay lines are satisfactory for signal delays and trigger pulses where the presence of moderate distortion is of no serious consequence. For use with oscillators, accessory aids such as phase-oscillators, must be employed to prevent distortion. These are networks which are added to the delay lines. Though they prevent distortion, their bulk is excessive and often exceeds that of the entire delay line.

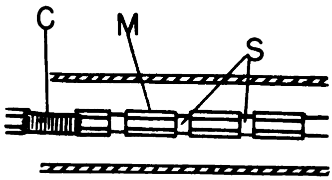

FIG. 13 : 8. USE OF METAL PATCHES IN TIME-DELAY CABLES
C, coil; M, metal patch; S, insulation

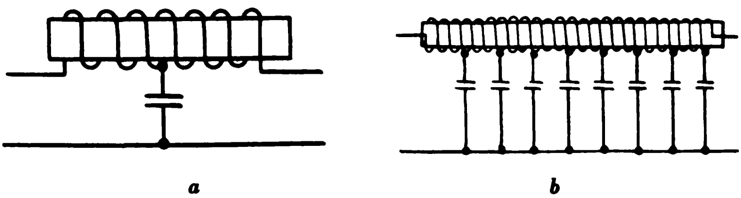

FIG. 13 : 9. NETWORKS OF LUMPED PARAMETERS
(*a*) Schematic of simple filter: condenser and two coils
(*b*) Delay equalizer: continuous coil with taps

A ready means for equalizing a time delay is to add capacity in bridge form. This increases in effectiveness as the frequency is increased. Metallic patches of varying length and insulated from the coiled conductor (Figure 13 : 8) determine the amount of capacity introduced. In the very high frequency range, the increase in delay matches the increase in capacity. Isochronism can be adjusted by varying the width or thickness of the patch insulation. Most of the bridge capacity is on the outside of the long coil. If a substantial part of the coil is covered with metallic braid, the conductors are screened

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from one another and equalization arising from the coil capacity is suppressed. The need for metallic patches or metal foil (known as equalization patches) decreases as the impedance in the line rises.

By winding delay coils in sections, inductance is lost and the delay per unit length of cable is decreased. By employing what is known as *floating patches*, we may obtain special effects. These patches are sheets of metal which are covered with low-loss dielectric and then wound with fine wire. By such means, time delay can be equalized within one per cent up to 4.5 Mc. One cable is wound with wire, insulated with #40 Formex and covered with a metal braid, which, in turn, covers a porcelain tube 0.25 inch in diameter. The patches on the core are 0.001 inch thick, 0.345 inch wide, and are spaced 7/16 inch from center to center, leaving a gap of 0.02 inch between patches. The patches are insulated by an impregnated paper 0.001 inch thick. A ten-inch length of this cable has a delay time of one microsecond and an impedance of 1150 ohms.

13.29. Networks of lumped parameters

Where very low impedance or very high voltage is required, delay lines consisting of condensers and coils are employed. Because of the lower dielectric loss in such cases, the attenuation is less. In the ordinary low-pass filter network consisting of a series inductance (L), and a capacitance (C), the delay rises with an increase in frequency. Ordinary low-pass filters may be improved by sectionalizing; Figure 13 : 9 (*a*) shows a simple filter with the inductance made up of two coils.

In delay equalizers the coupling between coils is varied. In practice, it is common to wind several coils as one coil with a number of taps; see Figure 13 : 9 (*b*). By suitable selection of the diameter of the coil, the gauge of the wire, and the thickness of the insulation, any desired coupling may be effected. The attenuation of such a network is much lower than that of a delay line with a distributed parameter.[11]

In trigger pulses of long delay, the impedance of a suitable network is 75 ohms. By the addition of sections, we can build up the delay to 2.4 microseconds in steps of 0.05 microseconds. One precaution should be observed: there should be no appreciable coupling between coils; the spacing between coils should be uniform.

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[11] A distributed parameter is one in which capacitance, inductance, or resistance is not concentrated or lumped.

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13.30. Supersonic delay lines

If an electric impulse is changed into a sonic impulse (which is what happens in every telephone receiver) and then back into an electric impulse, we have an effective delay device of relatively long duration called a *transducer*. In the megacycle range, nothing excels quartz as a crystalline device for *piezo-electric*[12] transformation. For liquid media, mercury and water are among the best.

Supersonic delay lines find two wide uses: as triggers and range markers, and as reproducers of pulses. For pulse delays, the bandwidth must be of appreciable size if distortion is to be avoided. It is also possible to employ a solid block of fused quartz.

In mercury, the delay time is 17.52 microseconds per inch at 20° C, which is another way of saying that sound travels at this speed through mercury.

The speed of sound waves through water varies oppositely to that of mercury with temperature changes in the liquid. By mixing water and other liquids, the temperature at which maximum speed occurs can be varied.

The resonant frequency of an x-cut crystal of quartz is $2.36/d$ megacycles per second when d is given in millimeters. The electrostatic capacity of a 10-Mc x-cut crystal is $91.5 \times s$ *mmf*, where s is the excited (active) area of the crystal in square inches.

13.31. Bandwidth of piezo-electric crystals

The *acoustic impedance* is the term for the product of the density of a crystal multiplied by its voltage. As the acoustic impedance increases, the frequency response becomes broader. The assumption is made that the surfaces in contact are alike on both sides of the crystal.

The Q of a crystal can be expressed as a ratio,

$$h\pi r' V_1/4rV_2$$

where $r'V_1$ refers to the crystals; rV_2 applies to the contiguous medium; and h is the order of the harmonic driving the crystal. The spread of the beam of a crystal can be expressed as

$$\text{sine } \alpha = 1.22\ \lambda/d$$

where α equals half the spread of the angle; λ is the wave length of the oscillations; and d is the diameter of the crystal.

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[12] Sound vibrations applied to the faces of certain crystals like quartz, Rochelle Salts, and others generate currents in the crystals that are known as *piezo-electric*.

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As sound is transmitted through any medium, there is a loss in intensity. In mercury, the attenuation or loss may be expressed

$$db = (0.012 \pm 0.002) f^2 s$$

where f is the frequency in megacycles per second, and s is the distance traversed in feet. If the mercury is contained in a tubular vessel, the attenuation or loss in db because of the tube is

$$db = 0.054\sqrt{f}s$$

where f is the frequency; s is the distance traversed in feet; and d is the diameter of the tube in inches.

For use in television, crystals are employed that are resonant in the range of one to ten megacycles. If the acoustic impedance is large, the Q of the crystal circuit is lowered.

In the region of five to thirty megacycles, if the crystal is driven at an odd harmonic of its frequency, rather thick crystals can be employed. A disadvantage of such operation is the fact that the voltage generated is reduced by the same order. Thus, a crystal driven at its tenth harmonic, generates a voltage of the order of one-tenth of the fundamental. If it is to be operated constantly at its bandwidth, there must be compensation. The line capacity of a crystal decreases as the order of the harmonic increases. Thus, at the tenth harmonic, the line capacity has fallen to one-tenth of the value at the fundamental. If the only effective capacity is the live one of the crystal, the bandwidth will be determined by the load resistance for a shunt resonant circuit, increased by the order of the harmonic. The applied or received voltage would be increased in the same order, as the generator and the line have a high impedance. At this stage there is no disadvantage in operating the crystal at a harmonic. Because of the presence of stray capacity, compensation is never complete; hence, operation at a harmonic is to be avoided where there is a choice.

The size of the crystal is determined by the method of mounting, and the inner diameter of the tube. The active area of the crystal is equal to the actual inner area of the tube. Because of this, a plane wave is transmitted through the tube. In order to reproduce the delayed pulse with fidelity, the live capacity[13] should equal the stray capacity where the latter is at the minimum. If suitable matched, the ratio of live capacity to stray capacity should equal the maximum ratio of V_0/I, where V_0 is the output voltage and I is the input current for a

[13] Live capacity is an electrical property of the whole mass of the crystal.

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delay line that transmits a fixed bandwidth and feeds into a load of low impedance. In order to obtain the greatest ratio of signal to noise, the maximum value of the live capacity should be greater than the stray capacitance.

To be good, the mounting of a crystal should be properly supported so that there is no undue stress on it; otherwise, it may crack or bend. The axis of the crystal should be carefully aligned with the axis of the tube. The error in alignment should not exceed 0.2α (α = angle of spread of the emitted beam). In attaching the electrodes to the crystal care should be exercised so that the sonic operation is not obstructed. Where the medium of transmission is an electrical non-conductor, e.g., distilled water or oil, it is necessary to plate the surface of the crystal with metal. For a liquid like mercury, no plating is required. The Q of a crystal is lessened and its bandwidth is increased by loading. In

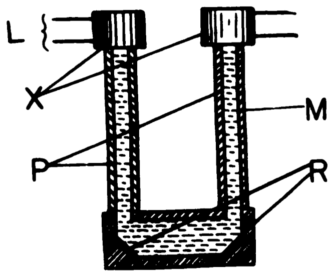

FIG. 13 : 10. CROSS SECTION OF FOLDED DELAY LINE EMPLOYING MERCURY
L, leads; X, crystal housings; P, metal tubes; M, mercury; R, corner reflectors

range units (trigger delays), the crystal is loaded by soldering metal to its backing.

13.32. Effective operation of crystals

For good reproduction of a pulse on a long delay line, multiple echoes must be suppressed. The energy of the pulse impinges on the reverse side of the crystal in its surrounding medium. At resonance, a crystal behaves like a half-wave section and it is necessary to match the acoustic impedance on both sides of the crystal. Where the lines are of mercury, a match is obtained by filling the void behind the crystal with additional mercury.

An absorbent backing for crystals is desirable on long lines, because all the incident energy is reflected from dry steel electrodes. For great stability of delay, the entire apparatus should be maintained at a constant temperature.

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13.33. Folded and variable delay lines

Straight lines on very long delays would require too much length. To gain the advantage of long lines without having to employ inordinate length, it has become the practice to fold the lines. Actually, two or more straight pipes are joined by corner reflectors as shown in Figure 13 : 10. These corner reflectors are plated with stainless steel, given a chromium finish, and ground to an optical flatness. The attenuation is then very low.

In variable delay lines, water is employed. The length of the column is varied by means of a screw which advances or retards the movements of the crystal. The rotation of the screw is noted on a calibrated scale which indicates the length of the column and the range.

The use of mercury lines running to a vibrating crystal, makes it possible to ascertain defects in the crystal by the use of a Q-meter. A crystal without imperfections has an extremely high Q at its natural period of resonance. The presence of bubbles, cracks or other imperfections causes a very great drop in the value of the Q of the crystal and indicates structural defects which are otherwise not evident.

It is comparatively simple to measure loss of voltage. The delayed signal is matched through a delay line with an undelayed pulse through an attenuator and the reading on the attenuator is recorded. The input of the delay line and the attenuator are in parallel; hence, the input voltage is the same across both. Loss in transmission is affected by the changes in temperature in the attenuator. The conductivity of water (attenuation decreases) increases with a rise in temperature.

13.34. Potentiometers

The vital component in a potentiometer is the resistance element. For a precision instrument, some form of wire is always employed. An insulated mandrel serves both as the core and as a shape former for the winding. The potentiometer will be no more accurate than its winding. This, in turn, will depend upon the precision with which the mandrel is made, the uniformity of tension of the winding, and its spacing. Potentiometers may be linear or non-linear. In the linear type, the voltage at any point in the winding varies directly as the distance from its extremities; in the non-linear, the variation is otherwise. It is customary to wind non-linear potentiometers on tapered cards (Figure 13 : 11). The card is often a sheet of phenolic plastic (Bakelite, for instance) which serves as the mandrel. To ensure accuracy, the card should be free of such imperfections as cracks, nicks,

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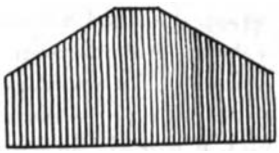
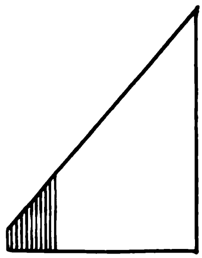
dents, and hollows. The edges of the card are rounded to a semicircle of very small but precise radius. The milled surface of the potentiometer is carefully buffed.



a

b



c

FIG. 13 : 11. TYPES OF CARDS
(a) Tapered, with winding for non-linear potentiometer
(b) Tapered, with small ratio of maximum to minimum resistance
(c) Tapered, with excessive slope, unfit for use in potentiometer

13.35. Resistance wire

The materials most commonly used for resistance elements are Nichrome and Advance. The former is composed of nickel and chromium, and the latter is an alloy of copper and nickel (13.5). In precision potentiometers, the specifications concerning the diameter of the wire and the thickness of its insulation are close to the limits of manufacture. Although Formvar[14] is expensive, it is much superior to enameled wire and is relatively free of bends and other defects. As already mentioned, the potentiometer should be wound on a machine with the wire under uniform tension.

13.36. Treatment of the winding

Following the winding, the resistance element is suitably coated, either with varnish or with some other suitable insulating compound. This serves to hold the wire in place and also to protect it from moisture, abrasion, and friction. During the curing process, it is not easy to prevent displacement of the wires by the varnish itself. For this reason, a special varnish must be employed. Where the contact arm touches the winding, the wire should be bared by removing the insulation. This

[14] A polyvinyl acetal wire insulation; it is thermoplastic (sets with heat) and is applied to wires by extrusion.

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is done by buffing, and the process should remove only the insulation but not the metal surface.

The prevalent form of potentiometer is cylindrical. This is usually wound with wire resistance. Most wire is wound on straight forms or rectangular cards which are then wrapped around a cylinder. Some are wound on a toroid (doughnut in shape); still others are wound and mounted on the inside of a hollow cylinder. The windings may be on metal or on an insulating base; if on the latter, it is common practice to cast the form in a mold; thereafter, it is ready for use. For great precision, the mold is too rough, and some machining is required. Where the utmost precision is essential, metal is best and most stable; an aluminum alloy is employed most frequently. The use of metal demands additional insulation.

Inexpensive potentiometers employ rotating shafts. The bearing is simply a reamed hole. Obviously, such holes lack precision and transmit the imperfection to the potentiometer. Shafts are of either metal or plastic; the latter is used in the cheapest type. Inherent defects are caused by distortion and deformation of such shafts. Somehat better is the metal shaft and a plastic sleeve. Superior even to this is the placement of the insulation in the hub of the contact arm which has a metal shaft of ordinary or stainless steel.

The nature of the contact is very important. On it will depend both the precision and the life of the potentiometer. In precision instruments employing fine enamel wire, the contact point is an alloy of platinum and silver to which is added a trace of gold, copper, and zinc. This alloy is known by the trade name of Paliney #7. If the resistance element is Climax (a copper-nickel alloy), the most suitable material for the contact point is an alloy of platinum and silver. Phosphor bronze is entirely unsuited for contact points.

The contact "point" is actually a small cylinder whose major axis should lie parallel to the axis of the wire if the efficiency is to be at the maximum. With a point thus oriented, only two wires are in contact at any one time, which is another way of saying that only one turn of the potentiometer is short-circuited. This kind of contact ensures the greatest linearity. For best results, the diameter of the cylindrical contact should range between 0.02 and 0.04 inch. Though attempts have been made to use a rolling contact, this is not so effective as a sliding contact. Phosphor bronze is too soft and wears away too rapidly; on the other hand, materials like Stellite (tungsten carbide) wear away the wires of the potentiometer.

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Another feature to be observed with care is the pressure in the contact. If this is excessive, it causes inordinate wear and short life; if it is insufficient, chattering and bounce and noise become too great. A pressure of 40–50 grams (1–2 ounces) is most desirable.

13.37. Non-linear potentiometers

The type of potentiometer to be employed is determined by the purpose intended and the precision required. The variation is continuous only where the contact is never broken. Ordinarily, the contact moves in a series of steps or jumps, rather than continuously. The steps are determined by the number of turns and the applied voltage. Usually the steps are so numerous and small that the interruptions are not noticeable. For most purposes, a total of thirty to a hundred steps proves adequate. It thus becomes practical to employ a multiple-point switch.

The most obvious means for obtaining a non-linear variation is to employ a card of continuously variable width. As can be seen in Figure 13 : 11 (*b*), this does not limit the ratio of the maximum to minimum change of resistance (slope). The greatest ratio cannot exceed ten to one; otherwise, the card on which the resistance is wound becomes too weak for practical use; also, as shown in Figure 13 : 11 (*c*), the wire will not stay on the form if the slope is too great. For safety, the best angle should not exceed 15°.

To summarize, non-linearity can be effected in several ways, as follows:

1. Winding the wire unevenly on a uniform mandrel
2. Employing wire whose cross-section is varied (as by etching or by plating)
3. Winding on a mandrel to which wedges are affixed so that the lengths of turns are varied

Still another method for obtaining non-linearity is to cause the contact arm to move in a special manner over a uniform winding. Thus, by the use of a circular moving arm making contact with a square card, it is possible to obtain a variation in voltage related to the sine and cosine of the angle swept out, as shown in Figure 13 : 12 (*a*). It is immaterial whether the card remains stationary and the arm moves, or the arm remains stationary and the card rotates.

13.38. Characteristics of potentiometers

Linearity of resistance is a most important quality. If the change in resistance of the winding is in exact proportion to the change in the

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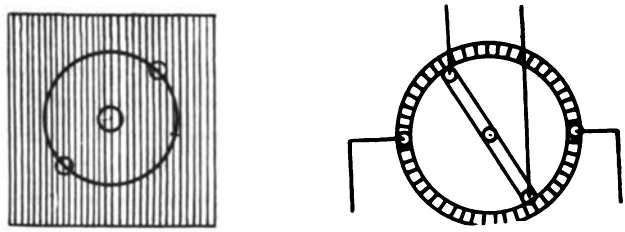
angle of rotation, the linearity will be perfect. By the *slope* of a potentiometer is meant the change of resistance produced by the rotation of the contact arm through a unit angle. *Angular resolution* is the least change in the rotation or the contact arm that produces the least change in resistance. By *voltage resolution* is meant the variation in voltage from one step to the next when the voltage across the terminals



a b

FIG. 13 : 12. WINDINGS IN POTENTIOMETERS
(*a*) Sine-cosine type; brushes rotate and make contact on winding of square card
(*b*) Common type in radar; rotating arm makes contact with circular winding

of the potentiometer is unity. Though it appears contradictory at first thought it is contended that a mandrel wound with 1000 turns can give a resolution better than one in a thousand.[15] This may be a fact when carbon brushes are employed, but does not apply to brushes of metal. The chief drawback to the use of carbon is excessive noisiness.

13.39. Noise

In potentiometers wound with wire, the chief causes of noise are vibration and poor contact. Rapid movements of the contact arm as it proceeds in its rise and fall cause jumpiness in the contact arm, and hence interrupt the contacts. When properly made, a potentiometer should be free from all noise except that due to the rotation of the contact arm as it slides over the hill of the wire into the valley between wires. Excessive speed, as already remarked, does not allow the contact arm sufficient time to follow the contours of the winding closely.

Another kind of noise in cheap potentiometers is due to the presence of insulating material between the contact point and the winding surface. This may be due either to the wear of the potentiometer, or to the presence of foreign particles. For this reason, potentiometers

[15] Because it is wound with 1000 turns, it would seem that there are 1000 steps in the potentiometer. A carbon brush may, by straddling two turns, cause less variation in voltage than that caused by the shift of one turn.

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enclosed in dust-proof containers are more reliable and silent. The presence of particules due to wear may be minimized by selecting the appropriate shape of contact, the right pressure, proper material, and brushes of the best kind. Bearings should never be lubricated, for greases cause adhesions and undesirable noises.

The over-all resistance of a potentiometer is determined by the area of surface of the winding, its pitch, and the resistance of the wire. The smaller the winding wire, the greater must be the care exercised to keep the tension uniform as it is being wound. Minimum resistance is set by the resolving power, which, in turn, depends on the pitch of the winding. Low resistance may be easily obtained by shunting an appropriate resistance across the winding.

Temperature rise controls the maximum power that can be dissipated in a potentiometer. Though there is a considerable range of operation in commercial potentiometers, torque usually does not exceed a few inch-ounces. Tiny potentiometers are being made in which the requirements for torque do not exceed a few thousands of an inch-ounce. In cheap wire potentiometers, poor bearings, improper contacts and arms may force the torque to relatively high values. Ball bearings and improved contacts decrease torque and minimize wear.

13.40. Testing for linearity

By taking a number of point measurements, as we test a potentiometer for linearity, either resistance or voltage may be measured. Voltage readings are preferred because heat changes in resistance can not be considered.

Testing for linearity by the use of cathode ray tubes has the advantage of presenting the data on errors in visual form. The potentiometer under test is compared with a standard potentiometer of great accuracy.

In the types of potentiometer known as "helipots" and "micropots", the windings are so arranged that the contact arm is never interrupted as it passes from end to end, touching every part of the length of the wire. In most standard potentiometers, the winding is on a circular form. In radar, a common type of potentiometer has two brushes at the end of an arm and two taps 180° apart; see Figure 13 : 12 (*b*). If the output of such a potentiometer is fed into a high impedance, such as the plate of an electrostatic cathode ray tube, the winding should be linear because of the linear relation between the output voltage and the angle of shaft. If the potentiometer is employed

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to feed current into a deflecting coil, the requirements will differ. For use with PPI indicators and for computers, sine and cosine potentiometers are required. Though the life of carbon brushes is long, the drawbacks of inaccuracy and excessive noise prohibit their use where precision is needed.

13.41. Variables condensers for shift in phase

In the measurement of accurate time intervals, as in radar systems, either transient pulses start oscillation trains of a given frequency, or a continuous train of sine oscillations initiates pulses at designated moments of time. The *O* to *V* (*O*-voltage) points of oscillation then become a series of accurate marks of time. Time is measured continuously by shifting the phase of the oscillations and causing a marker pip to follow a *O-V* pip. Should the oscillations shift 360 degrees, the wave would not be distinguishable from the unshifted wave, but the marker would move in time an amount representing one cycle of oscillation. Additional shift would cause the marker to move a proportionate amount further. Because of shift in phase, the markers are made to coincide with the echo of the transmitting pulse; the measure of the delay in time of the echo is a measure of the distance producing the echo.

In one method for producing a shift in the phase of oscillations the original oscillations are split into four equally-spaced 90° phase components by means of an R-C bridge, and these components are then recombined in proper proportions by means of a mixer to obtain the resultant of the desired phase.

Two types of condensers available for four phase shifts are manufactured by Cardwell, and by the Western Electric Company. The Western Electric model (also the Nielsen) is entirely shielded and compactly made. It has a very high impedance, and no rotating contacts. In the Western Electric model the top plate is composed of four sectors and the bottom plate is circular. The capacity is varied by the rotation of a dielectric plate (Mycalex) mounted eccentrically with respect to the condenser plates, both of which are fixed.

The proper shape for a four-electrode condenser is a perfect circle. In the Cardwell condenser, the stator is composed of four sets of rectangular plates; each set is isolated electrically from its fellows. The rotor consists of two sets of specially shaped plates mounted perpendicularly to each other on the rotor shaft. The capacity is varied by changing the degree of meshing of the rotating and stationary plates.

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The error in shift in a Western Electric condenser does not exceed 2°, and in the Nielsen it does not exceed 1° of the rotor position. For example, if the shift moves ten degrees, the plates move ten degrees, plus or minus 2° for the Western Electric model, and 1° for the Nielsen. Even though the change in capacity of any one element of a Western Electric condenser is only approximately a sine wave, the errors introduced by opposite pairs of plates cancel each other, leaving the total effect a pure sine wave.

To meet the requirements of parallelism, flatness, and smoothness, the surface of the rotating dielectric sheet must be ground with great care. The edges of the sheets must be carefully machined, bored precisely, and assembled between collars mounted on the shaft. Because the Western Electric and the Nielsen condensers are in sealed containers, corrosion is reduced to the minimum. Such condensers are operated at low speeds and for periods of a few seconds at a time.

13.42. Condensers for scanning

In order that a radar antenna may scan rapidly and continuously with a sharp beam, we must employ a scanning condenser. This type is also needed to transmit data on position, to follow an antenna, and to select suitable rates of repetition, as determined by the geometry of the display. Further difficulties are introduced because the relation between the radiating beam and that of the shaft controlling motion may not be directly proportional, that is, not linear. For this reason, a linear saw tooth sweep voltage[16] controlled by a synchronous signal from the scanning shaft is not feasible. At high speeds, it is not practicable to employ potentiometers or rotary inductors. Probably the best means to accomplish these ends, i.e., to maintain synchronism, is to employ a voltage divider combined with a special condenser.

13.43. Voltage dividers

If a constant A.C. voltage, E_t, is impressed across a circuit, as in Figure 13 : 13 (*a*), the output voltage, E_o, across a condenser, C_b, will be

$$E_o = E_t \frac{C_a}{C_a C_b} = KE_t$$

If C_b is a variable condenser with plates suitably shaped, and the motion of the condenser shaft duplicates that of a radiated beam, then

[16] Voltage applied to the deflection plates of the cathode ray tube which acts on the beam and causes it to sweep across the face of the tube.

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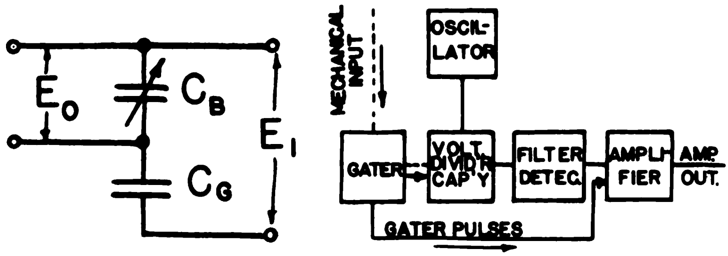
the output voltage is employed to generate a sweep voltage for radar indicators. C_b should be variable because C_a, the fixed and stray capacity to the ground, is negligible. Such a condenser can operate at speeds up to 2000 RPM. Its tolerance is very small.



a *b*

FIG. 13 : 13. VOLTAGE DIVIDERS
(*a*) For alternating voltages employed with condensers
(*b*) Block form of connections for producing sweep voltages with condenser divider

13.44. Producing sweep voltage waves

Figure 13 : 13 (*b*) shows in block form the connections for producing sweep voltages of arbitrary form by means of a condenser voltage divider. The oscillator produces a constant amplitude voltage at a frequency of one million cycles. The voltage from the oscillator is applied to the rotating voltage dividing condenser. The shaft of the condenser duplicates the rotary motion of the rotating antenna so that the variable voltage across the condenser (its output as it turns) is applied to the deflection plates of the cathode ray tube after passing through the amplifier. The amplified voltage as modulated by the condenser produces the saw tooth sweep voltage of the cathode ray tube. The synchronism of the motion of the beam of the cathode ray tube and the motion of the beam issuing from the antenna is brought about by employing one rotating shaft for both condensers, to wit, the voltage divider condenser and that in the pulse circuit. The gater (which produces rectangular pulses) controls the duration of the pulse that is shaped or modulated into the sweep voltage. The filter detector removes the part of the envelope wave except that which is applied to the deflecting plates of the cathode ray tube.

13.45. Brushes and mountings

Carbon brushes in motors and generators at sea level may operate satisfactorily for thousands of hours. At altitudes reached in airplanes,

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carbon brushes may last only ten or fifteen minutes. As a motor (or generator) continues to operate, a film of copper oxide forms on the commutator; this serves as a lubricant. At any high altitude, the film dissociates (decomposes) and the lack of lubrication causes the wear on the brushes to increase enormously. By impregnating the brushes with a chemical such as lead iodide, the lubrication can still be supplied. Despite this, it is nevertheless desirable to avoid the use of such brushes, as the commutation on small equipment becomes gummed up. Where it is necessary to limit the drop in voltage across the brushes to a very low value, a material consisting of silver, copper, and carbon has been employed. One adverse effect of such material is caused by the low resistance of the materials. As particles fill up the crevices between commutator bars, they act as a short-circuit to the turns connected to the commutator. To prevent this, the mica separators between bars are not undercut, resulting in the unpleasantness of increased sparking. Further, the contact and friction of similar metals (copper on copper, for instance) causes sticking or adhesion (called *galling*). By employing dissimilar metals, frictional electricity, known as *triboelectric effects* may be generated and these can prove very harmful on occasion.

When heavy currents are generated, pigtails (13.11) should be used to connect the brushes and brush holders. Otherwise, the passage of high current through the springs of the brush may heat them unduly and destroy their temper. In small fractional horsepower motors, the brush often makes poor contact with its holder—usually some kind of tubular receptacle—because of oil, grease, or dirt. Springs and brushes of beryllium-copper retain their springiness even at high temperatures.

Insulating brush caps should always be employed to prevent accidental contact with live brushes and circuits. There are motors in which even a slight circumferential (tangential) movement is undesirable. For such motors, the brushes are in the form of a segment of a cylinder mounted on an arm that swings about an axis in the center of curvature of the brush and parallel to the shaft of the generator.

13.46. Bearings and friction

Any choice between ball bearings and sleeve bearings should be resolved in favor of the former. Sleeves made of compressed powdered metal are self-lubricating and efficient. These are effective both at normal and at high torques but at very low torques there is danger of

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seizing (gripping). Where very high speed is necessary, only ball bearings will suffice. Unfortunately, ball bearings require involved precautions at high speeds. For the lubrication that is essential at great speed, only oil can be used; grease is too slow. As the particles of grease are too big to clear out of the path of the balls quickly they cause the balls to slide, rather than to roll, and this creates excessive heat.

The life of sleeve bearings can be maintained by employing packed wool or felt saturated with oil as an extra lubricant. In dirty or dusty surroundings, sleeve bearings have the advantage in resisting the presence of grit better. Even then, they should be oiled at regular intervals. Where apparatus is to remain unattended or idle for a long period, sleeve bearings are far more reliable because they present a large area for lubrication. Under the same conditions ball bearings would corrode severely.

Where friction must be reduced to the absolute minimum, only ball bearings will suffice. The bearings must then be fully enclosed or sealed; otherwise, dirt will cause loss of lubrication as well as leakage. If the bearings operate around a vertical shaft, their life is reduced because of the loss of lubricating material. Shielding the ball bearings is a partial solution but, unfortunately the storage space for oil is too limited. On all but the smallest motors or generators, oil-slinging discs or rings are desirable. These are washers ground to a knife edge which rotate on the shaft, thereby developing a centrifugal force by which any particles of oil that find their way along the shaft are slung off into a well or receptacle. The oil is thus prevented from finding its way into the commutator and windings of the coil.

By employing insulating material such as fibre glass and silicones, motors can be made smaller because they can be run at a higher temperature. Even here, however, there is a limit imposed because the lubrication is not effective at high temperatures. An attempt at extending the limits has been made by using silicone oils and greases. Special bearings made of steel balls and bronze races have found favor but they are hard to find.

13.47. Permanent magnet motors and generators

As the number of magnetic alloys of high magnetizability has increased (Alnico, for example) permanent magnet motors have come into use. In electrical characteristics they resemble shunt motors; their output varies from one to several hundred watts. Generators up

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to five kilowatts have been built. In addition to the advantage of decreased bulk, such motors are easily reversed by reversing only the feeder voltage. Control of speed is also simplified. A very large overload, however, may cause a loss of field strength (by demagnetization), or even a shift of field poles. In tachometers, which measure the speeds of rotation, electric generators produce currents directly related to the speed. Field pieces made of Alnico insure constancy and uniformity of the magnetic field, enabling the generators to maintain a strictly linear relation between speed and output. In addition, other refinements such as ball bearings, commutators of silver composed of many bars, laminated armatures with slots skewed, ripple is reduced to a minimum and yield the desired qualities.

13.48. Special motors

For motors that are readily reversible, the split-field type has found considerable use. This is a series motor with two windings of opposite polarity. One end of each field winding is connected to an armature brush; leads are brought out for the other brush and for the two free ends of the field windings. By connecting the line voltage across a brush and one lead from the field, the motor is caused to rotate in one direction; by connection to the other lead from the field, the motor rotates in the opposite direction.

13.49. A.C. motors

Common types of A.C. motors fall into a few well-known classes such as *split-phase*, *universal*, *shaded pole*, and *capacitor*. In larger motors, the types are *polyphase*, *repulsion* and *repulsion-induction* motors. Barring A.C. commutator motors (universal), speed depends on frequency and on the number of poles. Where control of speed is essential, and universal or commutator motors are excluded, some form of mechanical variation of speed is adopted.

An inexpensive type that is frequently used is the *split-phase* motor which has high starting torque and good regulation of speed. To offset these advantages, however, it requires a large starting current and it is not suitable for loads of high inertia. Furthermore, they cannot be reversed while in operation; they must first be brought to a halt, and then reversed.

The *capacitor* motor, is superior to the preceding but it is considerably more costly. It can start on smaller currents and it operates smoothly and quietly. The starting torque is low, and this type is particularly adapted for fans, blowers, and light loads.

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Perhaps the most simple and least expensive of the A.C. motors is the *shaded pole*. This type is made only in small sizes, because its efficiency is rather low and its regulation of speed is poor. In one model which incorporates a short-circuited band around a part of the pole the direction cannot be reversed; in another model, with two sets of coils, either of which may be short-circuited, the rotation is reversible. These motors are widely used on small clocks that run at synchronous speeds, 600–900 R.P.M. In the telechron clock, a shaded-pole motor having ring rotors runs at 3600 R.P.M.

The *repulsion-induction* motor has high starting torque, and a low initial current; they are expensive and are not made in small sizes. Speed and direction are easily controlled by a shift of the brushes. These motors are seldom built for less than 1/4 horsepower. A drawback is their poor regulation of speed. They are widely used on blowers, fans, and coil-winders, where variable speeds are essential.

13.50. High frequency motors

High frequency motors are employed in the range of 400 to 1800 cycles. For large sizes, they are squirrel cage;[17] also, in three-phase operation, they are widely used. It is possible to obtain 30 horsepower or more from a motor having a six-inch armature and only eighteen inches long. In the larger sizes, the windings are water-cooled. In small motors of 1/10 H.P. or less, capacitor motors are employed.

13.51. Motors of low inertia

A motor of low inertia is wound with two sets of coils whose axes are perpendicular to each other. They are manufactured in small or medium sizes. To reduce inertia, squirrel cage rotors must be small in diameter but exceptionally long. To improve starting torque, the resistance in the rotor is made high. They run well below synchronous speed.

In servo-motors (8.22), the ratio of the length to the diameter is small but the rotor is equipped with a small metal bowl, called a drag cup, which rotates in the field of a permanent magnet—like the disc of a watt-hour meter—in its metal housing. The magnetic field causes a drag on the rotor which is proportional to the velocity. This serves to damp out high acceleration irregularities of the rotor.

Rotors that operate on two-phase power are used in a variety of circuits. One phase is constantly excited from an A.C. line, while the

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[17] Descriptive of armatures that instead of windings have a series of copper bars set into the core of the armature parallel to its long axis.

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other phase is being fed from a servo-amplifier of the error signal has the same frequency as that of the A.C. line, the amplifier acts to raise the power level to a point required by the motor. If the error signal is D.C., a modulator unit is used (Brown vibrator).

A motor, to be suitable for use as a servo, should have a high ratio of torque to inertia. The ratio is kept high by employing a drag cup of the kind incorporated in induction watt-hour meters. Built of aluminum, the rotor is very light, and has a small moment of inertia; such a motor has a small output for a given total weight. Such a construction (drag cup) renders the motor well fitted for A.C. tachometers if one of the windings is excited by a single phase. A.C. and a single phase voltage strictly proportional to the velocity of the rotor is applied to the other windings.

13.52. D.C. motors with precision speed control

A D.C. motor with precision speed control is the usual type of motor but a single small coil is imbedded in the face of one pole. Part of the rotor opposite the coil is milled to produce salient poles; the coil has a voltage induced in it. The voltage is applied to a frequency discriminator and a rectifier circuit to produce a D.C. output which varies linearly with the frequency over a small range. The D.C. voltage is amplified and fed back to control the field of the motor. In one style of motor, the variation in speed is held to 7200 R.P.M. ± 3 over the whole range of loads and input voltages. Even this does not represent the utmost in speed regulation if a discriminator of greater slope such as a quartz crystal filter, is employed.

Still another type is a D.C. motor having two slip rings connected to points on opposite sides of the armature winding. Where two or more A.C. motors are connected together, the A.C. terminal voltages are equal, if the motors are turning in synchronism. The generator A.C. voltage changes with a lag or a lead of the armature; currents then flow in the A.C. leads in a direction that will restore synchronism between armatures. The ordinary A.C. synchronous motor behaves like the conventional synchro, except when the field is excited and the armatures are rotating.

At low speeds, synchronous action is weak; by means of relays, D.C. voltage is applied first to the fields, and then to the A.C. terminals, thus pulling all the armatures into corresponding positions with regard to the fields. Thereupon, the D.C. voltage is withdrawn from the A.C. terminals and applied to the commutating brushes, which causes the motor to start and run in synchronism.

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13.53. *Sources of power*

Up to 20 or 30 watts and for voltages not in excess of 300, dry batteries are convenient and feasible sources of power. They are favored because they are portable, silent in operation, and immediately available. They are also compact and clean, and require no filtering devices. These are, however, costly sources of power, and replacements are frequent. Dry batteries can supply between 15 to 30 watthours per pound. In the larger sizes. For small units, the ratio of energy to weight is still smaller. The output depends on the rate of current drawn. As the latter is increased, the output falls off, at first gradually and then swiftly. In other words, the character of the supply determines the over-all output. Even dry batteries can be recharged if they are not permitted to discharge too much and the zinc remains unperforated.

13.54. *Storage batteries*

If recharging equipment is available, storage batteries may deliver hundreds or even thousands of watts. For airplanes, automobiles, and electronic equipment, they have found the widest application. The Edison alkaline battery is expensive, has high internal resistance, and requires a large space for storage. Very small cells have a voltage of two. Most passenger automobiles employ six-volt batteries; large trucks and airplanes require twelve volts; military planes and tanks, twenty-four to twenty-eight volts; farm lighting equipment and large vessels, thirty-two and 110 volts.

13.55. *Engines*

Engines are used on large ground systems, portable ground systems, and ultra-portable systems, engines of ten kilowatts or more are in use because weight is of no consequence. Such engines, either Diesel or gasoline, are very reliable. Diesels are materially heavier but they are less liable to minor troubles; when trouble does occur, is very serious. Coupled with this drawback, Diesel fuel is not so easily obtainable as gasoline.

13.56. *Portable systems for ground use*

The portable systems for use on the ground range from one to five kilowatts. They are of the maximum weight that can be carried by men, and for this reason extraordinary efforts have been made to reduce the weight. They are usually air-cooled, which also adds to the weight. To increase their portability, they are made up in two-pack units which

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can be coupled together by belts, or directly. In the field, it may be difficult to align direct-coupled units properly because to do so effectively requires a very massive and heavy base or foundation. Belt-connected units, on the other hand, are easily coupled and require no alignment. Different units may be connected, regardless of speed, because uniformity is of no consequence. It is practicable to run high-speed generators from low-speed engines or vice versa. The actual increase in weight caused by the separation of the units is a drawback.

13.57. Ultra-portable systems

An ultra-portable radar system should be easily carried by one man such as a paratrooper. It should weigh no more than fifteen pounds. It should produce 150 watts. In one common type, a two-cycle single-cylinder engine drives a generator directly. The frequency is commonly 400 cycles and the power is 125 watts. A magneto supplies the ignition. The speed of the engine is controlled by an air-vane governor. There must be a shut-down of at least ten minutes every twenty to thirty hours to permit cleaning the exhaust ports which become fouled with carbon. High octane gasoline in combination with tetraethyl lead is bad because the spark plugs are fouled and the valves are burned. By employing valves made of Stellite and aircraft spark plugs, such troubles may be lessened if not entirely avoided.

13.58. Merits of two- and four-cycle engines

Though the four-cycle engine is superior,[18] the two-cycle type has fewer parts and requires less maintenance. It requires no change of oil, no lubrication of external parts, and no periodic adjustment of tappets.[19] A serious disadvantage is that the engine is subject to failure because of the mixture of oil and gas. If this defect could be remedied, there would be a decided preference for two-cycle engines.

13.59. Methods of cooling engines

One method of cooling engines is by airblast supplied by a fan or independent engine. Cylinders are equipped with cooling or radiating fins, which are either machined out or actually cast integrally with the cylinder block. Through improvements in molds and methods castings are now made with more and thinner fins.

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[18] In a two-cycle engine, one ignition (explosion) occurs with every two strokes (forward and back) of the piston; in a four-cycle engine, one ignition occurs with every four strokes of the piston (twice forward and twice back).

[19] Mechanisms on engines that control the amounts of openings of the valves.

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In the system known as *radiant cooling*, water is taken from the jacket of the engine. Auxiliary parts required are a water-circulation pump and a thermosiphon system. This means of cooling does not prevent change in either the temperature or the performance of the engine. External conditions affect such cooling methods.

Probably the most effective form of cooling is that known as the *vapor phase* system. The cooling is accomplished by the heat of vaporization of water by means of a centrifugal fan through a radiating condenser. As no circulating pump is required in this system the available power of this engine is increased. Where weight is important, this method is to be recommended because it requires less liquid.

13.60. Types of ignition

If a battery is employed for ignition, a high-voltage induction coil, a distributor, and an interrupter or break are necessary accessories. This means of ignition is reliable and effective, provided the battery is maintained properly charged. Also, if self-starting is necessary, the battery can supply the necessary power. The disadvantage is that should the battery fail, as when it is improperly charged, there will be no means of starting the engine.

A generator having a permanent magnetic field is a *magneto*. In an ignition system, it requires an induction coil, an interrupter, and a distributor as accessories. Having a permanent magnetic field, a magneto requires no external exciting device. Of all means of ignition, this system is considered the best, even though the engine must be started manually.

To decrease weight, a method of taking the ignition directly from the generator has been adopted. This can be done only with a magneto. It is always used on ultra-portable units.

Any device for ignition used near a radar unit must be thoroughly shielded from the surrounding equipment. In common practice, flexible metal hose covers the wires, and the spark plugs are separately and fully shielded.

13.61. Control of speed

Speed may be controlled either by mechanical or by electrical means. In the mechanisms for controlling speed, such as the old-fashioned governor, a pair of balls mounted on hinged arms swings about a vertical axis; the balls move outward when the speed is increased, because of increasing centrifugal force. Though entirely mechanical,

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such a governor is a rather intricate system of levers and it requires appreciable care and maintenance.

In the electrical control, the governor is a solenoid actuated by the output of the generator. Such an electrical governor is stable under all conditions. It is quite practicable, even for the control of voltage and frequency where the limits set are not too wide.

13.62. Exciters

The vast majority of small D.C. generators (below 15 K.W.) employ self-excitation. The minimum of equipment is necessary; no additional generator or other sources of power are needed. Self-excitation is suitable where the current in the field is adapted for the control of the generator and the latter does not become inoperative below saturation.[20]

Where the current in the field of the chief generator is large, or the generator is operating below saturation, independent excitation should be supplied. This controls the output, not from the field of the main generator, but from the exciting field, and thus reduces the controlling 10 per cent or less. Customarily, the exciter is attached to the main generator.

13.63. Exciters for A.C. generators

When the D.C. winding is mounted on the same rotor core as the A.C. winding and both have a common field, the exciter generates its own field and the output of the exciter supplies the main field of the generator. Such a scheme is effective on small A.C. generators because it is both compact and economical. When greater range is required the exciter should be independent and attached to the main generator.

13.64. Generators on aircraft

On aircraft 27 volts D.C. is commonly produced from generators connected with each engine. All are joined in parallel. The variation in voltage does not exceed two volts. As already indicated (13.45) the wear on brushes at high altitudes is excessive and even with all exceptional precautions, this wear on brushes is still much worse than at ground levels. Where maximum compactness is desirable, three-phase A.C. generators combined with selenium rectifiers afford a convenient D.C. source of power. If slip rings are used, the density of the current is much lower than it is with brushes.

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[20] Saturation is the condition of iron (or any magnetic metal) that has reached its maximum magnetic strength.

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13.65. *Converters*

Converters are of two classes: *motor generators*, and *dynamotors*.

Dynamotors are used on loads of moderate power and voltages not above 2000. They have higher efficiency and lower weight than inverters (13.65) which require a transformer and a rectifier. In effect, a dynamotor is a rotating direct current transformer. Its field is a standard shunt- or series-wound coil; on the armature may be several independent windings. The primary circuit comprises the brushes, the commutator, and the input voltage; where a single winding occurs on the armature, a tap taken off represents the secondary coil. Where two windings appear on the armature, one is the secondary, and the ratio of its turns to those of the primary determines the voltage output. Although the power in a dynamotor may reach 2000 volts, that of the common run of them is much lower.

On large planes such as military bombers, the dynamotor winding is adapted for an input of 27 volts. On automobiles and other landcraft, voltages may range from six to 110 volts. The voltage output may vary from fourteen to 1200 volts. Currents vary from milliamperes to five amperes. Efficiency is moderate, running from forty to sixty per cent. Unfortunately, the regulation of voltage is poor; input may be varied up to ten per cent.

The motor generator practically explains itself. It is a combination of a motor and a generator coupled mechanically to the same shaft. The power output of the motor should be approximately that of the generator. Motor generators are flexible but not too efficient, as it is obvious that they have losses both in the generator and in the motor. They are also bulky and heavy.

13.66. *Inverters*

For D.C. powers or voltages in excess of that delivered by a dynamotor, it becomes necessary to use an *inverter*, or motor-generator for A.C. power. They normally are built to give an output ranging between one hundred and 2500 volt-amperes and operate at a frequency of 400 or 800 cycles. If the frequency is raised from 60 cycles to 400 cycles, the saving in weight may be fifty per cent; but in a further increase in frequency, from 400 to 800 cycles, the reduction in weight is negligible.

In England, the frequency may vary between 1400 and 2800 cycles. Usually, a motor of the shunt or compound type, operating on 27 volts D.C. is directly coupled to a generator and mounted on one frame. In

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an inverter, one common field winding serves both the motor and the generator; the armature may be common to both or separate. In the motor-generator (alternator), the motor and the generator are complete individual units, electrically. Both kinds are known as inverters. Common practice is to place the alternating field on the rotor. In the common run of inverters the fields are wound on salient poles; high-frequency inverters of 800 cycles and more employ slotted (induction) fields.

As most alternating power in radar equipment is converted to D.C. or employed for heating, it is not necessary to ensure a sinusoidal wave form. As a matter of fact, in the inverter output, the wave form may vary even with variations in the load. As the end desired in power supplies for radar is a constant or stable D.C. voltage it is essential to preserve a fixed ratio of the A.C. maximum voltage to the effective voltage; this ratio is also known as the *crest* or *amplification factor*. Where the rectifier employs a condenser input filter,[21] the output changes with the crest or maximum voltage. If the input filter uses a choke, the form factor[22] becomes important.

13.67. Starting current

At the instant an inverter is connected to a D.C. source, its momentary starting current may be triple the normal full rated current. On large inverters, such an overload may be harmful. Accordingly, starting current is limited by relays. In the carbon-pile regulator, speed is regulated by pressure on the pile and this, in turn, varies its resistance and modifies the field current that flows through it.

13.68. Vibrators

For output of power that does not exceed 150 watts, the vibrator has several features to recommend its use. Commonly, the vibrator used on autombobiles has an output of 50 watts, and the wave is square. What is known as a "power vibrator" may run up to 1000 watts. Compared to a dynamotor, a vibrator is much lighter and more compact, and it can supply several outputs from one unit. As an illustration, a vibrator, plus its transformer, rectifier, and filter, may supply 5 *ma* D.C. at 2500 volts, 5 *ma* at 150 volts, and 100 *ma* at 250 volts. The entire unit may weigh only six or eight pounds. It

[21] A condenser input filter is made up of a capacitance and a resistance, and filters out or suppresses the A.C. ripple to produce the D.C. output.

[22] The ratio of its effective value to its average value of an alternating current. The form factor of a sine wave is 1.11.

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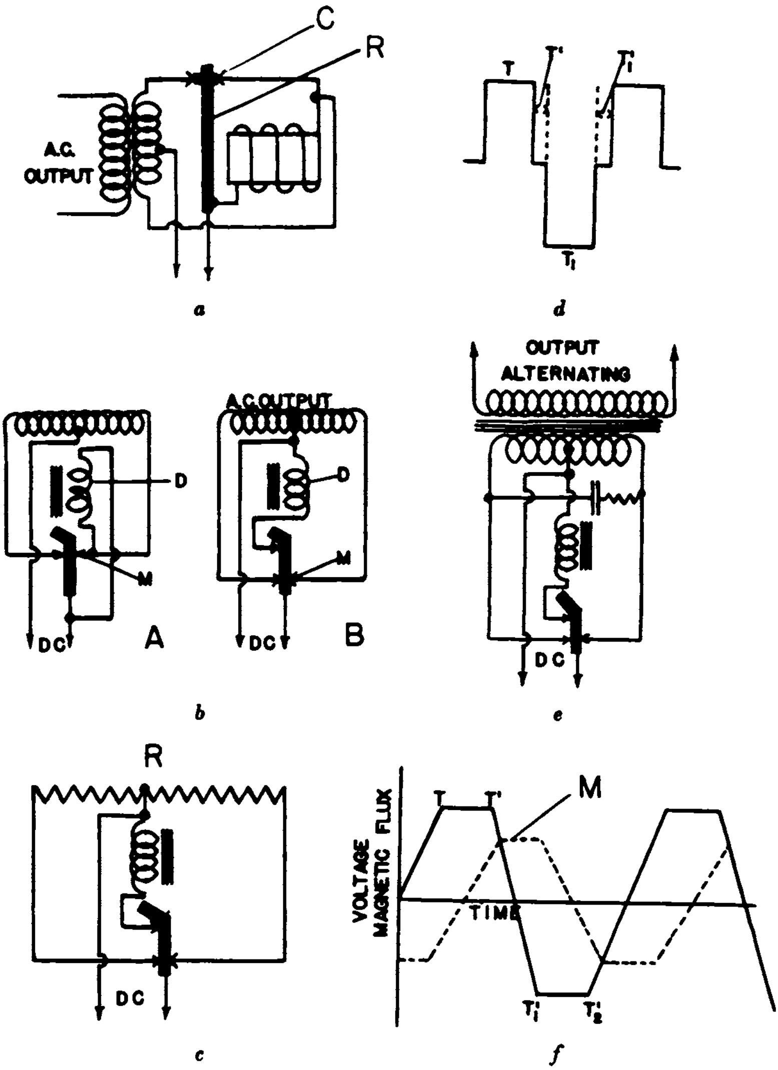

FIG. 13 : 14. TYPES OF VIBRATORS

(*a*) Simple form, for converting A.C. into D.C.: C, contacts; R, vibrating reed
(*b*) Shunt (A) and series (B) vibrator rectifiers: D, driver coil; M, contacts
(*c*) Vibrator connected across resistance (R)
(*d*) Plot of voltage wave in (*c*)
(*e*) Connections for vibrator showing use of buffer condenser to suppress arcing
(*f*) Curves showing relations of voltage and magnetic flux in (M) in vibrator

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receives its energy from a storage battery of six to twenty-four volts, and its efficiency can run as high as 60 per cent. A drawback to vibrators is the difficulty of regulating the voltage of the output.

A voltage regulation of 20 to 25 per cent for the D.C. output and 15 to 20 per cent for the A.C. output is common. Frequency varies slightly, the range falling usually between 100 to 125 cycles per second. Though the wave is described as square, it actually has a poor shape. Vibrators run from 4 to 6 watts per pound of weight. For small powers, they are appreciably cheaper than dynamotors. In the range of voltage between 1000–1200, there is a distinct preference for vibrators. Dynamotors are bulky and heavy; furthermore, a spark interference or "hash" is hard to suppress. A further advantage of a vibrator is the ease with which it can be repaired, requiring no greater labor than the insertion of a new vacuum tube.

Another way of viewing a vibrator is as a single-pole double-throw switch. The vibrator shown in Figure 13 : 14 (*a*) is a reed bearing one or more pairs of contacts which vibrate between similar stationary contacts. The ordinary buzzer or doorbell is a close relative, structurally. As ordinary contacts are liable to corrode or oxidize, the contacts in the vibrator have a slight sliding or wiping motion which serves to keep them clean. The spacing of the contacts is very critical. For power vibrators where several contacts are connected in multiple the time the contacts remain closed, the symmetry of the voltage wave, and the efficiency are especially important. Unless the contact spacings are equal, the contact points will be ruined in short order.

The life of a vibrator is practically determined by the lasting quality of its contacts; these wear away through burning and friction. There is no better way to adjust contacts than by means of an oscilloscope into which the output is fed from the transformer of the vibrator.

A vibrator may be of the shunt as in A, or the series drive as in B of Figure 13 : 14 (*b*). In the former, the driver coil is connected across the reed and one contact, and the contact is normally open. When the voltage is applied, current flows from the battery through half of the transformer winding, the driving coil, and back to the battery.

13.69. Synchronous and non-synchronous vibrators

In the *non-synchronous* vibrator, the polarity is changed by the make-and-break of the contacts that make and break the primary current; rectification takes place through a vacuum tube. Such a vibrator is employed for converting D.C. current into A.C. current.

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In the *synchronous* vibrator, the reed of the vibrator is equipped with an extra set of contacts that serves as a synchronous rectifier. The spacing of the contacts in the secondary coil exceeds that of the primary coil, thus permitting the secondary contacts to make *after*, and break *before*, the primary. In the usual synchronous vibrator, both the input and the output circuits have points in common because the contacts for the electrical connections are made through a single metallic reed. Such a vibrator is employed on low-voltage sources of power; maximum voltage is limited by the insulation. In the ordinary vibrator, 300 volts and 100 milliamperes are the maxima.

13.70. Circuit of a vibrator

Figure 13 : 14 (*c*) shows the circuit of a vibrator.

When connected across the resistance R the wave of voltage may be represented as shown in (*d*); T is the time the current flows in one direction; T' is the time the circuit is open and the moving contacts travel from one fixed contact to the other, T_1 is the time the current flows through R in the reverse direction, and T'_1 is a repetition of T'.

If we consider the ratio of the closing time to the entire time of a cycle, we may represent it as

$$T_t = \frac{T + T_1}{T + T_1 + T' + T'_1}.$$

This is known as the *time closure factor* or efficiency. The vibrator illustrated in the diagram has a factor varying from 0.8 to 0.95.

The greater the closure factor, the better. If E is the applied D.C. voltage and T_t is the closure factor, then

$$E_a = ET_t = \text{average value of } V$$

Peak Voltage	$E_m = E$
Form factor	$F_f = E_e/E_a = 1\sqrt{T_t}$
Effective voltage	$E_e = ET_t$
Amplitude factor	$F_a = E_m/E_e = 1/T_t$

The shape of the voltage wave depends upon the character of the load. Thus, when it feeds an inductive load, the shape of the wave will be quite different from that when the feeding is a pure resistance. The magnetizing current of the inductance lags 90° and is supplied by the battery while the contacts are closed. When the contacts are open,

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the current is broken and the maguetic field around the inductance collapses. The energy stored in the field is dissipated in the arc at the points of contact which may be damaged by the heat and duration of the arc.

This destruction by arcing, which occurs when the contacts are separated, can be overcome by employing a buffer condenser. Suppose we connect up a vibrator as shown in Figure 13 : 14 (*e*). As already stated, the shape of the wave depends on the character and amount of the load. Through the transformer of the vibrator, the strength of the magnetic field is kept below 50,000 lines per square inch (about 7700 gausses). Such low values are required because at the start of the vibrator, the total magnetic flux is twice the steady flux.

In the ordinary transformer employed on power circuits, a small sine alternating voltage causes an initial rush of current that may exceed ten times the normal operating current. The excess of current is determined by the momentary voltage when the circuit is closed, on the strength of the steadily operating magnetic field, and on the magnetic saturation of the core. If we take the worst possible case—closing the circuit when the instantaneous voltage is at the maximum—the maguetic flux will increase to twice the permanent state.

In the transformer of a vibrator, the input voltage is roughly a square wave. The maximum of the maguetic flux reaches twice the value during steady operation; the maximum current is twice the normal operating current or more; the exact amount is determined by the density of the maximum flux and the saturation characteristic of the material of the core.

In Figure 13 : 14 (*f*), T represents the time of closing contact and the point when the vibrator is energized. The current and the magnetic flux produced by it will begin to build up. At T' the contact will be broken and it will remain open until T'_1. In the period of time from T'_1 to T'_2, the current will still continue to flow because the condenser in the circuit will maintain the flow; hence, the magnetism will not decay in this period. At T'_1, the contact will again close and remain closed until T'_2, when it will begin to open. During the time interval, $T'_1—T'_2$, the maguetism will build up in the opposite direction. In a few cycles after starting the magnetism will vary symmetrically about the time axis.

In a vibrator transformer, the leakage reactance[23] must be kept as

[23] The reactance arising from the magnetic flux leaking between the primary coil and the secondary coil.

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low as possible. Like all squares wave, the voltage output comprises a great number of harmonics. As reactance is determined by frequency, the presence of high-frequency harmonics causes high reactance. In other words, the reactance will exceed several times that of a pure sine alternating wave of the same fundamental frequency as the square wave. Leakage must thus be minimized. The window of the transformer should be completely filled with winding. The primary and the secondary coils should be interlarded or sandwiched; the space factor should be kept high. The density of the magnetic flux should be kept low and it should not be greater than the allowable value for maximum value of the applied voltage. The laminations should be very thin to keep the magnetizing current down to the minimum. Also, the stacking factor should be high and the air gap as low (small) as possible.

The size of the buffer condenser can easily be gauged by a few trials. For greatest effectiveness, the condenser should be connected across the primary coil. When connected across the secondary coil, the reflected capacity, which is the equivalent capacity in the primary, has a bad effect on the leakage reactance. Because of its weight and bulk, a primary buffer condenser is not always employed, especially where the voltage is low and costs must be kept down. For the low voltage, a condenser across the secondary coil is more advisable. We obtain the best results however, if the condenser can be placed across the two windings.

As the magnitude of a condenser required varies inversely as the square of the applied voltage, it is a necessary consequence that at low voltages large condensers are necessary. The size will depend also on the nature of the materials of the core, on the frequency of the vibrator, and on the contact closing factor. Transformers of high magnetizing current require large capacities. The buffer condenser will depend upon the frequency of the vibrator and the closing factor.

With age, the frequency of the vibrator decreases because the reed loses its resiliency. The closure factor also lessens due to the wear of the contacts. As a result of the foregoing age effects, the buffer condenser must be increased to maintain the effectiveness of the vibrator.

It is to be noted that a resistance is placed in series with the condenser to limit the current. The alternating current may be rectified by vacuum tubes, dry disc rectifiers, or synchronous contacts. Full-wave rectification is employed. When a condenser is included in the vibrator circuit, a half-wave rectifier will not operate. The reason is that when the capacity of the condenser is correct on one half-cycle, it

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is inadequate on the other half-cycle; the lack of balance will quickly destroy the vibrator.

13.71. General requirements of relays

A relay is an electrically operated switch. A good relay has contact points that close with minimum bounce and chatter. The surfaces in contact should be large enough to carry the current without undue heating; they should be made of highly conducting material, and they should resist wear. The force that operates the contact points should be sufficient to prevent welding of the contact points; and arcing, therefore, should be slight at initial amounts of current. As a matter of fact, it is the initial flow of current that sets a limit to the area of the contact surfaces of the relay.

For best operation, the contact points should open swiftly and sharply; the separation should be sufficiently large so that any arc formed will be rapidly extinguished. Where currents are very strong, the spacing should be large and the contact points massive; gaps should be several in series for very strong currents. The current capacity of the relay will diminish with high voltage, low pressure of the surrounding atmosphere or gases, and excessive arcing. The arcs that result from the separation of the contact points may be so great that artificial means, such as the "blowout coils" that are widely used in massive power circuit-breakers, may be required to extinguish them.

The size of the contacts, which are usually of silver for low power, will depend upon the currents they are to carry. Thus, for four ampere, contacts 1/8 inch in diameter will be sufficient; for six amperes, 3/16 inch will suffice; for twenty amperes, 3/8 inch. By employing a double-break contact, the capacity of the current is increased by 50 per cent over that of a single break. If the contacts operate in an atmosphere under pressure, they can carry more current. Contact material is of prime importance. For instance, palladium can carry two or three times as much current as silver at the same voltage. Platinum contributes to long life of the contacts. Tungsten is about as effective as silver, but it can be employed at voltages two or three times that of silver.

The best contact material should have high conductivity for electricity, and for heat; it should have a high melting point; it should not vaporize readily; and it should resist mechanical wear and abrasion. By the expression "contact follow-through" is meant the motion that follows after contact is made. For contacts mounted on leaf springs,

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the follow-through motion permits the contact to carry out a wiping motion which helps to keep the contact points free of dirt and oxide films.

When employed on very low voltages, contacts fail because the voltage is insufficient to break through the films that form between the contact points. These are non-conducting and serve to insulate the contact points. By sealing the relay in a dust-proof container, dirt and dust can be kept out. Also, by mounting the relay so that the contact arms are vertical, dust and dirt will not readily accumulate on the contacts.

Arcs, which are conducting paths formed from vaporized metal, are easily extinguished by increasing the length of the gap. Thus, for a current not exceeding one ampere, a gap of 0.01 inch is sufficient; for

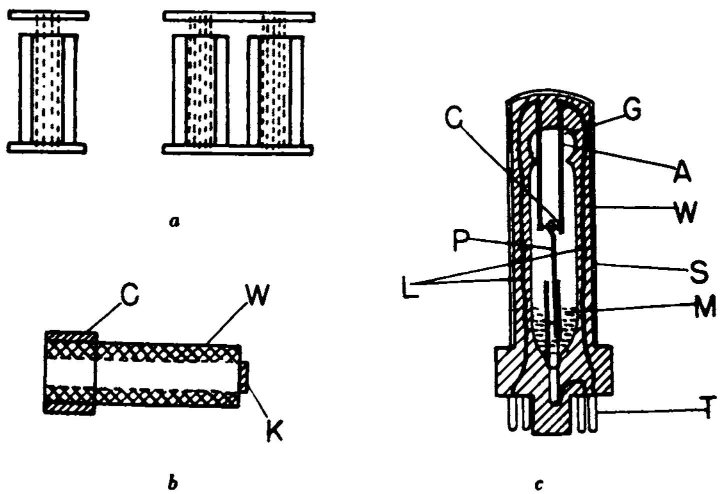

Fig. 13 : 15. Relays
(*a*) Single and double gaps crossed by magnetism in single- and double-coil relays
(*b*) Cross section of coil with delay slug: C, copper slug or band; W, winding; K, core
(*c*) Interior of mercury relay: G, class container, C, contacts; P, moving arm; L, leads; W, windings; M, mercury; S, metal shell; T, terminals (contact arms)

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fifteen amperes, a gap of 0.025 inch is adequate. When the current exceeds twenty amperes, two gaps in series should be employed. The advantage of quick action is the fact that the arc is readily extinguished and the resultant heating is lessened.

On ordinary relays, where no special precautions are taken, the contacts bounce and chatter, both on closing and particularly on opening. Contacts of the better type are specially liable to this weakness. If the inrush of current is severe, bounce is highly destructive. For ideal contacts, the surfaces should be large. It is physically not possible to preserve alignment in contact and make provision for less unit pressure between contacts. By reducing pressure, we lessen the ability to break down the non-conducting film. In most of the better relays, one of the two surfaces in contact presents a curved face of large radius.

If relays are to operate at high voltages at radio frequencies, it is essential to seal the contacts in a vacuum chamber. Similarly, relay contacts that might set off explosive gases or mixtures should be sealed for protection.

13.72. *Magnetic circuits of relays*

In a single-coil relay, the magnetism must cross one air gap, and in a double coil relay, two; see Figure 13 : 15 (*a*). As the magnetism in each gap participates in the pull. As the total *mmf* required is less.[24] For a large pull, or heavy currents, plunger-type coils are employed. Rotary types, however, are vibration- and shock-proof.

Leakage of magnetism (magnetic flux) represents waste. To minimize this, coils should be short, and cores should be made of materials of very low reluctance. The coils employed in telephone relays are long and their leakage is correspondingly great. Especially is this true where, because of the presence of conducting slugs on the ends of the armature it is necessary to wind the coil on the heel end of the core (remote from the armature). Because of the abnormal leakage in such coils, they require as much as 25 per cent more ampere turns.[24]

For relays that operate on alternating current, shading coils mounted on the faces of the poles will minimize chatter and reduce hum. In the majority of such relays, the cores are solid; in those of best design, the cores are laminated.

In materials of low cost on magnetic circuits, the magnetism that remains after the current has died out (residuary magnetism) is often

[24] Magnetomotive force; for details, see Appendix.

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high. On D.C. relays that are highly sensitive, the minimum air-gap must be made large to avoid armature sticking to the face of the pole when the current in the coil becomes zero. Two easy methods of overcoming this sticking are: to spot-weld a non-magnetic metallic disc to the face of the pole or to the armature, or to mount a screw of non-magnetic metal in the armature, which will serve as a spacer to control the minimum air gap. Sticking may also be overcome by increasing the tension (or pressure in some types), but only at the expense of an increasing current through the operating coil. In relays of the highest type of sensitivity, where the air gap is reduced to the minimum, cores should be made of Permalloy, or of similar magnetic alloys, which have very high permeability and low residuary magnetism.

If the cross-section of the core is increased, the magnetic path is increased, and the density of the flux is decreased. Should the magnetomotive force (ampere turns) remain unchanged, the magnetism through the air gap, and hence the pull, can be increased without limit. Actually, weight, size, and sluggishness of the armature impose limits because these bring about electrical and mechanical increases in inertia.[25]

13.73. Temperature limitations of relays

For safe operation, it is customary to allow two watts per square inch of radiating surface of a coil for enameled wire, and 3.5 watts for silk-covered wire. If the coil is sealed in or enclosed, 1–1.5 watts are allowed. Heat increases the resistance of the coils and this cuts down the current; as the power depends on the flow of current, heat causes a diminution in power which may render operation defective. If the relay operates from a constant source of voltage, heat may prove too much for normal operation. On the other hand, if the relay operates from a constant source of current, its operation will be unaffected.

Power for operating relays may vary from milliwatts to watts. Both the impedance and the power factor of relays are affected by variations in air gap. For most alternating current relays, which operate on 60 cycles, the power factor ranges between 2/3 and 1/4. As the inductance increases with a short gap, which means a path of less magnetic resistance (reluctance) and hence a larger magnetic flux, the

[25] Electrical inertia is caused by the inductance in a circuit. It behaves toward current flow as mechanical inertia does toward motion. Electrical inertia (inductance) slows up the growth of current when it is building up and retards its diminution when it is dying out.

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current through the coil when the armature is closed is only 60 per cent of the amount when the armature gap is open. Ordinary 110-volt alternating current relays have an inductance of a few henrys.[26]

It is well to note that on sensitive relays, an increase in the number of contacts calls for a more-than-proportionate increase in the operating power. Where a single-contact relay may operate on 15 milliwatts, a double-contact one may require 60 to 70 milliwatts.

13.74. Relation of air gap to relay operation

As the air gap is decreased, both the magnetic flux and the pull caused by it increase. The pull on the armature grows as the gap decreases. With the armature in the closed position, the pull is several times that when the armature is fully open, and the current remains unchanged. To the extent that the resistance diminishes as the air gap closes, the current in the coil can be decreased below the operating value, until the amount of magnetism falls so low that the restoring spring can overcome the pull of the armature and open the gap. This amount of current is known as the *release current* of the relay; the current required to pull the armature in from the open position is the *operating current.*

The length of the air gap determines the minimum current, which is dependent on the magnetizing current of the iron, and also on the spring-restoring force that acts on the armature. The release current is determined by the length of the closed air gap, the falling magnetic curve of the iron, and the force of the spring. If the residuary magnetism in the core is at the minimum, the ratio of the currents on open and closed circuits should approach the ratio of air-gaps on open and closed circuits. Accordingly, a close differential relay is less sensitive than an ordinary relay, for the gap when open must be large in order to maintain a ratio of unity between open and closed lengths. Where the air gap and resistance are constant, a close differential relay is most effective for a moving coil.

In an ideal relay, the pressure on the contacts when closed, should remain constant until the current through the coil attains the quantity that will cause the movable contact to shift from the closed to the open position with full pressure immediately applied. Upon release, the relay should operate in the reverse order. This would be the ideal operation. In workable relays, contacts are erratic, and the range of

[26] Henry is the unit of electrical inductance; it is the inductance of a circuit where a current change of one ampere per second induces an electromotive force of one volt.

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the current in the coil is near the operating value when the pressure of the contacts is slight. We can avoid trouble and approach ideal conditions by increasing the range between operating and releasing currents.

13.75. *Controlling time of operation of relays*

We can obtain high speed of operation by several safeguards: low inductance, light moving parts, high input power, short strokes, and laminated magnetic parts to reduce eddy currents. Most significant is the inductance. Telephone relays, operating at 12 milliseconds, require 10 milliseconds for the current to grow to the operating point, and 2 milliseconds are required for the armature to respond. We can decrease this time by increasing the voltage and the capacity of the condenser across the break, and by interposing a resistance in series to limit current from the power supply. The necessary condenser must be large; the majority of sensitive relays are slow-acting.

One method of decreasing release time, and also reducing the effect of residual magnetism, is to introduce a small steady *mmf* in the operating winding circuit. This can be done by employing a small permanent magnet or by a separate winding through which a steady current flows. When the main winding sets up an opposing *mmf*, the resulting magnetic flux diminishes very rapidly and neutralizes the *mmf* of the residuary magnetism.

Except in relays employed for specific high speed operations, an operating time of 5–10 milliseconds is considered very rapid. Alternating current relays are far more rapid then direct current. Certain specific measures will deliberately slow up relays; for example, we may attach some mechanical device to an armature, or a *dashpot* (operating like a door check) may be connected to the relay. By such means, operating and release times approaching a minute may be obtained, though the power supply may become excessive.

A common device to delay a relay is the *lagging slug* or coil. By placing a heavy copper band (slug) at one end of the winding; see Figure 13 : 15 (*b*) or by slipping a copper tube over the core, delays of a fraction of a second can be obtained. In effect, the slug or band is a single-turn, short-circuited secondary coil.

The counter *mmf* caused by the current induced in this slug delays the build-up of magnetism when the armature is attracted; when the relay current is shut off, it (the *mmf*) delays the decay of magnetism in the air gap, and so retards the release of the armature. Near the armature end, the shorting slug has a greater effect on the operating

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time; at the heel, the shorting slug affects the release time more. A sleeve placed over the core affects both operations. The time of operation may be increased to 0.1 second, and the time of release may be increased up to 0.5 second.

Another type of relay, which operates on the principle of the thermostat, is known as the *thermal relay*. In its ordinary form, it consists of a heating element across which is applied a control voltage. The contacts are actuated by a mechanism that responds to changes in the heating element. By such means, we may obtain delays running to several minutes. Such relays are fairly sensitive and can be easily adapted for changes in the surrounding temperature.

A simple mechanism, based on thermal action, consists of a thermistor (13.8) in series with the relay winding. This is a convenient means of creating delays running into several minutes. Actually, the delay is subject to slight changes of surrounding temperatures, applied voltage, and the current through the relay. In the standard connections, a large condenser, or an inductance, is shunted across the coil of the relay. This continues to supply energy even after the current is interrupted. If the internal impedance of the current source is low, the operating time will be short; if the impedance is high, the operating time will be long. The circuit should always be loaded with resistance to prevent oscillations.

13.76. Mercury relays

A mercury relay is usually enclosed in a glass container filled with inert gases under pressure (e.g., argon or helium) as shown in Figure 13 : 15 (*c*). The contact surfaces are covered with mercury which is drawn from a well at the bottom by capillary action; in normal operation, with the relay contacts vertical, the spacing permits a bridge of mercury to connect the contacts. To increase the duration of the shorted conditions, the tube should be tilted. Because the moving parts are small and light, and because of the presence of the mercury, the action is very rapid and the chatter or bounce is negligible. Both current and voltage capacity are large. The average maximum current is 5 amperes during a period of 100 seconds; 10 amperes for 10 seconds; 50 amperes for 10 microseconds. The momentary voltage should not exceed 500. These relays are usually wound with two coils which may be connected in series or in multiple. The operating current with the coils in series and cooperating is 6 or 7 milliamperes; the release current is 4.5 to 6 milliamperes, and the time of contact is 8 per cent of the maximum.

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Chapter 14

RADAR IN PEACETIME

14.1. Guiding airplanes for landing

Our opening chapter dealt with the wartime uses of radar and the vital part it played in the last war. It is fitting that we close with some of the peacetime functions of radar and the roles it will assume in the future.

In guiding an airplane to a landing, what is known as the *ground control approach* (G.C.A.) has proved very effective on even moderately busy airfields. Two separate beams are employed (**10.19**): one beam scans vertically, the other scans horizontally. The radar equipment is often mounted on trucks and trailers, so that any runway can be selected in a matter of minutes. Using this arrangement, an airplane can be safely landed at the rate of one every two or three minutes. The pilot needs no radar aboard his plane; he requires only a radio receiver and his plane is guided down orally by the ground crew. Because of the very narrow beams employed, the accuracy or resolution is very high. Errors at a range of one mile will not exceed ten feet in elevation and twenty feet horizontally. As the airplane and the runways are visible on the screen of the cathode ray tube at all times, it becomes possible to guide the pilot continuously. What has made landings difficult, from the standpoint of radar is the fact that with many airplanes in the air above an airfield, all types of ensuing interference arise. Despite this, with the G.C.A. we can guide planes down at the rate of one every two or three minutes.

The G.C.A. is really a "talk-down" method. The pilot of the plane is guided entirely by instructions received by radio from the ground. It requires the use of two complete radar units with PPI indicators (7.1). On one unit, known as the general search unit, operating on a

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wave length of ten centimeters, the airfield is made visible on the "scope" for a radius of many miles. On the other radar unit, employing a wave length of three centimeters, known as the sector unit, can be seen all planes that are present in the region. When an airplane is identified, the crew (on the ground) performs the actual task of bringing the airplane to a safe landing. This radar requires two antennas of extremely narrow beams, one horizontal and the other vertical. Both antennas are of the multiple-dipole type with a backing reflector and they are fed from a variable dimension wave guide (10.19). The cathode ray oscilloscopes of the three centimeter system give the range, azimuth and elevation of the airplane with high precision.

14.2. Use of beacons

During the last war, beacons were widely employed. In peacetime also, their usefulness is at once apparent. They permit a pilot to get his bearings even when he is completely enveloped in clouds, fog, or darkness. They do, however, require the presence of a radar on board the plane. Most radars are equipped with a switch for shifting from "search" (ordinary radar use) to "beacon". The length of the pulse on beacon is relatively long. The beacon station is really, as its name suggests, a radar lighthouse. It consists of a receiver tuned to accept the beacon pulses sent out by the airplane, and a transmitter which is set in operation by the received pulses. The pulse of the beacon transmitter has a characteristic spacing interval, so that the appearance of the spaced pips on the screen of the cathode ray tube is sufficient to identify the beacon. In the series of pips displayed on the screen, the first indicates the position of the beacon station, while the succeeding pips serve to identify it by their spacing and number. Thus, a single beacon will show a radar-equipped airplane its range and its azimuth (with respect to the beacon).[1]

Echoes play no part in the operation of the beacon nor is the frequency nor intensity of the beacon pulses related to that of the initiating radar pulses which simply serve as triggers. It follows that the beacon signals can be separated widely from the radar echoes and need never be confused with or lost among intense permanent echoes, clutter or background "hash".

As a beacon transmitter sends directly to the radar receiver, its range characteristic resembles that of a radio transmitter, that is, the intensity of the signal from a beacon varies inversely as the square of

[1] For further details, see Appendix.

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the distance, and not as the fourth power (2.4); therefore, to double the range of a beacon, we must increase its power by four, as compared to sixteen (2.4) for a radar. As a beacon transmitter must send and respond to all directions of the compass, the gain of its antenna (2.4) is much smaller than it is in a search radar. As a partial disadvantage, however, a beacon is required for transmission at a very low angle, so all its transmission is restricted to the horizon.

By interrogating two different beacons, the pilot can at once fix his exact position in space with great precision. As a beacon transmits equally well over the horizon, trouble may ensue when several airplanes are interrogating a beacon at the same time. In such an event, each pilot observes the responses made to the others.

14.3. Navigating with Loran

In what is known as *loran* (LOng RAnge Navigation), transmitting stations are set up, spaced a few hundred miles apart, and operating at relatively long wave lengths. This, of course, is necessary for long range that far exceeds the line-of-sight transmission.[2] By the use of low frequencies, we may take advantage of the reflection from the ionosphere (10.15). Signals are broadcast from shore-based stations in short pulses. At the ship (or plane) they are received by a special receiver whose indicator measures the difference in the times of the arrival of the signals. From the charts, the difference in time is converted to the position of the hyperbolic lines on the earth's surface.

For a navigator to obtain a "fix", that is, to estimate his exact location, three transmitter stations are required (Figure 14 : 1). Let us suppose that a ship is somewhere between two of these transmitters. The navigator can identify the stations from the character of the pulses. If he receives both stations at the same time—because the velocity is the same for all waves in free space—he is somewhere on a line equidistant from both stations. If he receives a signal from station A, say a hundred microseconds before the signal from station B, he knows that he is on a line nearer to A than to B. The difference here would be approximately twenty miles.

Now, suppose that he observes the difference in time intervals between stations B and C (each recognizable by its characteristic pulses) as 50 microseconds. He is again aware that he is on a line so much nearer to one station than to the other. The intersection of the two

[2] Because microwaves ordinarily travel in straight lines, radar distances are limited by the hump of the earth; that is, they extend only as far as the line-of-sight, the horizon.

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lines, A with B and B with C gives the navigator his position. As a matter of fact, the time intervals appear as distances on a screen of the cathode ray scope. The navigator is provided with charts which show lines separated by convenient distances. Knowing his loran stations and the time intervals, he can at once locate the lines on the charts, and their intersections will give him his "fix".

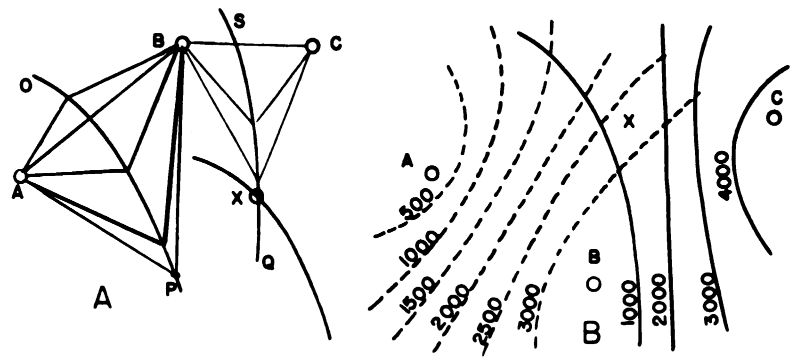

Fig. 14 : 1. Use of Loran
A, method of determining "fix"; B, hyperbolic reference lines

14.4. Navigating with Racon

In a *racon* (short for RAdar beaCON), the power of the radar transmitter on the plane or ship may be very low. When its pulses strikes the beacon, the latter broadcasts a powerful series of pulses. All that the pilot or navigator needs to do is to note the distance to the beacon. On his chart, he swings an arc with the beacon as center and the distance as radius. Then he takes another bearing from another beacon and draws another circle with the new beacon as center. Where the two arcs intersect is the position of the plane or ship.

14.5. Navigating with Shoran

An extremely useful form of beacon is the *shoran* (SHOrt RAnge Navigation).

In Shoran, a mobile radar (on board plane or ship) stimulates two short-range shore-based beacons. The plane's radar sends out pulses alternately to these beacons. Each beacon sends out signals. The time from plane to beacon and back to plane is converted into distance. The pulses received are aligned with the markers (pulses) on the scope of the receiver, and the distances are read. Knowing the location of the beacons, it is simple to ascertain the "fix" of the plane, for

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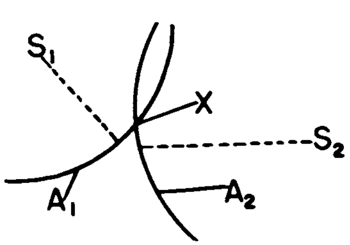
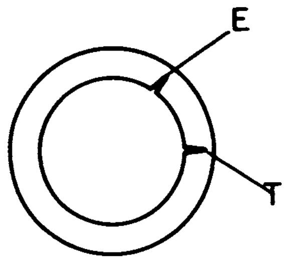
the distance from each beacon is known. The accuracy in Shoran runs as high as 50 feet in a distance of 300 miles.

During the war, Shoran was used for accurate bombing. Suppose in Figure 14 : 2 is a location to be bombed. Using the distance from the shoran station S_1 to X as a radius, and the position of the station as a center, a circular arc, A_1, is swung. Then, locating another shoran station S_2, a new arc, A_2, is struck, passing through X To hit X, the



14 : 2



14 : 3

FIG. 14 : 2. USE OF SHORAN FOR DETERMINING "FIX"
FIG. 14 : 3. SCREEN OF CATHODE RAY TUBE AS USED IN ALTIMETER
T, transmitter pip; E, echo pip

bombing plane travels along the circular arc until it reaches the intersection of the two arcs; there it drops its load of bombs. The plane follows the circular arc by keeping the echo pip in one position, thus indicating that the distance of the plane from X does not vary.

So accurate is this method of locating a geographical point—the error is not more than fifty feet—that it has been used to correct existing errors in maps. At one time during the war, when we were planning to bomb locations in northern Italy from a base in Corsica, it was discovered that the map of Europe was in error. The latitude and longitude of Corsica on the map were out respectively 60 and 180 yards from their true bearings.

14.6. Other uses of Shoran

Today, shoran is employed by oil and mining companies. The location of magnetic strata affects the bearings of magnetic detectors. The magnetic variations in the earth's field are plotted for large areas. These magnetic field maps are accurately correlated with the geographical points by means of shoran stations and radar-bearing airplanes.

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14.7. *Tail-warning (T-W) radar*

During the late war, many planes carried a very short range radar known as T-W. This stands for *tail-warning*. When a hostile plane approached one of our planes from the rear, the radar operated a warning bell. The tail-warning radar is now being used as anti-collision device. Placed in the nose of a plane, it gives warning of craft that are approaching. On the other hand, for extremely fast airplanes such as the modern jets, the time for remedial action is too short for the unaided senses. More than a warning is required in these circumstances. The controls of the airplane should be manipulated without the intervention of the pilot.

14.8. *Radar and the weather*

Were Mark Twain alive today, he would see that we are doing much about the weather. We send up balloons well into the stratosphere and by their corner reflectors (14.13), we can follow their paths for several scores of miles. On radar screens, these tell us the direction and speed of air currents well above the ceiling of airplanes. Also, from indications on our radar screens, we can detect and examine cloud formations which yield information to those who have become expert in interpreting these formations and their relations to weather forecasts.

14.9. *Comparison of radar and television*

The question is often asked by the layman: Can radar be used to receive television? This can best be answered by a brief analysis. In television, the screen of the cathode ray tube is swept entirely from top to bottom, a line at a time (ignoring "interlacing"). In radar, the PPI scope is intensity-modulated, that is, the grid voltage of the cathode ray tube is varied by the echo. In television, the grid voltage is varied by the video signals.[3] In radar the persistence qualities (in PPI) of the screen are usually very high, and an echo remains on the screen for a good part of a minute. In television, which must be adapted to thirty complete pictures a second, the persistence of images should be very short; otherwise, the pictures would be superimposed and confusion would ensue. So, to adapt a radar receiving set for television, the sweep of the tube should be changed from radial to straight across, both from right to left and from top to bottom. The persistence of the screen should be made extremely short.

[3] The signals received by the television receiver corresponding to the echoes received by the radar receiver.

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14.10. Radar as altimeter

As an altimeter, that is in the determination of height above ground, or *terrain clearance*, radar plays an important role. A radar for this purpose could easily be fitted into a suitcase and carried by one man; yet the appalling accidents that occur occasionally indicate that they are not used as generally as they should be. As the maximum height we are required to measure in an airplane is certainly not more than 50,000 feet, our radar should be sufficiently strong to send out a pulse from which the echo produced would be observable at the maximum range of ten miles. The power required is slight; as the echo comes from the earth, resolution or sharpness is not important. Bearing these facts in mind, we can construct our radar altimeter.

The beam to be sent out is rather broad. To generate this, dipole antennas are used; these are mounted beneath the plane, one for receiving and one for transmitting. As the frequency is relatively low, about 500 megacycles, and the wave length correspondingly long, 60 cm, each antenna is about a foot long.

The sweep of the indicator of the cathode ray tube is circular, as shown in Figure 14 : 3, and it travels clockwise around the screen. A complete sweep occupies the period of one pulse, and as these are sent out about 100,000 a second, there is no flicker. The angular distance on the screen of the cathode ray tube between the transmitting pip and the echo pip measures the altitude, or height. As 1/100,000 of a second is ten microseconds, the duration of the pulse is sufficient for the echo to travel 5000 feet or about a mile. A pulse of one-quarter microsecond is sufficient and the power of the pulse can be of the order of ten watts.

It is customary to use two scales, each with a sweep ratio of one to ten; that is, the frequencies of both pulse and sweep can be decreased to a tenth, so that the higher altitudes can be read on the meter. The rate of repetition is held very constant by means of a crystal-controlled oscillator. Errors are remarkably small, varying from sixty feet at a mile to one hundred feet at four miles.

14.11. Use of radar to prevent collisions

The thought occurs that if radar altimeters can be used effectively to guard against collision with mountains, it should be fairly simple to provide anti-collision radars for all purposes. With such a radar on board an airplane, we could see in all directions, regardless of fogs, clouds, or darkness. The terrible accidents that occur periodically

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indicate that we have no panacea in radar. With the enormous speeds of modern airplanes, for both military and commercial service, radar should effectively detect an approaching craft at long distances.

Let us consider an extreme example. Two airplanes of the jet-engine type are flying toward each other at six hundred miles an hour. The distance between them is diminishing at the rate of twelve hundred miles an hour, or twenty miles a minute. Even a three-minute warning would require detection at sixty miles. For radar on ground or ship, this would not be an impracticable performance. For entirely airborne radar, it is still not possible.

It would seem that the more workable plan at present is to channel, by strict regulation, all aircraft into air "avenues". These air lanes would be entirely one-way and at different elevations, giving us the advantages of surface traffic, and still more, the added range of the third dimension.

In approaching a large city at moderate elevation in an airplane, the background of echoes from buildings and skyscrapers often presents itself as a solid mass. The echo from an airplane could easily be lost in such a background.

14.12. Radar in map-making

We could assume that in the making of maps radar should play a preeminent part, and to some extent, it does. We should expect that by the use of a PPI indicator, we could at once receive a visual map of an area over which a radar-borne airplane is hovering. To a degree this is true; yet what we see will depend upon elevation, the resolving powers of the radar, the angle from which the surface is observed, the character of the surface, and other factors.

The greater the height of the mapping plane, the larger will be the field it embraces. But this advantage will be offset by the lack of details. A moderate-size river, or a railroad, may give a distinct echo at five thousand feet, yet be completely invisible at twenty-five thousand feet. The narrowest possible beam, with the smallest corresponding wave length (perhaps one centimeter), will give us maximum resolution (11.7); that is, we shall be able to distinguish separate objects at their best.

Just as the size and shape of shadows will vary with the angle and elevation of the sun, so radar echoes will show corresponding variations. A sixty-story skyscraper viewed from directly above may give a small, sharp echo, whereas if it is scanned from an angle close to the

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horizon its echo may be enormously larger and diffuse. Unfortunately, for the present purpose of making maps, the character of a surface may often determine the character of the echo.[4] Thus, on a radar screen, water appears in one guise, clouds in another, and wooden buildings in still another; surfaces of metal and of rubber, though of the same size and contour, will present utterly different echoes.

One of the reasons radar echoes may be obscured is *clutter*. This is due to the fact that the radar echoes are too abundant from objects in which we are not interested. Thus, the echo of a torpedo boat destroyer might be lost because of sea clutter in rough weather. The echoes returned by the waves create a background of echoes in which the echo of the vessel is lost. So the echo of an airplane may be merged with the background echoes from the tall buildings of a city. Unless we can take advantage of some qualitative difference between the wanted and the unwanted echoes, the solution of the problem is impossible. The qualitative differences in the examples cited is caused by the relative motion of the target and the background. In what is known as the Moving Target Indication (MTI), the echoes on the screen are subtracted after a delay from the succeeding echoes and the difference of the two sets of echoes appears on the screen. Permanent echoes are cancelled and the moving target is all that is visible.

How striking this difference in reaction can be is brought out by the following illustration. During the late war, rubber life-preserving rafts were important in saving the lives of pilots and seamen. Yet, of all things, such rubber rafts presented no radar echoes, so craft sent out to spot them by radar missed them completely. To make them visible, a device called a *corner reflector* was added to the equipment of rubber rafts.

14.13. Corner reflectors

The object of a corner reflector is to present *always* the effect of a flat metallic surface to the radar beam. A flat metallic surface produces the maximum radar echo when its greatest area is perpendicular to the radar line of sight, just as a mirror will throw the most intense beam when its surface is perpendicular to the bisector of the angle

[4] The study of pips has acquired the name "pipology". It soon becomes evident with the use of radar that a knowledge of the character of the echoes comes only with training and experience. Though it is simple to say that a pip indicates an object so many miles distant, and located in a specific direction, it is another matter to answer the question, "What is causing the pip?" Is it a mountain, a body of water, a cloud, a ship, a rainstorm, a tornado, or what? A definite answer comes with the skill born of experience.

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made by the sun, the mirror, and the observing eye. A practical corner reflector consists of either three right-triangular, or three square, surfaces meeting at right angles, as at the corner of a cubical box. Figure 14 : 4 (a) shows two types.

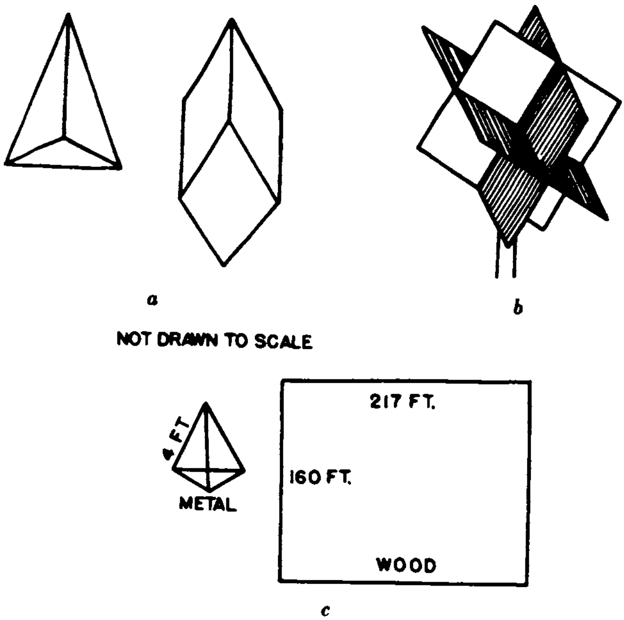

FIG. 14 : 4. CORNER REFLECTORS
(a) Two types consisting of metal planes
(b) Cluster of types shown in (a)
(c) Metal reflector and equivalent wood surface for comparable echo

If the wave length is very small compared to the reflecting corner, the latter becomes extremely effective. With a single flat surface, the moment its plane or surface makes an angle other than a right angle with the radar line of transmission, it becomes wholly ineffective. With a corner reflector, the best angle for the radar echo is the one at which the radar beam makes equal angles with each of the bounding faces of the corner. However, the variation from the maximum as these angles change is quite gradual. By making a number of these corner reflectors into a cluster, as shown in Figure 14 : 4 (b), they can be made still more effective.

The more accurately the angles are set up on such a corner reflector,

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the more effective it will be. On board a rubber raft employing a collapsible device, precision cannot be high. On the other hand, when a corner reflector is set up on a firm foundation on land and made of rigid materials, the sensitiveness of this device to angular errors in its construction is most striking. The smaller the wave length of the beam pulse that strikes the corner reflector, the greater is the effect of angular error. On the other hand, the effective surface of the reflector as an echo-producer is enormously greater than its arithmetical area; as the wave length is decreased, this effective area is increased.

The planes or surfaces of a corner reflector can be made of any material that is a good reflector of radar. The truer the angular junction, the more effective is the reflector. As the frequency is increased, the need for greater accuracy is enhanced. On a 10-cm wave length, the angular error between adjacent surfaces should not exceed 1.7° departure from a right angle where the length of a side is two feet. The visibility of a corner reflector from an airplane varies as the length of the sides. From a ship's deck, the visibility of a corner reflector varies as the square root of the increase of the sides.

To take an example, a precision corner reflector, with four-foot triangular sides, presented an effective area of 600,000 square feet to the transmitter of a 1.25-cm wave-length radar. The echo from this relatively small reflector was more pronounced than that from a wooden building 217 feet long by 160 feet wide: see Figure 14 : 4 (*c*). With the 1.25 cm radar, this corner reflector was detectible at thirty miles distance. An ordinary corner reflector with eight-foot sides, suspended from a balloon, has been traced for sixty miles. The reflective power of a flat surface exactly perpendicular to the line of transmission of the radar will be determined by the wave length of the radar. Thus, a square plate one foot on a side is the equivalent in effectiveness of a sphere six feet in radius for a 10-cm radar; see A in Figure 14 : 5. For a 1-cm radar, a one-foot square is the equivalent of a sphere sixty (60) feet in radius, as shown in B.

14.14. Limits of radar

What are the limits of radar? On earth, one centimeter (30,000 megacycles—30,000,000,000 cycles) is the shortest wave length feasible. Below this wave length, the earth's atmosphere and its water vapor become too absorbing for practical use. In space there is no lower limit.

There is no upper limit. Radar has been beamed to the planet

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Venus (when it was 25 million miles distant), and the echo was clearly received, though the time for the pulse to travel and return was about five minutes. The transmitter employed 2500 kilowatts of power to be effective.

We have noted that one of the limits imposed on radar sensitiveness is the inherent noise of the radar set components and the static always present in our atmosphere. Amplifiers, in the past, have contributed

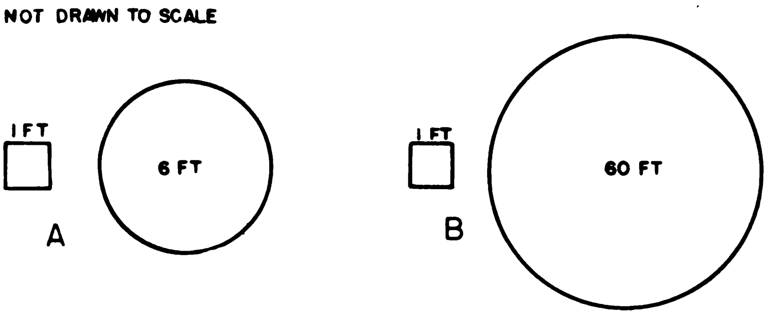

FIG. 14 : 5. EFFECTIVENESS OF METAL PLANES AT DIFFERENT FREQUENCIES
Equivalence at wave length: A, 10-cm; B, 1-cm

most of the noise. With the use of *masers* (name derived from Microwave Amplification by the Stimulated Emission of Radiation) for amplification, the noise of amplifiers has become negligible. As a result of the use of masers, the sensitiveness of a radar receiver can be stepped up from 100 to 1000 times over the amplifiers employing standard vacuum tubes.

An explanation of the operation of a maser requires a knowledge of solid-state physics. In brief, the substance of a maser (ammonia gas, crystals of aluminum oxide—ruby—calcium tungstate, and other materials have been used) consists of molecules with different energy states, i.e., some are emitting energy and some are absorbing energy. By suppressing the absorbers and passing microwaves through the emitting molecules, their energy is contributed to the microwaves whose energy can be greatly enhanced or amplified.

For successful operation of a maser, a certain amount of impurities must be present. In a ruby, for instance, it is the presence of chromium in the aluminum oxide that imparts the red color. The calcium tungstate mentioned above needs traces of uranium, or of rare earth metals, such as neodymium or samarium.

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By introducing feedback into an amplifier, it becomes an oscillator. Masers are remarkably stable or constant. Employed as oscillators for the control of clocks, so constant is the frequency that the error now in a maser clock is one second in ten thousands years (100 centuries).

Employed in radar telescopes, a receiver with a parabolic antenna dish of fifty feet diameter containing a maser amplifier can easily equal in effectiveness a radar telescope of five hundred feet diameter equipped with a vacuum tube amplifier. Incorporated in the largest existing telescopes, masers will permit us to fathom the extreme limits of the universe as predicted by Einstein.

14.15. Pseudo-radar

Because of its sensational performance in times of war and peace radar has captured the attention of the public and much has been ascribed to radar (especially by the popular press) based not on fact but on the lively imagination of lay reporters. Electromagnetic waves (in the microwave region) cannot penetrate the ocean depths, and sea water is just as impenetrable as a metal for radar uses. To avoid detection by enemy radars, it was necessary for submarines to remain submerged.

The ASDIC apparatus on board naval vessels is *not* a radar. A high-pitched sound wave is generated and beamed through the ocean depths. Upon striking an object such as a submarine, the sound reflection or echo is received and amplified by the ASDIC receiver. The interval of time between the transmitted sound pulse and the returned echo is a measure of the distance to the object detected.

At present there is no true radar device that is usable by the blind. The ultra-sonic devices, designed to catch popular interest, are really transistor radios which utilize what was once a disadvantage. When the first radio sets were built and marketed, the shielding was negligible. When the operator approached an early radio receiver, it often squealed. The body (the hand) acted as the plate of a condenser, and if the set was regenerative, it broke into oscillations, audible as a squeal.

A small oscillator could be suspended on a blind man by straps, like a portable camera. A small plate or electrode coupled to this oscillator could be carried like a cane or wand and as it approached any object it would cause the oscillator to squeal; the closer the object, the higher the pitch and volume of the squeal. But this is radio, *not* radar.

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For astronomical purposes, we now have both radar telescopes and radio telescopes. They are *not* the same. The moon is an inert body. Radar signals have been transmitted to the moon and the echo has been detected more than two seconds later by a *radar* telescope. On the other hand, what are known as radio stars and galaxies are enormously powerful emitters of microwaves which are received by *radio* telescopes.

14.16. Radar in the future

What of the future?

The vistas that spread before us are dazzling. Radar is an infant. Effective though it has been, it is still clumsy and ungainly. Anyone that has examined the inside of a proximity fuse must appreciate how much has been crammed into the cramped quarters of the nose of a shell. It contains a full radar transmitter and a complete receiver. As the shell in flight approached within fifty feet of its target, the beam from the tiny transmitter produced an echo reflected from the target and triggered the explosion of the shell, showering the target with high-velocity fragments.

To have built a radar unit into a space no larger than a man's fist is already to have done what borders on the miraculous. At the other extreme, we may cite an example of a radar installation that is truly colossal. In the Distant Early Warning line (D.E.W. line) north of the Arctic Circle, the United States has erected a chain of immense radar stations to detect missiles and aircraft coming from the direction of Siberia. In Thule, Greenland, our Government has erected four radar units with rectangular antennas, each as large as a football field. The weight of each antenna is fifteen hundred tons; the power of the transmitters is several thousand kilowatts. We are accustomed to think of wave guides as round or rectangular piping employed in microwave radar and running in length not more than a few yards. Yet in Thule, the wave guides from the transmitter to the antennas exceed twenty-one miles in length.

Add to this the ability to withstand the shock of the shell-propellant, to preserve its functions though subjected to an acceleration of 20,000 g (20,000 times that of gravity), and one's imagination must surely be stirred by the feat. At such accelerations, a speck of solder weighing a grain at rest increases in effective weight to three *pounds* under the acceleration attained in the bore of an anti-aircraft gun. This should give us some slight concept of how rugged the vacuum

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tubes must be—tubes, nevertheless, made of glass, to a precision of 0.0001 inch.

It is, therefore, not unreasonable to anticipate that in the future, by the use of miniature tubes and printed wiring circuits (where the path of the conductor is stamped on a surface), radars will be marvellously light and compact. Instead of wave guides of metal, we shall employ plastics coated with the sheerest film of metal. The last word has not been spoken as we enter into the realm of microwaves. There is still a huge gap in the electromagnetic spectrum between the shortest waves used in radar at present and the longest waves of the infra-red region.

It is not inconceivable that with the use of highly concentrated beams of ultra-microwave lengths, compact radars could be placed on all automobiles and trains, making a collision between vehicles an impossibility, for the radars would operate brakes without human intervention.

The country and our coastlines will be criss-crossed with radar beacons, so that an airplane in the skies will identify its position as easily as we do our ambulatory course in passing from street corner to street corner. The interruption of river and ocean traffic because of the fog and the dangers of collision has already become unnecessary; we need but employ the existing equipment to sound the death knell of these time-worn bugaboos.

Reflecting markers of different sizes and contours on the ground which require only a radar not unlike an altimeter, could identify routes and hazards. In view of their utility, the cost of installation and the expense of upkeep would be negligible.

It would be most pleasant to discuss radar in relation to peaceful pursuits only, but, alas, we must face the world as it is. With the introduction of nuclear bombs, science has acquired devices for modifying our environment in modes undreamt of a few decades ago. Microwaves that travel in straight lines are limited in distance to the horizon. Unlike long radio waves which are reflected by the ionosphere (the Kennelly-Heaviside layer) and so can cover great distances, the ionosphere is transparent to microwaves. They are therefore not reflected.

The explosion of a nuclear bomb near or above the ionosphere can greatly add to the density of this layer and make it opaque to microwaves. It is as though we had suddenly spread a sheet of metal where the ionosphere lies. This will enable us to reflect microwaves and cover

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great distances. It will also prevent radar detection of missiles that fly above the ionosphere.

It has been mentioned that the sensitiveness of a radar receiver is limited by "noise" or "grass". In analyzing the components that make up noise, we find that the inherent noise of a set is dependent upon the Absolute temperature (a scale that begins at 273° below 0° Centigrade) of its parts. As our ability to maintain low temperatures improves, components of radar sets will be kept at very low temperatures and the sensitiveness will be greatly enhanced.

It is said that radar won the War for us. It will remake civilization in the future. With its aid we shall transform and enlarge the scope of our senses. The day is not far distant when the blind, equipped with tiny radars, will go about their daily chores with sound replacing their sight. As bats have been for millennia, the blind will be guided by the pitch of echoes reflected from surrounding objects. They will learn to gauge obstructions from the quality of sounds carried to their ears.

Though we have reached a practical limit in the size of optical telescopes, radio-telescopes, which utilize the enormous parabolic dishes of radar coupled to hypersensitive receivers, are opening vistas in astronomy undreamt of a few years back. The amplification of signals emitted from the farthest reaches of space is made possible by radar methods. For the same reasons, we shall be able to receive intelligence and convey messages to artificial satellites many millions of miles away.

Until the introduction of the magnetron, which is capable of producing power in the thousands of kilowatts at centimeter wave lengths, it was not possible to construct linear accelerators of great size. With the aid of high-power magnetrons in the future, linear accelerators will produce particles with energy running into multi-billion electron volts. With such aids, nuclear scientists will penetrate the heart of the atom and discover the secrets of matter.

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Glossary

AMPLIDYNE GENERATOR—Special form of D.C. generator employed with servomechanisms.

ANTI-TRANSMIT-RECEIVE (A-T-R)—A vacuum tube switch interposed between the transmitter and the receiver to prevent echo energy from passing to the transmitter.

BEACON—A radar device for accepting radar signals and then radiating a coded signal which identifies the beacon.

BEADED INSULATION—Beads on the inner conductor of a coaxial cable serving to keep it in place and insulate it from the external conductor.

BLOCKING OSCILLATOR—A circuit for generating pulses and controlling their repetition rates.

BROADSIDE ANTENNAS—A group of antennas arranged in one plane.

CATHODE RAY TUBE—An evacuated tube containing a gun and a fluorescent screen. A beam of electrons generated in the gun is focussed on the screen. Movements of the beam, suitably controlled either magnetically or electrostatically, produce the radar display on the screen.

CAVITY RESONATOR—A hollow copper or brass chamber employed as a resonant circuit at ultra high frequencies.

CHARACTERISTIC IMPEDANCE—The ratio of voltage to current of a traveling wave in a radio frequency line.

CHOKE JOINT—A joint between sections of a wave guide designed to prevent leakage of energy by interposing quarter-wave length slots.

CLAMPER—Usually a diode so connected as to clamp a wave form so that the wave form is tied or clamped to a reference line.

CLIPPING—Cutting off the tips or tops of a wave form by means of a diode heavily biassed.

COAXIAL LINE—A two-conductor cable consisting of a metal tube and a central conductor within it from which it is insulated.

CORNER REFLECTOR—An arrangement of metal planes or sheets forming right angles and possessing high reflecting qualities to radar beams.

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Cosecant Squared Antenna—A paraboloid reflector with its top bent forward to produce a special beam with a power density pattern which varies as the square of the cosecant of the angle formed by the altitude of the reflector above the earth and the slant range of the reflector.

Crystal Mixer—A crystal of silicon or germanium enclosed in a suitable housing into which is fed the RF signal and the output of a local oscillator; the combined or beat output is fed into the IF amplifier.

D.C. Restorer—Another name for a clamper when it serves to restore a D.C. component to a wave form that has been filtered out by a condenser.

Delay Line—An artificial transmission line simulated by a network of condensers and coils, for introducing a delay to a wave form of a microsecond or less.

Differential Synchro—Like a synchro-generator or motor, it has a stator identical in structure with theirs. Its rotor is cylindrical. The differential synchro can supply the sum or difference of the angular positions of two input shafts.

Dipole—A half-wave antenna.

Directional Coupler—A short length of closed wave guide coupled by either one or two apertures to an RF transmission line for the purpose of measuring the power in the wave guide line.

Double Stub Tuner—An arrangement of two stubs spaced less than a quarter-wave length apart and making contact with the inner and the outer conductors of a coaxial line. The lengths of the stubs can be varied and by this means standing waves on the line can be eliminated.

Duplexer—Another name for the T-R device.

Duty Cycle—The ratio of the power input of a magnetron to its pulsed power output, 0.001.

Echo—The reflected signal emitted by an object or target in the beam of a radar transmitter.

Echo Box—A metal box of very high Q equipped with a dipole for producing echoes in the laboratory and used for measuring the output of a transmitter and the sensitiveness of a receiver.

Folded Dipole—A half-wave center-fed antenna coupled to another half-wave antenna at its ends.

Gain of Antenna—The ratio of the maximum power radiated by a directional antenna to that radiated uniformly by a fictitious antenna in all directions.

Gun—The part of a cathode ray tube in which electrons are liberated and formed into a narrow beam.

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Hollow Wave Guide—Copper or brass tubing of round or rectangular cross section for use as transmission lines of very high frequency waves.

Hunting—Oscillations in servomechanisms caused by the delay or lag between an angular error and the application of the torque for correcting the error.

Impedance Matching—The adjustment of the impedance of transmitters, receivers, etc. and the RF lines to which they are connected so that the maximum of energy is transmitted to the antenna, and when the echoes are received the maximum is transmitted from the antenna to the receiver.

Indicators—The cathode ray tubes and the associated circuits and connections for producing the radar displays on the screens.

Intensity Modulation—The application of the received signals to the control grid of the cathode ray tube to produce an intensification of the electron beam during the reception of the signals.

Iris—A metal diaphragm partly closing the wave guide and employed for matching purposes.

Keep Alive-Electrode—An auxiliary electrode, negatively charged, near the gap terminals of a T-R tube for maintaining a glow discharge to fire the spark more quickly.

Klystron—A two-chambered velocity modulated tube.

Lobe Switching—An arrangement for alternating the feeds to an antenna so that the two halves of the antenna radiate alternately at different angles.

Local Oscillator—Usually, at microwave frequencies, a reflex klystron (which see), whose output is combined with the RF signals producing the input for the IF amplifier.

Loran—Long range navigation by means of shore stations transmitting at relatively low frequencies.

Magic T—A coupling unit consisting of a shunt T and a series T for connecting wave guides and serving as a valve or switch for electromagnetic energy by matching its branches with the connecting wave guides.

Magnesyn—A rotary inductor consisting of a toroidal coil as stator and a permanent magnet as a rotor.

Magnetron—A multichambered metallic tube serving as a diode on which an intense magnetic field is impressed externally and perpendicularly to the internal electric field existing between the cathode and the anode. It can produce enormous power at microwave frequencies.

Matching—See *impedance matching*.

Modes—The configurations of the electromagnetic field in hollow wave guides.

Modulator—A circuit controlling the operation of the transmitter and the shape, duration and repetition frequency of the pulses.

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MOTORBOATING—Undesirable coupling of stages in an amplifier producing oscillations resembling the sounds of a motorboat.

MULTIVIBRATOR—An oscillator consisting of a circuit of two triodes in which the output of each tube is coupled to the grid of the other.

NOISE—In radar, better known as "grass", the display on the screen of a cathode ray tube when the receiver is activated but no echoes are being received. For an echo to be visible, it is necessary that it rise above the "grass" or "noise'.

PARABOLOID—A dish reflector whose section is a parabola.

PARASITIC ANTENNA—An antenna placed either behind or in front of a driven antenna and parallel to it, reenforcing the radiation from the driven antenna. When placed behind the driven antenna, the parasitic antenna is called a reflector; when placed in front, a director. The antenna fed from the transmitter is the driven antenna.

PIEZO-ELECTRIC CRYSTALS—Some crystals such as quartz and Rochelle Salts possess the property of generating electric charges on certain planes or surfaces when pressure is applied to other planes.

PLAN POSITION INDICATOR (PPI)—A type of display in which the sweep runs radially across the screen and rotates in synchronism with the antenna.

PLUMBING—Another name applied to hollow wave guides which physically are metal pipes.

PULSE DURATION—The length of time power is sent out or radiated by the radar antenna without interruption.

PULSE FORMATION—Control of pulse shape (usually rectangular) by the modulator.

PULSE REPETITION FREQUENCY—The number of pulses emitted per second by the radar antenna; usually from 400 to 5000 cycles per second.

Q—A measure of loss of power in a resonant circuit. It is the ratio of the resistance, R, of the circuit to the square root of a fraction, inductance divided by capacitance; in symbols $Q = R/C$.

RACON—Navigation with radar beacons known as racons for moderate distances.

RADIATION RESISTANCE—The ratio of the power radiation of an antenna to the square of the current at the input terminals of the antenna.

RANGE MARKERS—Fixed calibration marks on the screen of a cathode ray tube for measuring range.

RECOVERY TIME OF T-R TUBE—The time interval between the end of the transmitted pulse and the time when the signal power in the receiver is half the size it would have if no ions were present.

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Reflectors—Metal screens, plates, or antennas placed behind the driven antenna to prevent back radiation and reenforce the forward radiation.

Reflex Klystron—A velocity modulated tube containing only one chamber which serves as a buncher and also as a catcher after reflection (see velocity modulated tube).

Rotary Spark Gap—A rotating metal disc with spark terminals affixed; employed as a modulator for discharging the pulse-forming network.

Saturable-core Reactor—A coil with an iron core designed to saturate with small currents and when used after saturation presents extremely low reactance.

Sawtooth Generator—A means for producing a sawtooth voltage or current so that the sweep across the screen of the cathode ray tube is directly proportional to the elapsed time.

Screen Reflector—See *reflector*.

Series T—A short length of wave guide connected to the wide surface of a rectangular wave guide.

Servo *also* **Servomechanism**—A power-amplifying automatic system for causing a rotation of an output shaft to follow the rotation of an input shaft.

Shoran—Short range navigation requiring at least three beacons on shore.

Shunt T—A short length of wave guide connected to the narrow surface of a rectangular wave guide.

Skin Depth—The distance from the surface of a conductor (carrying high frequency currents) in which the current has decreased to $1/\epsilon$ (where ϵ is 2.718).

Skin Effect—The penetration of currents at very high frequencies only through the outermost layers of a conductor is known as skin effect.

Slotted Line—A hollow wave guide in which slots are cut for the introduction of probes or for tapping power in the wave guide.

Standing Waves—The distribution of current and voltage waves along a transmission line caused by reflection.

Standing Wave Ratio (SWR)—This can be defined as the ratio of the maximum voltage to the minimum voltage, or the maximum current to the minimum current, in the wave guide.

Stub Matching—A short-circuited length of line, adjustable in length and placed in parallel with a transmission line for the purpose of varying the impedance of the transmission line.

Sweep Voltage—A voltage increasing linearly with time and applied to the deflection plates of a cathode ray tube causing the beam to sweep across the face of the screen.

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SYNCHRO—A device resembling a small A.C. electric motor capable of matching the rotation of an independent rotating shaft.

TRANSIT TIME EFFECTS—When the time for the passage of electrons between the electrodes in a vacuum tube approaches that of an alternation of current, it becomes impossible to operate the tube effectively. Decreasing the interelectrode distances decreases the transit time, and because a limit is soon reached, ordinary vacuum tubes cannot be employed for amplifying currents at extremely high frequencies.

TRANSMIT-RECEIVE TUBE (T-R)—A spark gap contained in a sealed glass tube, partly evacuated, and serving to short-circuit the receiver when the transmitter is operating.

T-R BOX—The metal housing containing the T-R tube and coupling devices for connecting the tube to the wave guides from the transmitter and the receiver.

TRAVELING WAVES—Waves of voltage and current passing along wave guides when power is transmitted.

VELOCITY MODULATED TUBE—A vacuum tube consisting of two resonant chambers and a connecting passageway through which electrons traversing a closely spaced pair of grids become grouped as they travel, and on entering the second chamber, give up their energy at the resonant frequency.

WAVE GUIDES—Wires, coaxial cables, hollow tubes, and dielectric rods may transmit electric power and guide the waves in doing so provided the frequency is very high.

WAVE SHAPER—Circuit elements and vacuum tubes arranged to square, clip, peak, and otherwise adapt or alter the form of a wave.

YAGI ANTENNA—A group of antennas set up usually in a horizontal plane and consisting of a driven dipole, a reflector behind it, and one or more radiators in front of the dipole called directors.

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Appendix

SUPPLEMENTARY NOTES*

2.2: Decibel notation (abbreviated *db*) is defined as the logarithm of the ratio (to the base ten) of the power output to the power input multiplied by ten.

If the amplification of power is stated in decibels, then by dividing the number of decibels by ten, and raising ten to this power, we shall obtain the amplification.

Suppose an amplifier raises the power by thirty decibels: 30/10 equals 3; and 10^3 equals 1000. That is, 30 decibels is equivalent to an amplification of 1000. Sixty decibels is equivalent to an amplification of one million (60/10 equals 6; 10^6 equals 1,000,000).

Similarly, if a loss in a circuit is sixty decibels, the power is diminished by 10^6 or 1,000,000; that is, the power is reduced to 1/1,000,000. On the other hand, if the amplification is given and we seek the equivalent decibels, we proceed as follows:

Suppose the amplification is 1000; then, we note that 1000 equals 10^3 and 3×10 equals 30 *db*. If the amplification is 1,000,000, then we note that 1,000,000 equals 10^6 and 6×10 equals 60 *db*.

3.18: Two kinds of velocity must be considered in dealing with wave guides, phase velocity and group velocity. If a carrier wave is modulated by a signal, the speed of the envelope is the group velocity; the individual cycles of the carrier appear to move at a speed that is known as the *phase velocity*. The phase velocity in a wave guide may vary from the speed of light to infinity. The *group* (or signal) *velocity* is always less than that of light. At first sight, it would seem that we have encountered a flat violation of the principle that nothing can exceed the speed of light. In free space, group and phase velocity are both equal to the speed of light. In a wave guide, the phase velocity is

$$v_p = f\lambda_g$$

where f is the frequency and λ_g is the wave length in the wave guide. In free space, an electromagnetic wave travels with a speed $v_g = f\lambda$, where λ_s is the wave length in free space.

* Numbers refer to sections in text.

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If we divide these equations term for term, thus:

$$\frac{v_p}{v_s} = \frac{f\lambda_g}{f\lambda_s}$$

we obtain for phase velocity

$$v_p = v_s \frac{\lambda_g}{\lambda_s}$$

As λ_g is greater than λ_s, it follows that v_p is greater than v_s, the velocity of light. If we consider a carrier wave passing t through a wave guide, and modulated by a signal, the modulated envelope passes through at a speed less than that of light. The cycles making up the carrier units appear to advance with respect to the modulation envelope at a speed greater than that of light. This is the phase velocity.

3.20 (*a*): In attenuators containing only air or a vacuum, all losses occur in the skin depth of the metal penetrated. The higher the resistance of the metal, the greater will be the losses in the metal. In those attenuators that depend upon the insertion of a resistant element, the losses that occur in the resistance account for the attenuation. On the other hand, in cut-off attenuators, the amount of energy passing through the attenuator depends largely on the amount of energy reflected by the attenuator. In cut-off attenuators, the reflected energy is large and the energy passing through is small. The efficiency of a cut-off attenuator is high because the amount of energy wasted is quite small.

3.20 (*b*): A wave guide is considered as two linear conductors running along the center of the narrow sides of the wave guide and supported by a continuous series of stubs, then, when the width of the wave guide is less than twice the wave length, the supporting stubs are less than a quarter-wave length. Therefore, these will shunt the line with a low inductive impedance, stopping transmission. The height of the wave guide is limited by the requirement that it should not exceed half a wave length so as to prevent modes whose polarization is at right angles to the mode that is to be transmitted. On the other hand, if the height is made too shallow, then the power transmitted is limited because the electric field runs from top to bottom.

Theoretically, a wave guide can handle twice as much power as a coaxial cable, carrying the largest wave that traverses the wave guide. Practically, the attenuation in a wave guide is about half that of a comparable coaxial for the same wave length. A wave guide of square cross-section has the smallest attenuation for a given periphery and rectangular cross-section.

3.28: On open-wire lines, a movable stub is easily moved along the wires until a match is obtained. On coaxial lines and wave guides, a movable stub would involve difficult mechanical problems; instead, double stub tuners are employed. Two stubs whose lengths can be varied (as by means of plungers) are fixed in position along the line and spaced usually three-eights of a wave length apart. In a coaxial stub, the plunger short-circuits the inner

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and the outer conductors. In making adjustments, one stub is varied until the conductance at the junction of the tuner equals the characteristics conductance of the line; then the other stub is varied until the resultant susceptance at the same point is zero.

4.1: It can be shown that an electron moving at a speed not more than 1/10 that of light (so that the effect of relativity can be ignored) conforms to a simple formula: speed 6×10^7 volts where the speed is given in centimeters per second and the volts represents the voltage between electrodes. If the distance between electrodes is one millimeter and the voltage is 100, then the time to cross a distance of one millimeter will be $6 \times 10^7 (100)^{1/2}$ or 0.6×10^{-9} seconds.

At 3000 megacycles, the time of a complete oscillation is 1.2×10^{-9} seconds. This is twice as long as the time required to travel one millimeter. It would be impossible to sustain oscillations, for one terminal (the plate) would be getting its current just opposite in phase of that which is required at the time the electrons are being liberated (at the grid). Even at a spacing of one millimeter, the distance between grid and plate is excessively large for oscillations at 3000 megacycles. Note that in the lighthouse tube (**4.20**), the successful performance is determined by reducing the grid plate spacing to a tiny fraction of a millimeter. It is also evident from the simple formula of speed and voltage that by increasing the voltage, we increase the speed and decrease the transit time. Quadrupling the voltage from 100 to 400 volts, will reduce the transit time by half.

4.14 (*a*): In the period of several microseconds following the main pulse of of the magnetron, low-power oscillations occur which are gradually damped out. Nevertheless, they are sufficiently large by themselves to produce false signals that may hide or disguise the real echoes. The effect of the tail-reversing inductance is to add a low-frequency oscillation to the oscillations of the magnetron. The period of this oscillation is determined by the time constant of the circuit which consists of the inductance (tail-reversing) and the capacitance of the network. The output of the magnetron following the main pulse is reduced by the tail-reducing inductance.

The damping diode permits the positive pulses of the magnetron to pass through and, as a result, changes the low-frequency oscillations to a highly damped transient. Furthermore, the diode serves as a damper of high-frequency oscillations and also suppresses to an extent the pip produced by reflection.

4.14 (*b*): In a radar receiver, the bandwidth of frequencies to be amplified varies inversely as the duration of the pulse, that is, the shorter the pulse, the greater the bandwidth. For example, if a pulse is one microsecond and its bandwidth is one million cycles, then a half-microsecond pulse will require a bandwidth of two million cycles. To state it otherwise, as the duration of the pulse decreases, the high frequency response of the receiver must improve for the quality to remain constant. Ordinarily, the rate of repetition has no bearing or influence on the shape of the pulse.

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4.16: Insofar as the kinetic energy of the electrons is zero at the cusp (Figure 4 : 8 (*d*)), the efficiency of conversion from the D.C. energy (due to the D.C. field) to the energy of oscillation (due to the tank circuit) reaches 100 per cent in traveling from cusp to cusp. The conversion of the magnetron as a whole would be 100 per cent were it not for the energy that remains in the electrons when they strike the anode. This energy will depend on the distance traveled from the last cusp; hence, the smaller the distance from cusp to cusp (the smaller the cycloids), the less energy wasted and the greater the efficiency. As the size of the cycloidal paths (electron orbits) depends on the strength of the magnetic field, it follows that the cycloids can be made small and the efficiency high by increasing the intensity of the magnetic field.

4.19: As the resonant cavities of a magnetron are made up of an inductance and a capacitance, in effect, where the circular cavity largely is inductive and the flat connecting passage between the interaction space and the circular part is the capacity, it is possible to tune or vary the frequency by inserting plugs into the circular cavities, thus decreasing their volume and, hence, their inductance. A movable ring that can be shifted with respect to the capacitive slots may also cause the capacity to alter. In either case, the movements must be accomplished without disturbing the high vacuum that exists in the interior of the magnetron.

5.11: Two quantities have a linear relation when one varies directly as the other (here the input and the output are linear). The word *linear* is based on the fact that graphically, the relationship is expressed by a straight line. If the graph is not a straight line, the quantities are non-linear.

5.13 (*a*): In the transistor, two metallic points make contact with the surface of a germanium crystal which is highly polished and quite flat. The contacts, called the *emitter* and the *collector*, are very close together (about 0.01 inch). On the opposite face of the crystal is a third metallic contact of large area. Each separate point of contact is a good crystal rectifier by itself. Suitably biased with a D.C. potential, the germanium crystal can serve as an A.C. amplifier. If a low A.C. voltage is applied across the emitter and the base, it will appear in amplified form between the collecting point and the base.

5.13 (*b*): As the power of an echo when it reaches the receiver is extremely minute, it must be carefully conserved. Leaks of power must be prevented. The receiver crystal should be carefully matched to its transmission line so that none of the power is reflected away and all is absorbed by the crystal. Conversely, between the crystal circuit and the transmission line running to the transmitter there should be the maximum mismatch so that the minimum of the echo power finds its way into the transmitter.

5.21: We must bear in mind that the components in an amplifier have capacity because of their sheer bulk and spacing. These effects are undesirable and yet cannot be entirely avoided. If a condenser or a coil or a resistance is housed in a container that is large, its relation to other components

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may introduce so much capacitance that feed-back or regeneration will occur between stages. Such regeneration may cause oscillations. In audio amplifiers of radio, the oscillations produce "put-put" sounds similar to those of a motorboat engine and the phenomenon has received the name "motorboating".

7.9: Without the D.C. component which is excluded by the coupling condenser, the average signal component will be zero because the positive and the negative swings are equal. If this type of signal is impressed on intensity modulated indicators such as the PPI, the average brightness will remain unchanged. A number of large signals in succession will cause weak signals to fall below the minimum reproducible level. In the amplitude-modulated indicator, such as type A, the base line portion will not run diametrically across the screen but rather its position will depend on the form of the video signal. For the reasons just stated, it is necessary to incorporate into the signal the D.C. component previously removed. By the use of a D.C. restorer, the signals swings can be kept entirely positive.

With a diode connected as in Figure 7 : 5, the diode will conduct whenever the signal is negative. Thereupon, the condenser, C, will charge quickly and the negative maximum voltage will appear across the condenser terminals. In the course of a positive signal swing, the difference in voltage will be impressed in series with the signal. The repetition rate of the signal should be much smaller than the time constant, RC. When the diode is conducting, the time constant is very small because the resistance of the diode will then be very small. Even a tiny negative swing will be sufficient to restore the grid circuit to the zero reference.

7.11 (*a*): In order to conserve weight in airborne radar, it is customary to employ currents derived from potentiometers for indications both in azimuth and in elevation. The rotating element of this potentiometer is connected by gearing, shafting or servo devices to the rotating antenna. The stationary element of the potentiometer is simply a continuous resistance winding on a cylinder. The resistance winding is tapped at diametrically opposite points which are connected to a storage battery as a source of current. The brushes are mounted at opposite ends of an arm pivoted at its center. The deflection coil is connected to the brushes, and as the latter rotate in synchronism with the antenna, the current through the deflection coil is varied from zero (brushes midway between taps) to the maximum (brushes in line with the taps); intermediately, the current is a linear function of the angle formed by the contacts and the taps.

7.11 (*b*): An easy method of obtaining sine and cosine currents is by means of a square resistance card potentiometer with rotating brushes affixed to perpendicular arms. As the brush arms or the card rotates (it is immaterial which, for only relative movement is necessary) in synchronism with the antenna scanner, the voltage in each pair of brushes varies from zero to maximum, sinusoidally. When the brush arms are perpendicular, the voltages in each are sinusoidally in quadrature.

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A disadvantage of such a modulating potentiometer which somewhat offsets its simplicity is its high rate of wear, necessitating relatively frequent replacements; furthermore, brush contacts are inherently noisy. Such noise must be filtered out or suppressed so that no variations will be caused by it in the sweep amplitude.

8.13: It may happen that a synchro-motor is connected to a generator of a different size. *Unit torque gradient* is the torque gradient measured when a synchro-generator and a synchro-motor of the same size are connected together. As a synchro varies in size, so does its internal impedance; the latter determines how much current flows and hence how much torque is produced. Thus, when two synchros of like size are connected, the internal impedances of the stator circuits determine the amount of current flowing and the torque. Hence, the unit torque gradient of a synchro varies inversely as the internal impedance of the stator coils.

10.5: When the intensity of the electric field becomes very high as it does at points raised to a high voltage, the air around the point is ionized and power is lost in the process. If the conductor is a wire and not a point, then as the diameter of the wire is decreased the intensity of the electric field is increased. Should the wire be too fine, ionization will take place along its length and considerable power will be lost in the process. In the dark, corona is visible as a purple glow or luminosity. The shape of the discharge will depend upon the contour of the emitter.

10.7: The lines of electric and magnetic fluxes expand away from the generating antennas. They move outwards with the speed of light. By the expansion of the fields, oscillating electric and magnetic fields are set up. The frequency of such fields is the same as the frequency of the antenna current. The intensity of the fields varies sinusoidally with time. The variations of both fields are in time phase, that is, both fields reach their maxima or minima at the same instant. By the variations of the magnetic field, a voltage gradient is produced (electric field). Similarly, the electric field varies with time. Such a variation is equivalent to a current which is known as a *displacement current* (as distinguished from the ordinary conduction current). Like any other current, it sets up a magnetic field. It can be seen that each field sustains or generates the other and neither can exist by itself.

10.8: Though it is true that the major energy of the radar is in the principal beam, some of the transmitted energy is wasted in the minor lobes. If the only effect of their presence were to lessen efficiency, they could be practically ignored. Unfortunately, each minor lobe must be considered as a beam transmitting energy in another direction (from that of the main beam) on a smaller scale. If, then, an object falls within a minor lobe, its presence will be manifested by the appearance of an echo on the screen. If the receiver gain (amplification) is high, the amount of energy in the lobes may be appreciable. For objects at close range, minor lobes cause multiple echoes to appear. On a PPI screen, the echoes from the minor lobes will appear as

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short arcs equally distant from the center along with the primary echo. When the gain of the radar is very high, the echoes may merge into one, producing a long arc. When several objects appear in the beam, the effects of minor lobes may make the reading of the screen impossibly difficult.

10.16: Electromagnetic energy exhibits the phenomenon of polarization which is well known in optics. In larger waves, as in radar, the direction of propagation of energy, the directions of the electric field and the magnetic field vectors are usually perpendicular to one another. Fields may be circularly polarized when the E and the H (electric and magnetic) vectors at a given point rotate together at a constant amplitude. They are elliptically polarized when they rotate together and change magnitude simultaneously. Usually, waves reflected from the ionosphere are elliptically or circularly polarized.

10.17 (*a*): Variations in the dielectric constants of layers of air cause refraction, and reflections also cause radar echoes. If a radar antenna is pointed directly upward at the zenith, a series of fuzzy echoes is exhibited on the indicator screen. These are undoubtedly due to layers of air having different dielectric properties. For the same reasons, rain, clouds, storms, and pressure fronts can be observed up to fifty miles. By releasing balloons and tracking them by radar, wind velocities at different levels may be checked.

Besides the echoes produced by the foregoing, an odd form of echo known as "angel" has been observed. When a radar antenna is pointed vertically upwards, angel echoes have appeared on the screen in perfectly clear weather for a height of several thousand yards. Though there seems to be no perceptible relations between angels and the weather, it has been observed that they occur most often on summer nights. They have been observed on radars operating at a frequency between one and ten centimeters. These echoes appear to move with the speed of the prevailing winds. After considerable speculation and diverse investigations, the conclusion has been formed that angels are echoes produced by insects in the atmosphere.

Thunderstorms have been noted as far as 250 miles (because of their height, the range is great). For observing rainfall, the A-scope is most suitable; for observing storm clouds, PPI-scopes are more suitable.

10.17 (*b*): Another reason for the transmission of short waves to extraordinary distances is the formation of "ducts" over the earth's surface. The radio frequency waves are confined to a channel whose bottom boundary is the earth's surface and whose upper boundary is a layer of air that may vary from a few feet to a few hundred in depth. Propagation in ducts is restricted to frequencies of 1000 megacycles or more. There is a fairly close relation between the height of the duct and the wave-length. Thus, for a duct 25 feet high, the longest trapped wave-length is 1.8 cm; for a duct of 100 feet, 15 cm. The duct may be considered a kind of wave guide, the top and the bottom of the duct being considered the reflecting surfaces of the wave guide.

Because of the trapping of electromagnetic waves, distances greatly exceeding the limit of the horizon do occur; in fact, distances of several times

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this range have been encountered. Over oceans and other large bodies of water where the air is in immediate contact with water, a condition of saturation with water vapor leads to the presence of ducts. Favorable use of such ducts will arise with low antennas and low targets.

12.8: Very large echo box, several yards on a side, is excited for the purpose of measuring absorption by gas. The rate of decay of the oscillations is then measured. The decay should be caused by losses both in the walls of the echo box and by absorption in the gas. The attenuation is measured with the gas present, and then without. The difference should be the absorption due to the gas.

In measuring absorption caused by rain, a receiver and a transmitter are set up at opposite ends of a short path. Precipitation is measured with a rain gauge. Errors may commonly be caused by lack of uniformity of precipitation so that the larger the number of rain gauges scattered throughout the path, the smaller will be the possible error.

13.22: Mmf (magnetomotive force). Just as in an electrical circuit, the electromotive force produces a flow of current through the resistance of the circuit, so the magnetomotive force produces a magnetic flux through the reluctance of the magnetic circuit. Reluctance corresponds to resistance and magnetic flux to current. The product of the number of turns in a coil and the current flowing through it are the ampere turns which is a measure of the mmf.

14.2: In radar beacons, a radar signal is sent out by ship or plane and the beacons are fired or triggered to send out coded signals. Until this happens, the beacons lie inactive. The coded signal definitely labels or identifies the beacon. The frequency of reception of the signal from the beacon is different from that of the search radar; so the screen is clear when the beacon signal is received. If there is only one radar on board the ship, it cannot be used to receive both beacon and search signals *simultaneously*. Where two or more radars are available, one can be employed for search while the other can be used at the same time for beacon reception. The first dot (nearest to the center of the screen) gives the location of the beacon. The bearing of the beacon is given by the line from the center through the center of the beacon pips.

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