RADAR

A REPORT ON SCIENCE AT WAR

PUBLISHED IN THE UNITED STATES OF AMERICA BY THE GOVERNMENT PRINTING OFFICE

Reprinted by

HIS MAJESTY'S STATIONERY OFFICE, LONDON

1945

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RELEASED BY THE JOINT BOARD ON SCIENTIFIC INFORMATION POLICY FOR OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT · WAR DEPARTMENT NAVY DEPARTMENT

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1. Introduction

THE OFFICIAL derivation of the manufactured word radar is that it comes from the descriptive phrase, "radio detection and ranging." It would be more descriptive to make the phrase "radio direction-finding and ranging," for the direction and the range of objects in its field of view are the two basic qualities radar has to offer. And the big point about radar is that it can see farther than the eye can, even in the best visibility; and radar's ability to see is relatively unaffected by night, fog, smoke, or rain.

Radar, in consequence, has played a great and increasing role right from the beginning of the present war. It has, more than any single development since the airplane, changed the face of warfare; for one of the greatest weapons in any war is surprise, and surprise is usually achieved by concealment in the last minutes or hours before an attack. The concealment formerly afforded by darkness or fog or cloud or artificial smoke or the glare of the sun simply does not exist in the world of radar. The tactical thinking of an attacker or a defender must take this fact into account.

Radar is the basis of the defense against aircraft attack. This was, historically, its first active role, and it is still an important one, although fortunately now more important to the Japanese than to us. In the decade of 1930 to 1940, aircraft were beginning to travel with speeds only a half or a third less than the velocity of sound itself, so that the degree of warning which could be achieved by a listening watch was quite inadequate. A high-flying airplane is difficult enough to see visually even under the best conditions; and to find its range by the optical means that were the only ones then at our disposal was always hard and sometimes impossible. The accuracy of antiaircraft fire suffered accordingly, and it appeared that a successful defense against hostile aircraft by fighters would demand constant patrolling aloft and plain dumb-luck. Radar has made possible the timely alerting of all defenses, the "scrambling" of fighters and their coaching to a meeting with the incoming raid; and has provided a means for the aiming of antiaircraft guns at an unseen target with somewhat greater precision than used to characterize fire at seen targets when visual sighting was relied on. It can do all these things for the enemy, also, and to some extent now does. But right through the war our radar has been superior to the enemy's. It still is.

Another thing that radar can do and has done is to add a new dimension to sea warfare. It used to be that naval battles were decided by the factor of who happened to be "up-sun" from the enemy. Now our ships slug through whole engagements in which the enemy may be detected, ranged on, and sunk without a single man having seen him visually. During such a battle, our ships may be travelling in rigorously kept formation at high speed through narrow waters, but they "see" one another, and the shore, by radar.

Before radar, either of two things could bog down the strategic bombing forces which have been one of our major weapons right through this war. The first was weather at home fields so bad that the planes could not take off or land. The second was cloudy or partly cloudy weather over the target, when the chance of a visual bombing run was too small to justify committing the air force. Base weather, which radar is now helping our planes to defeat, limited operations far less often than target weather did. Now our bombers go out with radar which " reports " the ground beneath and all around in a faithful and convenient way, emphasizing such features as shore-lines, cities, mountains, lakes, and rivers. Not only can they navigate unerringly to the target area; they can, if target weather precludes a visual bomb run, line up on the target and bomb by radar alone.

It will be clear that the word radar refers to no single instrument. Indeed, an individual radar set may be a hundred-pound outfit, the size and shape of a small bomb, for installation in a fast airplane; or it may be a sprawling complex of shacks and trucks with its own telephone central, with a giant antenna structure, and with a whole company of soldiers to man it. It may be 5 tons of equipment disposed here and there as in a fast carrier, or it may be a couple of water-tight boxes on deck and a modest bulge on the mast of a PT boat. Despite the great physical diversity of the forms in which radar is used and embodied, a common set of principles is back of every radar, and once these principles are recognized radar is understood.

2. How Radar Works

In radar, unlike communications, the transmitter and the receiver are located at the same place, and more often than not have a common antenna. The transmitter is actually sending out energy only a very small part of the time; it sends out this energy in very intense bursts of small duration, called pulses. These pulses may be only a millionth of a second long. After each pulse, the transmitter waits a relatively long time—a few thousandths of a second—before sending out the next pulse. During the interval between pulses, the receiver is working and the signals it receives are the echoes of the powerful transmitted pulse from nearby objects. The nearest objects will give echoes coming very soon after the transmitter pulse is finished; those farther away give later returns. The elapsed time between the transmission of the pulse and the reception of its echo measures the distance of the object giving that echo—ship, airplane, mountain or building—from the place where the radar set is located. This is possible because the elapsed time is just that required for the pulse, which travels with the speed of light, to get there and back. Light travels very fast, as everybody knows, hence these intervals are very small. Their exact measurement is one of the technical triumphs of modern radar. Since light goes 186,000 miles a second, or 328 yards each millionth of a second, and since it must travel twice—out and back—the distance from radar to target, an object 1,000 yards from the radar will give an echo only six millionths of a second later than the transmitted pulse. This is a rather short time, by prewar standards, but we have learned how to measure time like this with an accuracy which corresponds to only 5 or 10 yards range, or about one-thirtieth of a millionth of a second.

The use of pulses, as we have seen, gives a simple means of measuring range. How, then, is the direction in which a target lies determined? This is done by providing the radar with a directional antenna, which sends out the pulses in a narrow beam, like a searchlight. This antenna may be rotated as the pulses are sent out, and we get back a " pip " (radar slang for a target indication) when the antenna is pointed toward its target. We get the strongest pip when the beam of energy sent out by the radar is pointed directly at the target. The bearing of the antenna—which is also the bearing of the target—may then be read off and used to point a warship's guns, or set the course of a bomber, or direct a fighter to intercept an enemy plane, or for other use the particular purpose of the equipment dictates.

An even more spectacular indication of the direction and range of the target is obtained with the use of the PPI—Plan Position Indicator. In this case, the radar echoes are caused to draw a map on the face of a cathode ray tube. The radar operator could imagine himself suspended high above the set, whether on a ship or plane or on the ground, looking down on the scene spread out below. No matter how many targets surround the radar set, each is indicated by a blob of light on the tube face—the direction of the blob from the center indicating the target's range. The whole picture is there. It is not like television; the blobs do not actually look like ships or planes, but are interpretable to a trained operator.

Still other ways of displaying radar echoes are used. On a battleship, for example, where exact range is desired to lay the 16-inch guns, the radar echoes are so displayed that the operator can read a range scale down to a few yards. In the case of Army antiaircraft fire, the radar antenna actually moves automatically so that it always points at the plane without help from an operator, and the guns follow automatically by remote control. Other types of radar use other types of displays, designed to perform one or another special purpose.

What we may call the sharpness of vision of a radar set—its ability to distinguish separately the echoes from two targets close together and at the same distance from the radar—depends on the sharpness of the radar beam. With an antenna of given size, the beam will become sharper and sharper as the wave length decreases. In fact, for a given antenna size, the beam width is just proportional to the wave length. The earliest radar worked on wave lengths of several meters, with correspondingly broad beams, unless large antennas were used. Then there was a great flowering of equipment working near a meter and a half, which was, at the beginning of the war, about the shortest wave length at which radio techniques had been worked out. The war-time period of development has witnessed an intensive exploitation of shorter and shorter wave lengths.

3. Early History of Radar

SUCCESSFUL radio detection devices, operating on the principles set forth in the previous chapter, were developed independently in America, England, France and Germany during the 1930's. Back of this discovery lay half a century of radio development, plus a handful of early suggestions that because very short radio waves are known to be reflected, they could be used to detect obstacles in fog or darkness. Back of it, but less remotely, lay the technique of pulse ranging, which made successful radio detection a reality.

The fact that radio waves have optical properties—the properties usually associated with visible light—was conclusively demonstrated as long ago as 1886 in the famous experiments of Heinrich Hertz, the discoverer of radio waves. Hertz showed among other things that radio waves were reflected from solid objects. In 1904 a German engineer was granted a patent in several countries on a proposed way of using this property in an obstacle detector and navigational aid for ships. In June, 1922, Marconi strongly urged the use of short waves for radio detection.

The beginning of interest in radio detection as a military device can be dated from communications experiments carried on by two civilian scientists working for the United States Navy, Dr. A. Hoyt Taylor, now Chief Consultant and Chief Coordinator of Electronics at the Naval Research Laboratory, and Leo C. Young, still an associate of Taylor's. In the autumn of 1922 they observed a distortion or " phase shift " in the received signals due to the reflection from a small wooden steamer on the Potomac. These results were embodied in a suggestion to the Navy Department that " destroyers located on a line a number of miles apart could be immediately aware of the passage of an enemy vessel between any two destroyers of the line, irrespective of fog, darkness or smoke screen."

In the summer of 1930, the same men in experimenting with radio direction-finding equipment, made the important observation that reflections of radio waves from an airplane could be similarly detected. As a result, in November, 1930, the Director of the Naval Research Laboratory submitted to the Navy Department a detailed report on Radio-Echo Signals from Moving Objects. Since by 1930 the threat of airpower had begun to assume serious proportions and any means of early detection of enemy aircraft had vast possibilities, the Bureau of Engineering ordered the laboratory to " investigate the use of radio to detect the presence of enemy vessels and aircraft." The method, which has been variously described as the " beat method " or the " Doppler method," used ordinary continuous radio waves and required at least two widely separated and comparatively bulky stations, one for transmitting and the other for receiving. It detected the presence of moving objects like aircraft by the interference of the main ground wave with the wave reflected from the aircraft when both arrived simultaneously at the receiver—one wave having traveled by the direct route along the ground and the other by a longer path from the transmitter to the plane and then to the receiver.

Army officers were shown the Navy equipment in 1930, and in January, 1932, the Secretary of the Navy officially suggested to the Secretary of War that it might be better adapted to Army than to Navy use, since such a system could hardly be installed on shipboard. However, the Army carried on development along other lines which brought about a complete mobile detector at a single site.

The United States Army had been working intermittently since 1918 on various sorts of heat detectors for the location of aircraft. In 1930 the responsibility for this development was transferred from the Ordnance Department to the Signal Corps laboratories which had just been placed under the direction of Lt. Col. (now Col., retired) William R. Blair. While heading the Research and Engineering Division, Office of the Chief Signal Officer, from 1926 to 1930, Colonel Blair had urged the use of infrared or radio waves to replace the Army's sound locator. In his new post Colonel Blair immediately instituted projects for aircraft and ship detection, continuing the work on infrared detection and undertaking experiments on radio detection using microwaves a few centimeters in length.

Experiments with microwaves at the Signal Corps laboratories did produce echoes from nearby targets. Until the advent of the modern cavity magnetron, however, it was not possible to generate microwaves with sufficient power for practical use. More successful results were obtained by the Signal Corps with detectors which picked up the heat radiated by airplane engines and by ships; there were numerous instances of successful tracking by airplanes, Navy blimps, and ocean liners entering and leaving New York Harbor by means of these detectors. In his annual report to the Chief Signal Officer in July 1934, Colonel Blair stated that with the radio method " a new approach to the problem is essential."

The Naval Research Laboratory informed the Signal Corps of its development, and thereafter there was a complete exchange of information between the services.

The principle of pulse ranging which characterizes modern radar was first used in 1925 by Dr. Gregory Breit and Dr. Merle A. Tuve of the Carnegie Institution of Washington for measuring the distance to the ionosphere, which is the radio reflecting layer near the top of the earth's atmosphere. The technique consisted of sending skyward a train of very short pulses, a small fraction of a second in length, and measuring the time it took the reflected pulse to return to earth. After the experiments, in which the Naval Research Laboratory participated, pulse ranging became the established method for ionospheric investigation in all countries.

Radar was born when it occurred to different persons independently and in different parts of the world that the pulse technique could be used to detect objects such as aircraft and ships. This idea seems to have occurred almost simultaneously in America, England, France, Germany, and perhaps also in Japan. Scientists in these countries worked secretly on problems of increased power output, shorter pulses, directional antenna systems, and many other practical aspects of the problem.

At the Naval Research Laboratory late in 1933 Mr. Young, who had taken part in the Breit-Tuve ionosphere experiments, proposed that this principle be applied to the still unsolved problem of getting the transmitter and receiver in the same ship. Robert M. Page was assigned by the Radio Division to this new project in January 1934, and during the next few years materially assisted in solving in quick succession the difficult problems of generating pulses of the proper length and shape, of building a receiver which would not be blocked by the transmitter pulses and therefore would pick up those extremely short pulses after they are reflected, and of designing cathode ray tube displays for the receiving pulses. The Naval Research Laboratory during this period was developing a highly important radar " duplexer " which permitted the use of a common radar antenna for both transmitting and receiving.

In 1935, on the urging of Rear Admiral H. G. Bowen, then Chief of the Bureau of Engineering, the Naval Appropriations Committee of the House of Representatives allotted $100,000 for research purposes to the Naval Research Laboratory—the first funds for the specific development of radar. The Committee later made inspection trips to the Naval Research Laboratory and continued to give financial support to its work.

In June 1936 representatives of the Bureau of Engineering witnessed demonstrations of aircraft detection at the Naval Research Laboratory and Rear Admiral Bowen directed that plans be made for the installation of a complete set of radar equipment, as it then existed, aboard ship. The relative handful of scientists at the Naval Research Laboratory were given a tremendous impetus in February 1937 when Charles Edison, then Assistant Secretary of the Navy, and Admiral (now Fleet Admiral) William D. Leahy, then Chief of Naval Operations, visited the Laboratory, witnessed a demonstration of radar and thereafter gave the project their wholehearted support. In April 1937, radar worked over salt water at the mouth of the Chesapeake on the old four-stack destroyer *Leary*.

The next 2 years were spent in designing a practical shipboard model. After much experimentation and many improvements, a radar set, built at the Naval Research Laboratory and operating on a wave length of a meter and a half was installed on the U. S. S. *New York* in December 1938. Early in 1939 it was given exhaustive tests at sea during battle manoeuvers. The commanding officer of the *New York* and the commander of the Battleship Division were both enthusiastic and gave their full support to the continuation of the work. It was at this point that the resources of American industry were officially called upon. The first contract was awarded in October 1939 to a commercial company for the manufacture of six sets of aircraft detection equipment.

The Army's first pulse radar was designed as a complete system at the Signal Corps Laboratories early in 1936, slightly anticipating a War Department directive to the chief signal officer on 29 February 1936 that the highest priority be given to the development of a detector for the use of antiaircraft batteries. By the end of 1936, echoes had been seen from radio pulses directed at commercial planes flying on a regular airway in New Jersey. By May 1937, a successful demonstration against test bombers was carried out at Fort Monmouth in the presence of the Secretary of War and members of Congress. The equipment not only detected the aircraft but passed on information about their direction, elevation and range so that searchlights were pointing at precisely the right point when the aircraft came within range. This demonstration resulted in the first substantial allocation of the Army funds specifically for radar development.

This was followed by the establishment of the Radio Position Finding Section of the Signal Corps Laboratories. This enlarged section went to work in a special guarded area at Fort Hancock, on Sandy Hook, overlooking the approaches to New York Harbor. The section was led by the late Paul Watson, and its work was directed by Col. (now Maj. Gen.) Roger B. Colton, then director of the Signal Corps Laboratories and now on duty with the Army Air Forces. Many developments by this group—the improvement of transmitting tubes so that the wave length could be reduced to 1½ meters, the introduction of a precise direction-finding technique called lobe-switching, and the refinement of pulsing devices, transmitters, and receivers—led to an antiaircraft detector for searchlight control and gun laying.

In November 1938 this equipment was given extensive tests by the Coast Artillery Board at Fort Monroe, Va. During these tests, in addition to locating planes for ground batteries, radar showed new possibilities. The set detected antiaircraft shells in flight, and also guided back to a safe landing an Army bomber which had been blown out to sea on its test mission as a radar target. Eighteen pre-production models were built in 1940 and 1941 by the Signal Corps Laboratories in order to get equipment in the hands of troops for training, while commercial quantity manufacture was getting under way.

In May 1937, Brig. Gen. (now General of the Army) H. H. Arnold, then deputy chief of the Air Corps, witnessed the demonstration of the short-range pulse detector developed by the Signal Corps Laboratories. A few weeks later the Air Corps formally asked the Chief Signal Officer to undertake development of a " long range detector and tracker." A radically improved form of transmitter tube was developed and a complete set demonstrated to the Secretary of War in November 1939, showed a range of more than 100 miles against bombers. As a result the long-range set was adopted as a standard item of Army procurement in May 1940. In August, the Signal Corps let a contract for quantity production of this equipment for use by the Air Corps.

From this beginning the Army Air Forces have come to be the largest service user of radar. Requirements set up by strategic and tactical air commanders in all theaters of operation, coordinated with tests of prototype equipment by the Air Technical Service Command and the Proving Ground Command, have resulted in the development of many new radar devices by the scientific laboratories.

Among the United States military applications of radar which the AAF pioneered in combat with land-based aircraft are: Early warning, low-altitude and high-altitude bombardment, short-range air navigation, short-range weather forecasting, and the technical coordination of air-ground operations.

During the early days of radar research and development carried on within the services, the cooperation of industry was exceptional. Research was carried on at industrial laboratories at the suggestion of the services, often without cost to the Government. Additionally, initial production of radar equipment was undertaken willingly by industry, even though such production necessitated entirely new methods and techniques. Much could be told with respect to industrial cooperation from the earliest days of radar to the present day.

Much of this cooperation was obtained through the efforts of Rear Admiral Bowen, and in recognition of this, Rear Admiral Bowen was recently cited by the Secretary of the Navy for " convincingly presenting this new weapon of war to commercial concerns qualified to produce it " and for " contributing in great measure to the expansion of facilities for manufacturing this type of equipment in the large volume necessitated by the outbreak of war."

British radar was developed at about the same time as the American systems but at a somewhat faster pace under the immediate threat to Britain's security. During the winter of 1934-35, the Air Ministry set up a Committee for the Scientific Survey of Air Defense, with Sir Henry Tizard as chairman. Among the suggestions it received was a carefully worked out plan for the detection of aircraft by a pulse method similar to that developed by Breit and Tuve for measuring the height of the ionosphere. This was submitted by a Scottish scientist, now Sir Robert Watson-Watt, then at the head of the National Physical Laboratory Radio Department. The first experimental system was set up in the late spring of 1935 on a small island off the east coast. Development during the summer led to the blocking out of the main features of the British Home Chain of early warning stations by fall. Work began in 1936 toward setting up five stations, about 25 miles apart, to protect the Thames estuary. By March 1938, all these stations—the nucleus of the great final chain—were complete and operating under RAF personnel.

The emphasis in British radar development then shifted to airborne equipment. Two types were envisaged: A set for detection of surface vessels (called ASV) and an equipment for detection of aircraft from nightfighters (called AI). Work was concentrated on ASV first; an experimental system successfully demonstrated during fleet maneuvers in September 1938.

By June 1939, experimental AI equipment was working; it was demonstrated to the chief of the RAF Fighter Command about August 1, 1939. The Air Ministry asked that 30 such systems be installed in airplanes within the next 30 days. Before the end of September all these systems had been installed, 4 having been ready on the day war broke out.

This emphasis upon airborne radar led to the observation that if sharp radar beams were ever to be produced by an antenna not too large to carry in an airplane, wave lengths shorter than the meter-and-a-half used in the early British airborne equipment would have to be employed. At 1.5 meters, conventional radio transmitting tubes were adequate to give the required pulse power, but no generator of waves much shorter was known, which gave more than about one one-hundredth the power required. Accordingly the problem of developing a generator of microwaves was given to a research group at the University of Birmingham, sponsored by the Admiralty. With the cooperation of British industry, the Birmingham group developed a practical form of the cavity magnetron. This, along with other developments, open the possibility of obtaining satisfactory power output at extremely short wave lengths, leading to the enormous widening of the powers of radar which took place after 1940.

4. Wartime Radar Development in the United States

THE TREMENDOUS expansion of American defense activities in 1940 brought about a new phase in radar. The development up to that time was remarkable for the way in which separate groups working in different countries in comparative isolation produced similar results. After 1940, development was a shared responsibility and a common achievement of service laboratories, industrial laboratories, and civilian government-sponsored laboratories in the United States and Britain.

It is perhaps symbolic that the era of mutual effort coincided with the adoption of a common name for the new means of detection. The British had called it " radiolocation " and RDF. The United States Army Signal Corps had used the term RPF (radio position finding). The Navy coined the word " radar " as an abbreviation for radio detection and ranging—and this convenient term was soon adopted by common consent in the United States and subsequently, in 1943, was officially adopted by the British.

An important step in unifying research and development activities on radar in the United States and in breaking the ground for entirely new techniques was the establishment on 27 June 1940 by a presidential Executive order, of an independent agency called the National Defense Research Committee to " correlate and support scientific research on the mechanisms and devices of warfare."

The Army and Navy were thus able to turn over to scientists mobilized by this committee a large number of problems of a long-range and somewhat speculative nature certain to involve considerable fundamental research. This research was accomplished through contracts with universities, nonprofit research institutions or commercial concerns. The NDRC set up no laboratories of its own and encouraged the fullest decentralization of effort. This structure was not basically altered when, a year later, the NDRC was made part of a new larger independent organization—the Office of Scientific Research and Development, headed by Dr. Vannevar Bush.

A Microwave Committee, headed by Dr. Alfred L. Loomis, was set up in July 1940 to explore the possibility of using microwaves in radio detection, a problem that appeared speculative in the extreme, since no good source of power at these wavelengths was known.

The efforts of American and British laboratories were combined as a result of an agreement between the two governments in 1940 for an exchange of scientific information of a military nature. A British Technical Mission, headed by Sir Henry Tizard, arrived in Washington in September 1940 and mutual disclosures were made of British and American accomplishments in radar up to that time. Members of the mission, with full War and Navy Department authorization, visited the Naval Research Laboratory and the Army Signal Corps Laboratories at Fort Monmouth and the Aircraft Radio Laboratory at Wright Field, as well as manufacturing establishments which were engaged in radar work. They demonstrated the cavity magnetron to American scientists and the United States equivalents were soon made.

On October 12, members of the British Mission discussed with the Microwave Committee two specific projects which they suggested that the United States undertake: A microwave aircraft interception (AI) equipment, and a microwave position finder for antiaircraft fire control.

These suggestions found favor with the Microwave Committee, and it was decided to set up a microwave laboratory staffed by physicists from a number of universities. After several possibilities had been canvassed, the Massachusetts Institute of Technology was prevailed upon to accept the responsibility of administering the laboratory under an NDRC contract. This new Radiation Laboratory, headed by Dr. Lee A. DuBridge, opened its doors in Cambridge, Mass., early in November 1940. The Radiation Laboratory's accomplishments and contributions have been a major factor in the rapid advance in radar techniques in this country.

The era of cooperation had now begun. Contracts to help develop components of the proposed AI equipment had been let by NDRC to several manufacturers. Another contract was made to provide model shop facilities for the improvement, under Radiation Laboratory direction, of the British magnetron. Hangar facilities under military guard were provided at the East Boston Municipal Airport, and both the Army and the Navy contributed aircraft for experimental purposes. Both services assigned permanent liaison officers to the Radiation Laboratory.

Meanwhile, in their own development laboratories, the Army and Navy concentrated on the urgent engineering problems involved in getting equipment out immediately for use in the field and with the fleet. By the time of the Japanese attack on Pearl Harbor the Navy had already installed on key ships not only radar for air warning, but also medium wave radar for surface search and fire control, while the Army had deployed in the field numbers of long-range aircraft warning sets, as well as antiaircraft gun and searchlight batteries equipped with radar. Navy installation of equipment on more and more ships, and Army training of additional Signal Aircraft Warning Battalions and antiaircraft batteries were proceeding at full speed by the end of 1941.

During that year, by contrast, not a single item of equipment based on the new microwave development was delivered for operational use. However, the research was already showing great promise for the future. A summary of important dates may indicate the early nature of this research. In January 1941 the Radiation Laboratory obtained echoes from its first microwave radar set. On March 10, in a B-18 airplane supplied by the Air Corps as a flying laboratory, there took place a successful flight test of a working "breadboard model" of microwave airborne equipment. In this flight it was discovered that this equipment was extremely effective in searching for ships or submarines at sea. By the end of the year the Army and Navy had both expressed interest in a microwave ASV development and a British Liberator had been equipped with a prototype for demonstration to the British Coastal Command. Before the end of May an experimental prototype of microwave AI appeared to the Air Corps to be so promising that it was turned over to one of the large industrial concerns to be engineered for production.

In the late spring of 1941 an experimental microwave sea-search radar equipped with a PPI was installed on the venerable destroyer *Semmes*. This radar was operating by May 14. Later that same months there was recorded the wholly automatic tracking of a target plane, accomplished by a prototype of the microwave antiaircraft position-finder.

On June 30, the Navy let its first production contract for microwave equipment based on the work of the Radiation Laboratory. This was for a production version of the equipment that had been demonstrated on the *Semmes*.

During November, the NDRC set up a model-shop facility to build small numbers of laboratory-designed equipment, in advance of large-scale production by established manufacturers. This organization undertook its first full-scale job on 15 December 1941 when representatives of the Signal Corps and of the Coast Artillery asked for the construction of 50 sets for harbor defense, similar to a laboratory prototype which, at the outbreak of the war, was operating experimentally at the Harbor Entrance Control Post in Boston. There was now under way a tremendous cooperative program of microwave development in which the Radiation Laboratory, the Armed Forces and the great electronic concerns all played an indispensable role. By 1943, the new microwave equipment was in production on a large scale and was beginning to have a significant role in maintaining the Allied margin of radar superiority over our enemies. At the present time the great bulk of radar equipment in use by the Allies is based on the microwave techniques which only seemed a speculative possibility at the beginning of the war.

The tremendous expansion of the radar development program may be measured by the fact that the personnel of the Radiation Laboratory increased in early 1941 to almost 4,000. Similarly the Radar Section of the Naval Research Laboratory increased its personnel to 600. The Radio Position Finding Section of the Signal Corps Laboratories grew into the separate Evans Signal Laboratory at Belmar, N.J., with a peak personnel of more than 3,000, part of which in turn became a nucleus for the Army Air Forces Watson Laboratories at Eatontown, N.J. A similar growth took place at the Aircraft Radio Laboratory at Wright Field. So intimately did airborne radar become involved in the design of military aircraft that this activity was taken over in 1944 by the Air Technical Service Command from the Signal Corps.

A tremendous amount of work has been carried out by the research and engineering staffs of many industrial concerns both large and small. In some cases, these firms, working either independently or on development and production contracts from the armed forces or NDRC agencies, have engineered certain types of radar sets all the way through from the basic idea to the finished product.

To a large extent, particularly in the microwave field, industry's great achievement has been to take the "bread-board" or prototype models produced in government scientific laboratories and make the design suitable for quantity manufacture and rugged service under combat conditions. The art has advanced so rapidly that the manufacturers have often been called upon to make major changes during the course of production to incorporate new lessons from both the laboratories and the battlefields. Field engineers from the factories have gone right out to the combat zone with their equipment to check on its performance and cooperate with the armed forces in maintenance and repair problems.

Army and Navy radar requirements were coordinated to the point where many sets and nearly all component parts were made interchangeable between them. The original Navy and Signal Corps nomenclature systems were superseded for new equipment by a joint "AN" (Army-Navy) system in which all sets or components developed for either service were given the same nomenclature in the supply catalogues of both.

Meanwhile, the radio and electronic manufacturing companies greatly expanded their facilities for development and production of radar equipment. Through the cooperation of the Radio and Radar Division of the War Production Board, many manufacturers of entirely unrelated items were converted to the production of radar components. So close has been the cooperation in development that it is often difficult to say whether a given set was essentially the work of one of the major electrical companies, or of the Army, the Navy, or an NDRC contractor.

The growth of this new industry, which hardly existed before 1940, is indicated by the fact that by 1 July 1945 approximately $2,700,000,000 of radar equipment had been delivered to the Army and Navy. This included approximately $1,000,000,000 worth of airborne equipment, $500,000,000 worth of shipborne equipment, $800,000,000 of ground equipment and $400,000,000 worth of miscellaneous radar. The scientific pioneering, engineering skill and plain hard work that these figures represent has been paid for over and over, as the following chapters will tell, by the accomplishments of radar in giving new eyes to our forces on land, sea and air.

5. Radar and Air Defense—The Problem on Land

THE ASSAULTS on England by the *Luftwaffe*, which the British had anticipated for so long, began on 8 August 1940, and rapidly increased in intensity. The first raids were directed at RAF bases, but by 7 September the mass raids on London had begun. England's defensive radar chain, begun 4 years before, was to have its first great test. Strangely, as it seemed to the British, the Germans did not try to destroy the stations by determined attack, although the great masts which marked each radar site afforded an unmistakable target. Neither did the Germans try to evade the coverage of that early radar by approaching as low as possible, which would have made the job of long-range detection much more difficult.

What happened, and why, is now well known. Despite a critical shortage of fighter planes and pilots, the British were able to spot each incoming raid in time to throw fighters against it. The necessity for constant airborne patrols of fighters was removed by the use of radar, and the few to whom so many owed so much were thrown into battle economically and with maximum effort. During that August, the average losses of the *Luftwaffe* in raids over England was 15 percent; the total loss was 957 aircraft. In the great battles of 15 September, said by some to mark the turning point, the Nazis lost 185 aircraft out of 500 which attacked. By the beginning of November, German tactics had changed, and the day raids were replaced by night attacks.

These night attacks increasingly put the reliance of the defender on radar. Not only was visual spotting more difficult, but the defending fighters encountered such poor visibility that the aircraft interception (AI) radar which had been developed with such foresight during the preceding 2 years had a major role in leading the fighters to their targets. A whole new technique of aircraft control was rapidly built up called GCI—for ground controlled interception.

During the day raids it had been sufficient to bring the fighters into the general vicinity of the incoming bomber stream, and rely on each pilot's vision and judgment for choosing targets, making interceptions, and pressing home his attack. At night this was no longer possible. Instead, a controller on the ground, watching the air situation on the PPI of a special radar set, chose a specific Nazi airplane as a target, gave detailed course instructions (called " vectors ") to the fighter under his control, and skilfully maneuvered the fighter to a position 1 to 3 miles behind the target, just below, and on the same course. When this had been done, the fighter was instructed to " flash his weapon," and the AI radar in the plane took over. This was operated by a special radar operator, who had no other duties, and the pilot was still a chauffeur obeying instructions, right up to the moment when he was close enough to his enemy to see the dim blur of the Nazi plane against the night sky. From this time on, the pilot completed the attack.

Needless to say, this complicated technique demanded teamwork of a very high order between ground controller and pilot, and between radar operator and pilot. And it demanded virtuosity of a very high order and a very special type on the part of the ground controller. Not everyone could be a controller, or a night-fighter pilot, or an AI operator, but many were found who did the job well, and some did it superlatively well. It was not unknown for a single controller, in a single night, to coach his fighters into the destruction of as many as six Nazi planes.

Two other technical devices, beside the early warning and GCI and AI radar, were required to make this complicated defense system the success it was. These were a communications system of the utmost reliability and ease of operation, to permit the controller to fly the fighter by telephone instructions; and an identification system for friendly planes, to make sure that the controller could tell which of the " blips " on his radar scope (" blip ": RAF slang for radar signals) belonged to the hostile planes, and which to friendly aircraft. In particular, the controller needed to know which " blip " was that of the fighter he was controlling.

In their foresight, which seems phenomenal now, the British had also provided these devices.

A communications system called VHF (very high frequency), which operated on a shorter wave length than any operational radio telephone had before, was ready for the Battle of Britain. It was free from static, highly reliable, and it played as big a part in winning the Battle of Britain as all the radar put together. All of the Allies, and the enemy as well, are now using VHF.

The British had an electronic gadget for identification, which they called IFF (identification of friend and foe). This was the electronic analogue of the painted insignia on a fighter plane; instead of making its signal to human vision, it made it to the radar. It had a special sign that a night fighter could use, on request from his controller, to identify himself individually. Today a vastly improved IFF, developed within the various laboratories of the United Nations, is used not only on aircraft, but on every combat ship in the Allied Navies. It has revolutionized the nature of sea warfare to be able to tell whether an approaching ship is friend or foe.

The great success of the complicated technical war fought by the RAF in the Battle of Britain had two effects, one good and one bad. The good one, which outweighs the bad entirely, is that it turned the *Luftwaffe* back and saved the island. The bad one is that the very success of the highly organized and undeniably cumbersome mechanism of radar and communications and airplanes and control centers which was the RAF Fighter Command in 1940 and 1941 tended to freeze the thinking about radar along the lines of static defense against air attack.

This enabled radar's detractors to say that we didn't need it, for we were going to fight an offensive war. What they meant was that we didn't need a complicated static system of radar defense, which was largely true. Even more harmful was the fact that it caused radar's friends to overlook, to a very large extent, what was found out empirically a good deal later: Radar is a superlative weapon of offense.

The record shows that even by January 1943 there had not been delivered from production any type of radar meant primarily for attack, with the exception of a few sets for control of main battery fire of ships, and some ASV sets which, as we shall see, were largely meant for antisubmarine work. The bulk of the Army's delivered equipment consisted of heavy long-range air warning sets, and searchlight control sets, resulting from early work of the Signal Corps.

While the *Luftwaffe* was being beaten back with the aid of British radar, and while the United States was still at peace, the U.S. AAF Fighter Commands were rushing the completion of the Aircraft Warning Service, using Signal Corps equipment and personnel for the radar phase of the operation, along the Atlantic and Pacific coasts and at vital bases overseas. The problem confronting the American air defense authorities was on a far greater scale than that solved in the compact area of Britain because of the enormous territory that had to be covered.

Emphasis was placed on getting the greatest possible range out of our aircraft detectors. For example, a radar with an effective range of 100 miles could cover twice the length of coastline and four times the area in square miles covered by a radar good only to 50 miles, besides allowing more time for interceptor planes to make contact with the enemy.

With the two ocean Navy still on the ways, the most urgent problem confronting the United States in the defense period was the protection of the Panama Canal. A new kind of military unit, the First Signal Company Aircraft Warning (Panama), proceeded to the Canal Zone in the spring of 1940. On 7 October, the first of the long-range sets, overlooking the Caribbean, went on the air, thus marking the beginning of the aircraft warning watch by American radar in protection of national security, as distinguished from the numerous laboratory and field tests of the preceding years. On its second day of operation, the detector picked up a commercial airliner from Miami at a range of 118 miles.

During the ensuing year production and installation were carried out at a maximum possible pace. Two kinds of long-range sets were produced: Fixed stations, their antenna arrays mounted on high permanent towers, and semimobile sets mounted on trailers for use in areas where roads were available.

The long-range detectors were shipped out on high priority to Air Force units at strategic spots along the Atlantic and Pacific coasts, in Alaska, at bases in the Atlantic and Caribbean acquired from the British in the exchange for American destroyers, in the Hawaiian Islands and the Philippines. Since the sites were selected for the widest radar coverage rather than for convenience, the task of installation was a formidable one, involving unremitting labors in all kinds of weather, in climates ranging from the tropics to the sub-arctic.

Commanders of overseas departments and continental air defense commanders, who were responsible for the installation and operation of the detectors, were assisted by special teams of officers and civilian technicians sent out by Signal Corps Laboratories.

Immediately after the outbreak of the war the result was that the radar program, already proceeding at the maximum pace possible with available defense funds, now expanded explosively, with practically all ceilings removed on the allotments for production and training.

The production problem was critical. Manufacturers new to the field had to be educated in radar techniques. Many of the needed high quality electrical materials were scarce, and skilled labor had to be trained. Special committees representing the Army, the Navy, and the War Production Board, balancing the capabilities of the radio industry against the urgent needs for radar in its different tactical and strategic roles, worked out priority and precedence lists to prevent the production of one kind of radar from being expedited at the expense of some other type which might be of more urgent importance to the plans of the Combined Chiefs of Staff.

Probably the most significant decision of all was to concentrate the bulk of the production effort on offensive rather than defensive equipment. This meant, for example, giving priority to naval radar equipment and to airborne radar, and in the case of ground equipment, shifting the emphasis to mobile sets that could be shipped overseas and be rapidly put in operation.

To make way for these offensive applications, the production of fixed station long range detectors was held to the minimum essential for the security of especially vulnerable points. Here the volunteer aircraft spotters and information center operators recruited for the Air Defense Wings by civilian defense organizations made a definite contribution toward winning the war in spite of the fact that the sirens in our cities never were called upon to scream their warning of a real air attack. The fact that the visual observers were on duty made it possible for the armed forces to concentrate the radar production effort on equipment for overseas attack rather than yielding to the play-it-safe procedure of spotting detectors all over the length and breadth of the United States.

We started to learn about ground radar in combat in the Pacific and learned more in the invasion of North Africa at the end of 1942. What we learned was that defense of ports and vital areas against night attack by aircraft was essential on the very first night after we moved into a place. The German raids during November and December emphasized the need for portable equipment which could be put in operation immediately. The German losses averaged about 20 percent during December, when the radar system was working, and the scale and effectiveness of the raids dropped off, demonstrating the value of a coordinated radar air defense in the field.

During early 1943, the bulk of the attackers came in very low, attempting to get under the coverage of the long-wave radar that the Allies were relying on; five new American-built microwave sets were valuable in supplying coverage against such low planes. This was the first proof that microwave equipment has a place in air warning, supplementing the original Signal Corps long-wave radar, improved versions of which, however, still play a part in safeguarding Okinawa. All these lessons have been implemented long since, in our equipment and our planning. Our island-by-island advance in the Pacific, which thrust advance airfields out among Jap-held bases, has emphasized the desirability of a promptly-set-up radar defense, and it is fair to say that we do pretty well at it.

There is another department of defense against air attack in which radar has played an enormous role. This is antiaircraft artillery. Modern aircraft fly so fast, and modern antiaircraft guns shoot so far, that the range at which it is desirable to pick up a target and commence to track its position accurately is often greater than the range at which a single airplane is visible on a clear day. This, and the night attacks, suggest the use of radar to point antiaircraft guns, and so does the fact that target range, which must be known with extreme accuracy for good control of fire, is so hard to measure with an optical range finder.

Recognition of the antiaircraft fire problem led the early radar workers of the Signal Corps to turn their earliest efforts toward a set which would permit effective ground gunfire against night-flying aircraft. At the time this research began, and until radar became operational, the standard equipment of Army antiaircraft batteries included sound locators, searchlights, optical range finders, and tracking telescopes. The system for repelling night air attacks was as complicated as it was inaccurate. First of all, an airplane was detected by gathering the arriving noise in listening horns which were turned toward the source. Of course, this information was always obsolete since the airplane had moved along while the noise was traveling toward the detector. Nevertheless, the data from the sound locator assisted in scanning the proper region of the sky with a searchlight. If the airplane was illuminated —which did not always happen with speedy, high-flying planes—it was then followed by means of tracking telescopes and optical range finders to supply firing data to the antiaircraft gun. It was the effort to overcome the tardiness of sound waves, and if possible to combine all these operations into a single instrument, that gave the greatest impetus to the Army's radar development program in its early stages.

In the " horseless carriage " era of radar, there was a transition stage which had a curious resemblance to the mounting of sputtering gasoline engines on wagon wheels at the beginning of the century. The transition appeared in experimental equipment built by the Signal Corps Laboratories in 1937 in which the listening horns were stripped away from the old fashioned sound locators and were replaced by directional radar antennas. Since the sound locators were equipped to swing from side to side and up and down, they enabled tracking of aircraft by radar until special mounts could be constructed for the purpose.

The progress of radar in the United States owes much to the constant support, both moral and financial, given to the Signal Corps project at this early stage by the highest officers of the Coast Artillery Corps, the using arm for antiaircraft fire-control equipment. During most of the development period a Coast Artillery liaison officer and a detachment of antiaircraft artillerymen were stationed at the Signal Corps Laboratories. The presence of these enlisted men was valuable because the design engineers were constantly warned against making the equipment too complicated for operation by troops in the field.

In November 1938 a mobile service test model, developed by the Signal Corps, was officially declared to have advantages " over the best sound locator." It was at this time that the Coast Artillery Board saw the practicability of eliminating entirely the intermediate stage of searchlight illumination, calling upon the chief signal officer for " eventual production of a radio detection device which will provide accurate azimuth, accurate angular height, and accurate slant range for use as basic firing data for antiaircraft guns."

It was therefore further improved for greater accuracy and was modified so that its output data, including an automatic calculation of the altitude of the airplane, could be fed directly to the M-4 and M-7 gun directors. While this equipment, largely because of its relatively long wave length, never was fully up to the requirements for accurate antiaircraft fire, it has given long and faithful service in all theaters of war in the hands of Army antiaircraft batteries as well as Marine Corps units in the Pacific. Many German and Japanese planes were shot down, damaged, or frightened away from vital targets by its use in connection with antiaircraft guns and searchlights.

In addition, a slight modification tripled the range of the set to 120,000 yards. This modification was used as a mobile early warning radar and for GCI, pending the delivery of sets especially designed for those purposes.

The improvement in accuracy possible with shorter waves led to an early effort, on both sides of the Atlantic, to develop a microwave position and finder which would not suffer from the same difficulties. A very considerable amount of work was put into this problem by NDRC, the Signal Corps, and three industrial laboratories, and by mid-1943 there resulted a radar which—partly by accident—had been developed hand-in-hand with the new type of antiaircraft computing device which was developed by a great industrial laboratory, collaborating with the Fire Control Division of NDRC. These two devices, with the new power-driven and automatically controlled guns now standard in the Antiaircraft Artillery, gave the United States the most accurate and powerful local area defense against air attack that the world had ever seen.

Battalions equipped with the new combination of devices saw service in Africa, in Sicily, and in Italy. The showing they made on the Anzio beach-head was a proud one. When the invasion of France was being mounted, one of the many novel undertakings was to get heavy antiaircraft ashore on D-day itself and ready for business by nightfall. So much had been learned about the importance of immediate air defense.

But all during the planning for the great invasion, antiaircraft men had their minds on something else. Enough had leaked out from the continent to make it clear that the Nazis were planning a weird sort of counter-invasion: the bombing of England by pilotless aircraft. The air forces were doing all they could to smash the launching sites, and to break up the pattern of French transportation which had to supply these sites with ammunition. However, the launching sites were the worst sort of target; they were hard to see in the first place, small and hard to hit and difficult to damage even when the area containing a site was discovered and blanketed with bombs. Nevertheless, the sites were smothered with bombs by the Eighth and Ninth Air Forces and the RAF and this probably delayed the attack. It seemed certain, nevertheless, that the attack would come.

There was one thing about the prospective attack that worried the anti-aircraft men a lot: you can't demoralize an automatic pilot. You can demoralize a human pilot, and a good deal of the effectiveness of air defense is due to this fact. An inexperienced pilot can be demoralized by the sheer volume and impressiveness of flak, regardless of whether it is effective or not; and even the most experienced pilot can be demoralized by effective flak, because he can figure out his chances of not coming back from a mission just as well as anyone else can.

When these chances start to rise above 5 or 10 per cent, pilots start giving serious thought to whether it wouldn't be better to get " lost," and to fail to find the briefed target, and pretty soon the raids stop. But you can't demoralize a gyroscope, and every pilotless aircraft that can get through the defenses will go straight where it was initially aimed and the only antiaircraft defense that will pay off is one which knocks down as nearly as possible every pilotless aircraft that comes along.

Our AAAmen knew that they were good; they couldn't help wondering whether they were good enough.

The pilotless aircraft, or buzz bombs, or *Vergeltungswaffe eins,* or whatever you like to call them, came. And it turned out, after an inevitable period at the start of learning exactly what they were and what to do about them, that the defenses were good enough. Now everybody knows that these defenses were not antiaircraft artillery alone. There was a great balloon barrage across the Downs, made by stripping the defenses of every British city which could spare a balloon, and some of the buzz bombs which got across the British coast got tangled in the cables of this barrage. The coastal radar for warning and fighter control, augmented by some brand-new and effective United States gear rushed there for the purpose did two things. It plotted the bombs accurately enough to trace their paths back to the French coast, and thus pointed out to Allied bombers the launching sites which were active. And it permitted ground control of the newest and fastest fighters, which alone could catch the buzz bombs. Britain's new jet planes, and gasoline of a higher octane rating than had ever before been used in combat, plus the fastest new United States P-51's were all engaged in shooting up the buzz bombs. Even so, it was clear to everyone, right from the first foggy day, that if the doodlebugs were to be dealt with, it was the antiaircraft that had to deal with them. For the balloons caught only those V-1's which were low enough on the right course to be caught, and headed for a wire instead of a space between wires, at that. And the GCT-fighter team was intended for dealing with somewhat infrequent raids of great intensity but limited duration, not raids of medium intensity which went on ceaselessly. The planes and the personnel wore themselves out just as firemen would do if they had to work 12 hours a day for 2 months to put out a fire. And most of all, when the weather wasn't flyable, the buzz bombs didn't know it. They kept coming; they could be seen on the radar, and heard up there in the soup, as they went by, but the defending fighters had to sit on the ground. No defense was left but the radar-controlled antiaircraft.

While it is perfectly true that capture of the launching sites—the best of all defenses—was what finally stopped the V-1's, only 6 weeks after the attack started it can be said to have been contained. One Sunday late in August 105 buzz bombs crossed the British coast, headed for London. Only 3 of them arrived. The Nazis were simply not getting their money's worth any more out of the enormous effort on their part that V-1 represented. At the end, the antiaircraft was shooting down the great bulk of the bombs, and doing just as well on cloudy days as on clear ones. Many batteries preferred to use " unseen " fire—radar controlled—even on days of good visibility, just to keep their hands in. There was no perceptible difference in effectiveness between seen and unseen fire, radar range data being used in both cases.

Most of the work was done by the British antiaircraft batteries, partly because of the immense organization England had built up during the years of German raids, and partly because most of the United States antiaircraft in England in the early summer was committed to move across to the continent as operations there progressed. While they were waiting to go, most of the United States batteries were moved down to the south coast to have a crack at the V-1's, and some of them hung up a record for accuracy which still stands—1 buzz bomb downed for every 40 rounds fired. Our antiaircraft men were very pleased at the showing our own batteries made; and it pleased them, too, that the United States-designed radar turned out to be a handier device against the buzz bombs than its British counterpart. General Pyle, comanding the British Antiaircraft Command, asked for and got every United States radar we could spare to outfit his batteries; and when the excitement was over he wrote General Marshall to say how grateful he was.

After the Battle of the Buzz Bombs, what happened subsequently on the Continent, although it would have been impressive only a few months earlier, was something of an anticlimax. The *Luftwaffe* didn't have the potential to give our AAA much exercise. When raids came within range of our radar and our guns the antiaircraft made a very good showing. And Antwerp had to be defended from V-1 attack, as did some of the other important cities. But we were rapidly winning the war, and antiaircraft is a weapon which, while very useful at any time, is absolutely vital only when your side has not yet started winning the war.

Needless to say, as our forces stride across the Pacific toward Japan they are accompanied at every step by the antiaircraft and its radar eyes. For the first few weeks after each new landing, the AAA is one of the most important features of the ground forces. Ships have to be unloaded, and depots and headquarters and hospitals and bivouac areas set up, and for a few weeks the Japanese have enough airplanes left in the vicinity to sneak in at night. Since we are winning the war, the work of the antiaircraft never lasts very long but it is comfortable to know that the shooting will be just as good in the dark as in the daylight.

6. Radar and Air Defense: The Problem at Sea

THE PROBLEM of defending a fleet of warships from air attack is somewhat more complex than that of defending a land area. The differences in the problem are reflected in different radar techniques.

First of all, the ships are moving. This means that since they are not especially vulnerable to high-altitude, heavy-bomber attacks, they will be subjected to close-in dive bombing, torpedo, and even suicide attacks; which, in turn, means that their inner defenses must be powerful. The fact that they are moving also puts a premium on the instant detection and destruction of enemy snoopers and reconnaisance planes. And, in addition, the fact that their carriers are steaming along complicates the navigation of carrier planes. Not only do they have to find their way to their target but they must find their way back to a small point in midocean some hundreds of miles on a zig-zag course from the point they took off.

Ships are moving in other ways too. They roll and pitch and yaw; they twist and turn and vary speed. All this means that the job of the radar controlling their gunfire is immensely complicated. It must take into account all this motion and still make sure the shell hits its speeding target.

Finally, the fighter defense of ships must be accomplished by aircraft which can take off and land from carrier decks. For practical purposes so far in this war, this has meant single-seater fighters. Night fighters meant for use over land have always carried at least two men: a pilot and a radar operator, the latter spending all his time in adjusting the radar and reading its indications. The Navy, however, was faced with the problem of supplying the already busy pilot of a hot fighter with radar reliable enough, simple enough to operate, and giving indications sufficiently easy to interpret, to permit him both to fly the airplane and to serve as his own radar observer.

This was the problem as it came to be understood during the years of 1940 and 1941, while the overworked British Navy was trying, in the face of sustained large-scale Axis air attack, to keep the Mediterranean life-line open. Ships of the Royal Navy were equipped with air warning radar, and all too frequently it was just that. It enabled the ship to alert its defenses in advance of a raid, to know how soon and from what quarter the raid was to be expected, and to have some idea of the strength; but it was not sufficient to defend the ships adequately. United States Navy observers with the British ships during this dark time came home convinced of the tremendous role that defensive shipboard radar was destined to play and of the magnitude of the problem yet to be solved.

As we have seen, the United States Navy already had in service air- and surface-search equipment, and work was forging ahead in constantly improving these types. To these, during the first years of the war, was added long-range microwave equipment designed specifically for control of defending fighters, and a start was made on the difficult problem of an AI for the Navy single-seat fighters. Meanwhile, the Navy at sea was working out doctrines for integrating these various types of radar for the defense of their task forces.

The result of their work was the creation of CIC—Combat Information Center—a concentrated, complex, and highly dramatic center of radar activity on our men-of-war. The purpose of CIC is to coordinate information—predominately from radar, but also from look-outs, from other ships, and from technical devices other than radar—evaluate this information and determine what the enemy is doing. The resulting information is then channeled to other essential control stations through the ship. CIC has grown and developed hand-in-hand with shipboard radar. In fact, it was originally called Radar Plot, its function being just that—to plot the movements of planes and ships tracked by radar, and to direct friendly fighter planes to an interception where enemy raids developed. As supplementary equipment grew in scope and application, so Radar Plot expanded into the present-day set-up.

The organization and primary operational functions performed in CIC varies with different types of ships. On carriers it emphasizes defense, being concerned primarily with fighter direction, control of aircraft, and AA defense. In battleships, cruisers, and destroyers, it is primarily concerned with gunnery or torpedo attack procedures with AA defense playing a secondary role. In a later chapter, we will see how CIC information is used for other purposes, but here we shall confine ourselves to its place in protecting our ships against air attack.

In the case of ships at sea the primary protection is by a constant combat air patrol. This is necessary because the time required to rig aircraft for launching, turn the carriers into the wind, launch the planes, and get them out to the point of interception with attacking aircraft is simply too long to give adequate protection. We can assume, then, that the Combat Air Patrol—the CAP—is aloft when the first warning comes.

By means of air-search radar, we are able to pick up our first indication of approaching planes, obtaining their bearing and range. By IFF, we are able to determine immediately that they are enemy. Meanwhile as new bearings and ranges come in, we are soon able to determine the course, speed and altitude of the attackers.

Immediately this information is passed to the bridge, to flag, and to gun control, which alerts the AA batteries. Meanwhile, other computations have been made and we know how soon our CAP will have closed with the enemy, and how soon any enemy planes which slip through the CAP can be expected to be sighted. By means of this same information, the CAP is able to intercept the enemy planes at a point favorable to themselves. At the same time, a backstop of other fighters is being warmed up on the flight deck.

Within a few minutes, our fighters have closed with the attackers sufficiently to see him in their own AI radar, or to sight him visually. From this point, they take over. If some raiders get through the Fighter Director Officer may assign the backstop CAP to take care of them. If some enemy planes get inside even the backstop CAP then the ship's AA fire takes over.

Radar equipped gun directors are trained on the incoming planes. They feed their range, altitude, and bearing information into computers which take into account the target speed, ship's motion, and many other factors to position the guns correctly to hurl their shells into the exact spot where the plane will be when the shells arrive.

Meantime, the other radars of the ship have been on the lookout for possible new raids from other directions.

Effective Navy AI equipment was the last part of the radar air defense setup to reach the fleet, primarily because weight and space restrictions required such a high-performance design. Japanese night attacks on our ships had been a considerable problem since mid-1943, and at first they were dealt with by improvised methods. Some adventurous Navy pilots conceived the idea of sending out night teams consisting of a torpedo-bomber, equipped with an American-designed ASV, and two radarless fighters. The fighters flew formation with the radar-equipped plane, the whole formation was vectored on by the Control Officer aboard ship as a single night fighter would be, and the American designed ASV doubled as AI to get the fighters over the intermediate stage of closing with the enemy, until they could sight him visually. "Butch" O'Hare was lost in one of the fight combat trials of this scheme. It was complicated, but it worked when it was most needed.

But the Navy's night operations are a far cry from that today. Our newest fighters are equipped with a superior AI which enables them not only to intercept possible night attacks but to carry a 24-hours a day offensive air war right to the enemy. Carrier-based planes with the planes of the Army Air Forces are over Jap airfields night and day. Radar makes it possible.

7. The War Against the U-Boats

From the beginning of the war, the Germans had decided to put a major effort into the destruction of Allied shipping by concentrated U-boat warfare, knowing that a German victory depended ultimately on driving us from the seas. The United States and Britain, on the other hand, knew that their ultimate victory depended upon defeat of the submarines and the pouring across the Atlantic of sufficient arms and men to mount a mighty land offensive in Europe. Consequently no effort was spared in the war of extermination.

More than most of the other phases of the European war, this Battle of the Atlantic was a technical conflict, with thrust, counter-thrust, and parry all being executed in terms of new devices and techniques. Keen minds were as important as courage. This is the story of radar, and it cannot tell of the improved depth charges, with higher-powered explosives which meant a greater killing radius and shapes that gave a predictable underwater trajectory, nor of the underwater sound equipment with which the ships hunted down submarines which had been sighted by radar, nor of the rockets which, from both ships and planes, holed and killed the U-boats, nor of many other technical devices which played important roles. But radar played a vital role in the war against the submarine.

It did not always look as if the submarine would be beaten. During 1942, they were sinking Allied shipping at the rate of 16,000 tons a day. The tropical breezes wafted into Miami the dull boom of exploding torpedoes, and the seas washed up the ghastly relics of sunken ships. Off Cape Hatteras, the ocean floor was dotted with sunken and half-sunken wrecks. In the situation rooms on both sides of the Atlantic, men grimly marked up the victims of the U-boats, and the sightings of submarines which had been reported.

There are three basic ways to fight the U-boats, and they were all being employed. The first is to attack, by bombing, the factories which make submarines (this is not enough—the existing submarines still have to be killed), and the base and repair facilities which submarines use in their home ports (the Germans beat this game simply with lots of reinforced concrete).

The second is to patrol the sea lanes which the submarines are known to frequent, or must frequent if they are to operate effectively, searching ceaselessly for surfaced submarines, and trying to turn every sighting into a kill.

The third is to gather merchant ships into convoys, and to provide these convoys with sufficient escort of the proper sort to make a submarine attack a foolhardy stunt.

All three of these ways were exploited. All three involve aircraft, although the third involves surface vessels even more importantly. The latter two ways involve radar as the primary detection means, and it is with them that we shall deal in this account. The bombing of submarine factories and submarine pens did not turn out to be a decisive factor, partly because it was abandoned when the search for submarines in the open sea began to go so well, and partly because of the fantastically thorough job the Nazis did of building shelters for their submarines. The strategic bombing of German industry was felt in the submarine-construction field, of course; but it was at sea that the Battle of the Atlantic was won.

As has already been seen, the British were designing airborne radar for the detection of submarines or other vessels on the surface even before the beginning of the war. The first operational use of this early equipment was made at the beginning of 1941, and it was immediately effective. The great effectiveness of radar in the war against the U-boats arises precisely because of the nature of the submarine. A submarine relies on submersion for concealment, but it cannot live indefinitely under water. In the days before radar, it could get along very well, even in hostile waters, by proceeding submerged during the day and surfacing to charge its batteries and take on fresh air during the night; its chances of being detected in the darkness were small. There is no night in radar's world, and when the ability of radar to see a submarine for some ten miles is combined with the ability of a highspeed airplane to travel some hundreds of miles in an hour, a systematic sweeping of the areas of the sea in which submarines are known or expected to be lurking becomes practicable. This is what the RAF Coastal Command undertook to do.

It became apparent to the Germans very soon that aircraft attacks on their U-boats were taking place far too often to be the result of a complete reliance on visual sighting. They suspected radar, for they had already made some experiments with a crude form of long-wave ASV, and in the spring of 1942 they captured intact one of the ASV radars of the form Coastal Command was then using. We were in the war by this time. Our Army and Navy were using an American version of this same British set. The Navy was also using a very similar equipment designed at the Naval Research Laboratory, which operated at a shorter wave length. After capturing the British equipment, the Germans countered by designing a receiver, for installation on U-boats, which covered the wave length range used by the ASV radar. This was intended to give a response whenever the beam from the radar swept over the submarine; and it gave this response when the radar-equipped airplane was sufficiently far from the U-boat to permit the latter to submerge and escape attack, if not detection. These receivers were hurriedly built and installed during the summer of 1942, and by the end of that summer it was clear to the Allies what was going on. While the number of visual sightings changed very little, the number of radar sightings declined markedly, and the number of radar " pips " which disappeared from the scope during the plane's run-in on the target told the story.

The Allies were ready with their next weapon—ASV on a wholly new wave length band. The United States and British radar laboratories, in collaboration, had developed microwave ASV equipment. Shortly after the attack on Pearl Harbour, the Army Air Forces requested that 10 B-18 aircraft be equipped with handmade microwave equipment, on an emergency basis. This was done, and by April 1942, this squadron, the first in any service, was carrying the war to the submarines themselves by searching them out and attacking them along the east coast of the United States, operating out of Langley Field. A large industrial company was also asked to modify for antisubmarine use some microwave AI sets which were then just about to go into production.

The original B-18 squadron moved with the U-boats, as their attacks and those of the Navy drove them farther and farther south, operating successively from Florida bases and from Trinidad as 1942 wore on. By this time the original squadron had been augmented by several hundred bombers to become the First AAF Antisubmarine Command, under the operational control of the Navy, as the Navy was officially charged with the protection of the seaways.

Meanwhile, the British made a request to the United States for a field test quantity of microwave ASV equipment. In March 1942, a lend-lease Liberator with the laboratory prototype of such a set was flown to England for Coastal Command trials against British submarines. It was soon followed by a second prototype installation, and 15 more sets were constructed here and delivered to the British before the end of 1942. The success of this equipment led Coastal Command to order and install in quantity a British equivalent of the American microwave ASV. This entered operational use during February and March 1943.

The United States Navy was also interested in equipping its blimps and patrol aircraft with a microwave ASV, and in February 1942, initiated the development of an improved set for this purpose. A preproduction model was flying in a blimp by July, and through a superhuman effort on the part of the development and production engineers, production equipment began to appear in January 1943, the number delivered rising rapidly thereafter. Hundreds of these equipments have been delivered to the British on lend-lease.

The sequence of events was, then, that the British started to use airborne radar to hunt submarines, the Germans started to escape by using a receiver to pick up the ASV signals—during the winter of 1942-3 the submarines increased in boldness—and by spring of 1943 significant quantities of microwave ASV, which the German receivers couldn't detect, were in operational use. The impact of microwave ASV on the sense of security into which the listening receiver had lulled the U-boat captains had a phenomenal result. During May, June, and July of 1943, nearly 100 confirmed submarine kills were made, two-thirds of them by aircraft. These kills destroyed the confidence of the German submariners in their security against air attack, and sent the technical men into a frenzy of guessing and development work.

Now began one of the greatest stories of the war, which for drama, bitter comedy, and significance can scarcely be equalled. Among the various suggestions dredged up by the German technicians was a possible modification of the old ASV which would make it proof against the listening receiver as it was then designed; a simple modification in the receiver would cope with this. This modification was made, and happened to be tried just in the area where a few planes were operating—the only ones—with that particular ASV change. The submarines came back with excited stories of signals on the new receiver that couldn't be detected on the old. Hope ran high, and worries were soothed. Yet the U-boat kills went on.

It was suggested that the Allies might be using an infra-red detection device, and submarines were painted with a special paint. The U-boat kills went on.

It was pointed out that the listening receiver itself radiated a good deal of radio energy (just as old-fashioned radio sets used to make squeals in the receiver next door). Perhaps the Allies had an airborne device for detecting this radiation and homing on it. One new design of listening receiver after another was hurriedly built and rushed through installation into use, with promises that it would be the one, give plenty of warning, and would not radiate perceptibly. But the U-boat kills went on.

By this time, the U-boat personnel were beginning to lose something of their confidence in the technicians who supplied them with equipment. Two scientific expeditions put to sea in U-boats fully equipped to search for the mysterious sort of radiation the Allied planes were using to detect the submarines. Civilian experts were on board, and the most complete and up-to-date German apparatus. The first such U-boat put to sea from St. Nazaire on 5 February 1944, and lived thirteen days. The second left Lorient on April 27, and lasted only nine.

Not until the fall of 1944 did the Nazi Navy get this mess all sorted out. By this time, they had decided that the only way for a submarine to live was not to come up at all, and they were busy installing an air-tube they called Schnorkel, which enabled a U-boat to breathe and to run its Diesels while still remaining submerged. The Allies were ready with a brand new set of tricks, but the war ran out.

Thus far, this has been the story of the search, largely by land-based aircraft, for submarines at sea, whether or not they were attacking Allied shipping at the time. Equally important over-all, and a lot more important to the immediate problem of getting the armies and the goods to Europe, were the measures taken to protect the convoys. Although these measures were largely defensive, their aim was the destruction of submarines. At both ends of the convoy route, the ships could have the cover of long-range, land-based aircraft, but the major part of the route lay outside of the endurance of land-based aircraft. And of course there were all too many days when the weather kept the airplanes on the ground.

The Navy's record in protecting convoys all the way across is nothing short of remarkable. The total loss by all types of ships in convoy was only 1/10th of 1 per cent. Radar played a major part in this record, from the Navy initiation of the convoy system.

The ships being convoyed were grouped in columns, steaming abreast, thus forming a large rectangle. They steamed at a speed equal to, or greater than, the maximum speed of a submerged U-boat. This meant that underwater attacks had to come from the area ahead of the convoy, which was protected by the Navy escort ships in fan-shaped formation. The underwater sound gear with which each escort was equipped prevented any submerged sub from sneaking through this line, and of course any surfaced sub could be spotted visually and attacked while it was still far from the convoy. In the days before radar, however, there was little to prevent the U-boats from surfacing at night or in foggy weather, and using their greater surface speed, attack from any angle, even from the rear, with great success. This type of attack, often by packs of U-boats, was responsible for the heavy losses on the early North Atlantic convoys.

Radar put a stop to these tactics. Scientists worked feverishly not only to develop improved shipboard search radar, but to train expert installers for every Navy Yard and turn out the thousands of trained operators needed. Soon all escort ships in the Atlantic were equipped. Surfaced Nazi submarines could be detected and attacked as easily at night as in broad daylight. Convoy losses took an abrupt and permanent drop. New electronic navigational aids also helped materially in the general navigation problem and in rendezvous.

Radar also eliminated stragglers from convoys which had previously been easy meat for the U-boats which trailed nearly every convoy for just such game. In preradar days, the convoy commodore and escort commander anxiously counted noses every morning to see how many of their charges had dropped behind or wandered off unnoticed during the hours of darkness. If there were any, they could almost be written off as sure losses. Search radar, however, enabled the escort commander to keep a 24-hour watch on the entire formation. A straggling or wandering ship was quickly discovered and an escort dispatched immediately to bring it back to the rest of the flock or to stick with it, protecting it from submarines, until its repairs could be effected and it could again catch up. The Nazis were deprived of the helpless sitting ducks which they loved to find.

Incidentally, the same radar served to reduce greatly the losses by collision that had previously beset many a convoy. Too often, the first warning the escorts had of some blacked-out hulk of a ship in the path of a vast convoy was the crunching of hull against hull and the calls of distress. Radar enabled all ships in the path of a convoy to be intercepted in time to divert them.

As fast as they could be built, escort carriers, or CVE's were sent with the convoys where they were most needed. Their planes were equipped, of course, with the same radar that has already been described. They marked the real doom of the Nazi submarine menace. By 1944, the United States Navy had so many CVE's and destroyer escorts that it was putting to sea special Task Forces whose sole mission was to hunt out U-boats in the mid-Atlantic the way patrol planes had hunted them nearer the shores. From one side of the Atlantic to the other, day or night, clear weather or foggy, there wasn't a square mile where a U-boat was safe from the prying eyes of radar, air-borne or ship-borne.

At the end of the war, the U-boats were being sent to the bottom at the rate of nearly one a day—and that kind of good hunting for the Allies had been going on for more than a year. That the war in Europe came to its successful conclusion as early as it did is due, in large part, to the failure of the U-boats to halt our vast flow of supplies. And that they failed so completely can be largely attributed to radar.

8. The Air Campaign Against Shipping

THE LARGER target presented by surface vessels enabled their detection by radar at greater range than a submarine. The British started to hunt for ships as soon as their earliest ASV was operational. The United States Navy by 1941 had adopted the policy that, as soon as possible, there would be some sort of radar search equipment in every type of Naval aircraft. The AAF was quick to install such equipment in all bombers designed for sea search.

Seaborne supply in the European Theater was never the do-or-die necessity to the Axis that it has always been to us, but when Rommel was in Africa his supplies used to come across to him mostly by ship. In these days of astronomical bomb tonnages dropped by the AAF, one tends to forget the ordeal of Malta, but for a long time this tiny British island took a more concentrated pasting than any place had had.

The Nazis and the Italians wanted the British off the island principally because of a small force of obsolete Royal Navy Swordfish, almost never more than a squadron, and, for 6 weeks in 1941, there were one or two planes in service only part of the time. These were torpedo biplanes which could make barely 90 knots with the throttle against the stop, and looked like one of the later World War I models; but they could lug torpedoes, and they had ASV. The radar was essential to their operating at all, for to be caught off the ground in a Swordfish during the hours of daylight was likely to be fatal. What they did was to go out at dusk, to search systematically to the limit of their endurance, and when they found something to attack it. They traveled in formation, because usually there would be only one or two ASV's working. One plane would detach itself from the others and drop a parachute flare beside the ships; the others would make their runs from the dark side, and drop their torpedoes. Then they would all go home for more gasoline and torpedoes, if the remaining hours of darkness permitted. They made quite a lot of trouble, and the bombings of Malta were the nicest compliment that the Axis could pay these old airplanes and their primitive ASV.

In early 1942, as we have seen, the Army Air Forces had been roused by torpedoings along the East coast of the United States to go submarine hunting with ASV. In addition to United States and Canadian copies of the early British ASV radar, Army aircraft began to be equipped with small but increasing numbers of microwave ASV, designed by the Radiation Laboratory to AAF requirements. One use of this equipment which accounted for a good many weary flying hours but never got into the newspapers was the air patrol which guarded the approaches to the Panama Canal. Ranging far out to sea, B-24s kept guard over a strip of ocean wide enough to keep a Jap carrier force from sneaking in undetected, and far enough out to assure that defenses could be mobilized in time to meet such a threat. They investigated every signal that they found on their radar, and in the many months of this patrol they never found a hostile force.

The Army Air Forces at Langley Field also had an establishment devoted partly to radar training and partly to the tactical development of means of using this new weapon and other allied technical devices. It was from the work of this establishment that the suggestion came for designing a radar attachment to permit not only radar detection of surface vessels, but the solution of the bombing problem as well, in order that the run-in and the bomb release could be made entirely on the radar.

NDRC was asked to develop such a device, an industrial company to engineer and produce it. By the summer of 1943 the first production of the LAB (for Low Altitude Bombsight) was coming off the line. Meanwhile, the Naval Research Laboratory, in collaboration with the same company, developed a similar attachment for Navy air-borne radar. The Army's LAB was designed as an attachment to the radar on the one hand and to the Norden sight on the other. Its principal design objective was to be just as accurate as it could be. When used as it was intended to be used, from low altitude against ship targets, it got one direct hit in three tries even during the training of the first crews who got a chance to use it.

Special Army Air Force squadrons took this equipment to the Pacific during 1943 and 1944, and made an impressive record against Japanese shipping around the Solomons, off New Guinea, and in the China Sea. Cold statistics showed the losses of aircraft and crews were lower, tons of shipping sunk per ton of bombs dropped were higher, and sightings and sinkings per sortie were greater for night missions with radar than for the daytime visual sweeps which were then being used against shipping in that area.

Under all the difficulties of operation from forward bases in China, involving hauling their own gas, making minimum sorties of 500 miles of which 65 percent were over land, and saving their bombs for the biggest targets, one B-24 squadron of the Fourteenth Air Force sank 110,000 tons of Jap shipping in the China Sea in a single month, entirely at night and entirely by radar.

The Fourteenth Air Force believes that the reason the Japs took away the United States forward bases of Liuchow and Kweilin in the fall of 1944 is principally that they were aware of these statistics from the receiving end.

Meanwhile, the Navy was in the airborne, surface-search radar business in a big way—eventually more so than the Army. At first all that was available was the original British design which had seven antennas in all, some of them as long as 16 feet, the total effect of which was drastically to cut a plane's performance.

The Naval Research Laboratory was able to reduce the number of antennas, but what was really needed was a more compact, lighter weight set. The modified ASV, installed in some numbers in flying boats and patrol craft, served well on many fronts, taking part in the antisubmarine campaign, searching for Jap ships in the Pacific, and making air operations in the fog-bound Aleutians a good deal less hazardous than they had been before. Later these same airplanes were reequipped with microwave ASV and still later with LAB.

But the problem of equipping the small, carrier-based aircraft of the Navy was urgent. So the Naval Research Laboratory went to a medium wave band, in which it had been experimenting, and produced a new airborne radar, the first lightweight set for carrier-based aircraft. Production began in 1942, and 27,000 sets were manufactured—more than any other single type of search radar. This was the set that can be said to have fought the war, until the last few months, for naval aircraft. Thousands of sets are still in use.

Recently, however, a much-improved type of ASV, working on a higher microwave frequency than had previously been used and therefore requiring only a small antenna, has been doing new wonders in the fleet. The impetus given the radar art by the single-minded devotion of the Navy to the cause of a radar set for every airplane cannot be overestimated.

The Navy also has and uses LAB. The Japs, unlike the Germans, have a shrinking empire which is held together by ships and shipping. And the fact that it is coming apart can be attributed, among other things, to the fact that no Japanese ship is safe from air attack, even on the darkest night.

9. The Strategic Air Offensive

THE IMPORTANCE of radar in strategic bombing rest on two facts. Strong defenses can force a large fraction of the bombing to be done at night, and, in daytime, if bombing is to be a genuine strategic weapon, it cannot depend on sighting its targets by visual means.

The Germans, when their daytime losses in the Battle of Britain grew too high, were forced toward the end of 1940 to commence night bombing of English targets. The techniques they used for finding their targets and hitting them in the darkness were primitive at first, but developed as time went on. They were from the start giving their flyers radio navigational aids of the general sort used on our peaceful domestic airlines to bring them to London, or wherever was their target, and sometimes to indicate when the computed point of bomb release has been reached. They were developing marker-flare and bomber-leader techniques which were definite forerunners of the RAF bombing pattern, when mounting losses and lowered morale and the increasing vigor and effectiveness of the British defense put an end to these Nazi experiments.

When the RAF Bomber Command took up the torch for strategic bombing, they had the experience of the *Luftwaffe* to build on. Because of the murderous day-time defense that the R.A.F. Fighter Command had mounted against the Germans, the British decided to commit their heavy bomber force to night operations entirely. Good sense and the German example told the RAF that night operations would be successful only if good aids to navigation were provided for every aircraft, and special means for target location were provided for Pathfinder aircraft which were to lead the main force. Geography was against them here. Where the Germans could put up the masts and towers of their radio navigational aids on the Channel coast and in the Low Countries, only a couple of hundred miles from London, the British were aiming at targets in the heart of Germany, as much as 500 to 700 miles away around the curve of the earth. The British early developed and installed a new type of navigation system, which has been referred to as radar, because it uses pulses, but is really not radar, because it does not use echoes. Installations were made on all Bomber Command aircraft, and this system could be relied on to get the main force in the vicinity of the target.

For the problem of finding the target exactly and hitting it, two approaches were used, each useful in its own sphere. A refinement of the pulse navigational system was used to guide leaders in to the target, and to indicate the moment of bomb release. These aircraft, as has often been told, dropped special flares on which aircraft of the main force sighted visually then bombed. This system was very accurate and most successful; the devastation of the Ruhr by the RAF in 1942 was done with its aid. It suffered from one limitation: the curve of the earth restricted its range. From the British ground stations that guided planes of the Pathfinder Force, the Ruhr was about the limit of the system's useful reach.

Clearly, something else was needed to take the Pathfinders in to targets that were well in Germany and to bomb Berlin. This was found in an adaptation of microwave ASV. This radar, in addition to showing signals from ships, shows them also from shore lines, mountains, cities, and the shores of rivers and lakes. In coastal waters, radar pilotage of aircraft simply by watching the scope is relatively easy; and even inland the patterns in which cities are laid out on the radar screen reproduce in general those on a map. Bomber Command decided to try to navigate and to bomb wholly by the indication shown on the screen of such a radar. The British were just commencing to use such modified microwave ASV radar in their Pathfinder Force for long raids, when we got interested in bombing targets we couldn't see.

Our Eighth Air Force came to England and commenced its operations in the late summer of 1942 with high hopes, a very small force, but with plenty of guts. It was, and to the end of its operational life continued to be, committed to the policy of daytime operation, and to precision bombing of carefully chosen, small vital targets. Its leaders, and those who had dispatched it from the United States, were aware of the British night bombing philosophy, with all it connoted of instrument navigation and Pathfinder technique, but their eyes were on another ball. They started to operate, and to learn the strategic bombing trade in the hard school of experience.

Our Air Force leaders found out that it is better to bomb a little less accurately in combat than on the practice range, than it is not to bomb in combat at all. Specifically they found out, as soon as they began to run raids into Germany, that operating without fighter escort was costly (hence the rapid development of the long-range fighter); that unescorted bombers must fly and bomb in large formations for mutual gunfire protection against hostile fighters, even though this makes the bombers a little more vulnerable to anti-aircraft, while formation release replaces pin-point aiming by a pattern of bombs on the ground; and that just plain navigation, to the target and back, was one of their biggest headaches. That first winter of 1942-43 they also found out that continental weather is bad; that the number of days from November to March when visual aiming on a target from 20,000 feet would be possible was far too small to occupy the full capabilities of the air force they were building up to be. All these lessons were to have a bearing on the use of radar by our strategic bombers.

The problem of navigation was attacked right away by getting from the British, and installing in airplanes of the Eighth Air Force, equipment which would enable them to use the same pulse navigation system as got the RAF Bomber Command over and back. This system was useful throughout the war; in fact, the German bombers which gave London its " little blitz " of February and March, 1944, used it as a navigational aid on their missions, employing reconditioned equipment from the hundreds of RAAF and AAF bombers which had been shot down over Germany.

The problem of bombing was something else again. The special pulse navigation system that the British were using was accurate, but it was limited in range, and the Eighth disliked to tie itself down to short raids. There was no range limitation on the B. T. O. (for bombing through overcast), which is what the British called their modified ASV for bombing by radar pilotage, but it was frankly somewhat inaccurate. The Eighth made some experimental installations of each equipment and kept on looking around for something that better fit their needs.

Meanwhile, the workers at Radiation Laboratory had been flying around with an experimental ASV equipment which worked on a new and shorter microwave wave length than had ever been used before. The beam it produced from a standard-size antenna was much sharper than that of the B. T. O., and the fineness of detail and faithfulness of the picture of the ground it produced were correspondingly very much greater. The need of the Eighth and the availability of the new wave length suggested that a set like the British B. T. O., but with the greater accuracy that a better radar picture would afford, might fill the bill. Such a set, which was also christened B. T. O., was requested by the Army Air Forces in mid-June 1943.

Since it was needed mainly to get the bombers off the ground during the bad target-visibility months of the winter, there was no time to be lost. While production engineers of two large companies worked on the problems of production design and procurement, the Radiation Laboratory undertook, with a great deal of help from the Army and from the Navy (which was likewise interested), to build 20 sets on a " crash " basis. These were to be used to equip 1 squadron of 12 planes, and to provide the necessary battle spares.

This is how the bomber-formation lesson that the Eighth had learned entered the picture: One squadron of radar-equipped planes could lead 60 times their number on every raid.

After a 4½ months nightmare of radar construction and installation, flight training and maintenance training, flying to England, and theater indoctrination, this is exactly what they did. When they got to the theater, they wanted to do more training over England, making simulated bomb runs and assessing their performance by taking vertical photos. But it was now October, and the Commanding General of VIII Bomber Command said, " I don't mind your training. But I want you to train over Germany, and I'll send a combat wing of 60 airplanes with each of you on every practice run." By that time he had an air force that could operate 10 to 20 times as often as the target weather would let it during the worst months of the winter, if he could only see through the undercast.

After being stood down from their first standby on 30 October, 9 of the B. T. O. Pathfinders took off 3 November for a " practice " run over Germany, each leaving a combat wing of 60 planes. Their target was the dock area of Wilhelmshaven, which 8 previous visual raids had missed; only 9 months earlier this had been the target for the first raid of the Eighth over German territory. They found the target overcast and they hit it by radar. Reconnaissance photographs taken later showed in detail what fragmentary observations through holes in the clouds had suggested during the raid; a good concentration of bombs around the aiming point, and very considerable damage.

" Mickey," as the Eighth called B. T. O., was in. During the rest of November 1943, the Eighth Air Force made more raids than it had ever made before in a single month. During December—in the previous December it had been grounded—it dropped its greatest tonnage of bombs for a month to that date (24,000 tons), and for the first time carried as big a bomb load as the RAF. During all this 2-month period, only four raids had encountered target weather which permitted visual bombing. The rest of the time, what was fast becoming the world's biggest heavy bomber force flew in formation behind the same few Pathfinder planes, and released their bombs on signals from the same few tired radar operators watching the scopes of the same few haywire B. T. O. sets.

This went on all winter. In March 1944, the first production equipment and the first United States-trained crews started to flow in. Although sets had begun to come from production by November, airplanes had to be modified, operators and maintenance men trained, early production designs shaken down and improved by the Signal Corps Aircraft Radio Laboratory, and the whole new project fitted into the machine of Air Forces procurement, training, supply, and replacement. For the most important winter of the European strategic bombing campaign, 12 airplanes and 12 " Mickey " sets led the Eighth.

As time went on and the missions mounted, it began to be clear that the first Wilhelmshaven mission had been a piece of beginner's luck. The overall bombing accuracy showing of B. T. O. was hard to measure, mostly because when B. T. O. was used, strike photographs showed only the solid cloud under the airplanes. But what assessment could be got showed that B. T. O. bombing was a good deal less accurate than visual bombing. This should not have surprised anyone, and in fact did not. The equipment was crude, the operators were learning on the job, a file of radar reconnaissance photographs of target areas had to be built up, and most of all, the gadget had not yet been integrated into Air Force operations.

The luck of B. T. O. on its first raid, like radar's success in the Battle of Britain, had a good effect and a bad one. The good effect was that the friends of radar could use the results on Wilhelmshaven to silence the critics of radar bombing at a time when the whole-hearted adoption of B. T. O. by the Eighth hung in the balance, and " Mickey " had plenty of skeptics to convince. The bad effect was that the people who believed most passionately in the future of radar bombing thought that B.T.O. was an instrument whose accuracy, once the crews were properly trained and the equipment shaken down, could rival that of the optical bombsight. This sort of thinking tended to set radar bombing up as the logical successor to visual bombing—as a competitor instead of a partner.

The fact that this was a mistake had to be found out experimentally, but it did not take long. Since visual bombing and radar bombing were thought of on an either-or basis, the techniques for the bomb run, from initial point to target, were different in the two cases. The decision as to which type of bomb run was to be made was supposed to be taken at the initial point, or soon thereafter. The trouble was that you can't tell if a melon is good except by cutting it open, and you can't tell if a visual bomb run will be feasible except by trying to make it. Everybody tried to make a visual run whenever this seemed to be at all possible, because of the better accuracy; and with " Mickey " taking the Air Force out on days of dubious target visibility, a lot of visual bomb runs were started that couldn't be finished. The only circumstances under which there was no confusion whatever were either those of solid undercast, and therefore a purely radar run, or not a cloud in the sky, making a visual run obviously possible.

It was clear that this had to be fixed, and it was. A technique for coordinating the work of B. T. O. operator and bombardier was worked out so that every mission, no matter how the bombs are aimed, is run in the same way. Radar is always used for every run to navigate to the initial point and to get squared away on the bomb run. The radar operator goes on as if he were going to do the whole job, and the optical bombardier keeps his sight lined up according to the radar sighting. This means that, if the radar is right, the telescope of the Norden is always kept pointed at the aiming point which is down there below the clouds. The slightest break in the undercast which permits the bombardier to see enables him to take over the run and complete it optically. This system joins the best features of radar and visual bombing, and makes the bombardier and radar operator a team instead of competitors.

The same early misplaced confidence in " Mickey " was shown in its properties as a navigational device. The radar picture it gave was so good that some navigators relaxed a little on their dead reckoning, figuring that they could look at the radar scope whenever they chose and orient themselves by comparing what it showed with a map. This works all right some of the time, but not all of the time. The catch is that there are frequently two different places which show near enough the same arrangement of towns, rivers, mountains, and land patterns in the area covered by the radar picture to fool a navigator who is the least bit careless, especially if the winds aloft have been different from the predicted ones. Radar is a wonderful device for navigation, but it must not be used for spot pilotage. It is an excellent source of information on ground speed, course, and winds aloft under all circumstances, and is therefore in a position to supply the basic data of dead reckoning, but full-time dead reckoning is still the basis of all navigation. A radar navigation error which resulted in United States planes visually bombing Switzerland illustrates the importance of dead reckoning.

While the Eighth Air Force was learning all this, and the Fifteenth was being fitted out with B. T. O. equipment and doing a superb job of making an everyday affair of using it effectively, the Army Air Forces back home were installing the same sort of radar on the B-29's that are now bombing Japan.

Radar has come to play a role in one more part of strategic air force operations. This is in assisting in the control of escort fighters. We have seen how the Eighth very early found the need for fighter escort, which grew greater at the far end of their longest missions, which distance was most difficult for fighters to reach. The story of the development of fighter aircraft which could fly from bases in England to Berlin, their fight on better than equal terms with Nazi airplanes that had just left their home field and then fly all the weary miles back home again is one of the greatest of the war. All this was done, and done in an incredibly short time.

Now the pilots of these fighters had a job which, for sheer difficulty, it is almost impossible to equal. The bombers carried full-time navigators and special navigation equipment, and still they got lost. The fighter pilot had no navigator but himself, no map table, and no navigation data except what he carried in his head or inked on the back of his hand. The bombers had two human pilots and an automatic pilot to fly a very stable airplane. The fighter pilot flew all the way in a hot airplane and then had to fight a fresh Nazi pilot when he got where he was going. And then he had to fly all the way home. He was his own radio operator, his own gunner, and his own engineer. And finally, since the speed of the fighters was greater than that of the bombers and therefore their endurance in the air (though not their range) was less, the escort for a bombing mission did not carry along with the bomber formation throughout, but was organized on a relay basis.

As many as six or seven different batches of escort fighters would take off during a single bombing mission, each intended to make a rendezvous with the bomber force at a definite point along the planned route. The first few would meet the bombers on the way to the target, each staying with them until the next relay came, farther along the line. The middle one or two relays would be assigned to protect the bombers over their target. The last few relays would bring the bombers home.

All this required careful planning, and it also required navigational ability of a high order in the fighter pilots. It is no wonder that it sometimes went askew. Sometimes there was difficulty through no one's fault; the air commander of the bomber force may have decided to alter the route home from the one planned, because of winds different from those predicted, or for any one of a number of good reasons. Hence there were occasions when the fighters went to the place in space-time where the bombers were to be and did not find them. Sometimes the fighters, coming away from a mission exhausted and sometimes shot up, perhaps with their instruments gone, got lost on the way home. A God-like ability to see the whole air situation all of the time, together with reliable long-range communications, would clearly improve the execution of this complicated and difficult operation—the escorted heavy bomber mission—to a very great degree.

Ground radar is in the business of seeing the whole air situation, as far as its range performance will let it, and looked like a natural to the Eighth. They tried some British ground radar working at a medium wave length, which helped a lot. But it did not have quite as long a range as they wanted and it didn't have quite the resolution, by which is meant the radar's ability to see as separate two aircraft which are close together.

For this reason the Eighth embraced a hand-built model of a microwave ground radar which came to England in the summer of 1944. Such are the changing fortunes of war that this set, which had been conceived by its designers as an air-warning radar for defense against hostile bombers, found itself on the east coast of England, as close as the Eighth could get it to their important German targets, helping to run the gigantic operations of the American strategic air force which was beating Germany to her knees.

It was a big help. Like all radars, this set could see only in a straight line, and therefore not over the optical horizon, but it could see a single plane out to that horizon, which amounted to two-hundred odd miles at the altitude the Eighth was using. Controllers sat at the copies of this set and gave navigation instructions to fighters, so that the jumping-off point beyond which the fighter was on his own was no longer the British coast, but a point at least 200 miles beyond. This very nearly cut in two the job of navigation that the fighters had to do.

A straggler, winged and lost, needed only to stagger within the range of this radar set to get his instructions for coming home. If he couldn't make it and had to ditch, the set spotted where he went down and pinpointed it for rescue, vectoring out to that exact spot the air-sea rescue planes.

The individual stories of what this set did are legion, but perhaps the best index to its popularity in the Eighth is the way the whole Air Force, from its commanding general on down, stoutly and successfully resisted all the efforts to take the set away. This had to be done when the excellence of this same equipment for other purposes was discovered through the use of the rest of the hand-built models. A sister set fought the buzz bombs, and they wanted the Eighth's set for that; sister sets, as we shall see, went out with the Tactical Air Commands,, and turned out to be the best thing yet for the control of fighter-bombers, and they wanted the Eighth's set for that. The Eighth not only hung on to its set, but just as soon as a suitable site on the continent was captured and cleared of Germans, it moved this radar to its final site. Here it could command the air in front of it as far as Berlin, and the air in back of it all the way to the English coast. A strategic air force had, for the first time, a single place in which its commander and its controllers could see every important detail of every operation.

One of the results of this ability, which was not fully realized in operations until the collapse of Germany put an end to the work of the Eighth, was that the fighter cover for the bombers could be managed on a much more economical basis. For the hostile fighters which were planning to attack the bombers could be seen as they took the air and formed up for their try, and escort fighters could be sent to meet them long before they got to the bomber stream itself. To borrow a term from basketball, the zone defense could be replaced by the man-to-man defense, and the chance of the *Luftwaffe* fighting through to the bombers in a surprise attack was ended.

It is safe to say that ground radar, of the utmost long-range performance and resolution, has firmly established itself as part of the pattern of Strategic Air Force operations.

10. Radar and the Tactical Use of Air Power

THE THREE aims of tactical air power are to destroy the enemy's air potential, to isolate the battlefield by the immobilization of transport, and to give direct support to the ground troops. Means for executing these principles have been worked out in the operations of our tactical air forces over the past three years, and the development is still going on. One lesson which was learned very early is that a fair-weather air force cannot be depended on for the isolation of the battlefield, and cannot offer a support as dependable as a ground army is likely to require. This suggests the use of radar in tactical operations. The bulk of the aircraft used for such work are single-seater fighter-bombers, however, which cannot carry much in the way of airborne radar, and whose pilots cannot spare time for the interpretation of any complicated display offered by such equipment.

Fortunately, most of the missions performed by tactical aircraft involve targets near the front lines, and therefore not farther from friendly territory than ground radar can be expected to see. The Tactical Air Commands of the Ninth Air Force, led by IX TAC, built up, in the 11 months between D-day in Normandy and the collapse of Nazi resistance, a pattern of ground radar control of fighter-bomber operations which will probably go into the book as a model of how it can be done.

Radar for the TACs was planned right from the start. But, until two months before D-day, the radar with which they were to be equipped was British GCI, which has stemmed directly from the Battle of Britain; and the operating set-up planned within the Command was based implicitly on the idea that the purpose of the radar was to locate enemy aircraft and to vector friendly fighters to make interceptions with them. This is an important purpose, without doubt. It serves not only to provide air defense over the forward troops and battle areas (where the Tactical Air Commands are responsible for such defense), but it enables the TAC to get along with its first mission: destroying the enemy's air power.

The staff of IX TAC felt that radar could do more for them than that. They had experience in northern Italy to build on. Down there, a very effective blockade of German transport routes leading to the battle area had been mounted by the tactical units of the Twelfth Air Force; but the perfection of this isolation of the battlefield had been marred by movement of enemy transport at night, when it was relatively safe from air attack. And a short spell of weather offering poor visibility from the air was all that the Nazis needed to get a makeshift but effective supply system working again. The Twelfth had enjoyed weather which was mostly good, but the Ninth was going into France and Germany, where days of good visibility during fall and winter are somewhat rare. IX TAC felt that, if radar would help them isolate the battlefield under visibility conditions when they couldn't do it otherwise, it would be worth hauling along.

They also wanted it to help them in a TAC's third job—that of giving direct support to ground operations. The targets dealt with by fighter-bombers doing this sort of work are predominantly hard to see from the air. They are such things as camouflaged gun batteries, tanks drawn up under trees, or pillboxes which have been carefully hidden. The downward visibility of a fighter-bomber cockpit is never anything to boast about, at best, and a pilot who is traveling at 250 miles an hour has to know pretty well where to look before he can see such a target. And if the visibility is impaired by clouds, haze, or smoke, he is likely to fail to see his target at all. The TACs supposed that radar could give a hand here, too.

For all of these purposes, the TACs of the Ninth Air Force and of the provisional First Tactical Air Force worked out a system of ground control stations making use of both the British GCI radar and newly developed radar from the United States. In the 2 months before D-Day the integration of the radar and the ground system was completed, and the tactical control of air missions began in Normandy almost as soon as we landed.

One further innovation was undertaken by the TACs. This was the modification of the United States microwave antiaircraft position finder already described to fit it for controlling fighter-bombers and other aircraft engaged in tactical operations. The reasoning back of this was simple: if the radar can find the position of an airplane and plot its track accurately enough to enable guns five miles below to fire a shell to the point in space which the airplane will reach twenty seconds hence, why cannot a controller, using such a radar, take an airplane to exactly the spot in space which is correct for the blind release of bombs or hit an unseen target, or the right spot in space for the beginning of a dive-bombing attack—which will be carried out visually—on a target that the pilot isn't able to see when he begins his dive?

The positioning-finding accuracy inherent in the radar is excellent, and the problem of attaining accuracy in aircraft positioning was largely one of working out means for convenient presentation of radar data to the controller, and techniques permitting the controller and the pilot to work together. The actual modification of the radar was performed by the British Branch of the Radiation Laboratory, and the RAF cooperated in the tactical development of the whole scheme.

By September, when our rapid advance was halted all along the Western Front, radar in IX TAC had been shaken down and ready to go. The weather was rapidly getting worse, and the radar had work to do. Radar-controlled missions included general navigational assistance to all missions, insuring the visual identification of targets which were difficult to see, and the protection of friendly troops and armored units against United States attacks which would otherwise have resulted from failures in navigation; level bombing missions managed by the antiaircraft sets, and carried out above the overcast by fighter-bomber formations, or at night by nightfighters which had been put out of a job by the decline of the *Luftwaffe;* control of day and night photographic aircraft, to insure that the areas covered by their pictures were the ones they were sent out to get; and the more classical GCI function—the vectoring of friendly fighters to intercept hostile aircraft. On a couple of occasions, ground radar even detected the movement of hostile ground vehicles, and alerted the defenses. Then came the German offensive at the turn of the year.

Major General Elwood R. Quesada, in an official report, said in part: " In terms of a continuing operation (radar's) work during the period of the German breakthrough was outstanding. During this unhappy period ' The

Bulge ' contained no well-defined geographic features . . . the whole thing could be flown around in less than ten minutes. . . . Roads were ' chockablock ' with movements. . . . We couldn't distinguish our vehicles from theirs. . . . It was our hope to track by radar each flight directed into the Bulge. . . . The number of American lives saved by our ability to stop attacks on our own columns and installations cannot be measured; nor can we measure the number of Germans killed because our fighter-bomber boys can be informed with assurance that other columns are enemy. . . ."

At the beginning of the German break-through, much of the TAC radar, which had to be close to the front lines in order to be useful, was forced to fall back, but this movement was accomplished in an orderly way, little equipment was lost, and sets not in immediate danger stayed on the air. As soon as the advance had been contained, the radar was moved back up to what had become the front lines, and control was resumed. Increased German air activity accompanied the offensive, and planes controlled by the ground radar came in for their share of the kills. During December, aircraft under the control of one single ground radar of IX TAC accounted for 161 German planes destroyed, 72 damaged, and 11 probably destroyed. A single controller on a single day was credited with 12 ME-109s destroyed and 11 damaged. In the Battle of the Bulge alone, TAC radar had more than paid its way.

Medium bombers, in addition to fighter-bombers, play a part in the pattern of tactical air force operations. What has radar to offer them? In the European Theater, our medium bomber force had made bombing accuracy their keynote. Coming in over their targets at 10,000 to 12,000 feet, they were racking up circular errors many times smaller than the high-altitude strategic bombers could on their deeper, more strongly opposed raids. The mediums needed all this accuracy, for their targets were small: bridges, both road and rail, marshalling yards, and other targets important to transport. One medium wing in Italy had a 6 months' record of dropping, by visual means, within 400 yards of the briefed aiming point over 90 percent of the bombs it lifted off its fields. For radar to be useful in extending the operations of these aircraft over periods of poor visibility, it would have to offer accuracy of the same order as the mediums were used to.

In 1943 and early 1944, the only radar blind-bombing equipment which could meet the medium bombers' requirement for accuracy was the RAF ground-station system already mentioned. This was used by our mediums, in a form incorporating American improvements, but it still suffered from severe operational disadvantages inherent in its design. In the last months of the European war, the British system was replaced by an American system developed by the Aircraft Radio Laboratory in collaboration with a commercial laboratory. This system demonstrated in combat an accuracy better than the previous system at its best; and it removed the principal operational drawbacks of the earlier device. The accuracy of our medium bombers in the Pacific war need no longer depend on the suitability of the weather for visual bombing.

Tactical bombardment of the heavies of the Eighth Air Force had opened the invasion of France, paved the way for the Allied breakthrough out of the beachhead, and was frequently a factor in assisting with the ground advance. Five main Army cooperation missions were run by the Eighth Air Force, and it is perhaps only a coincidence that bombs fell on friendly troops only in the two of these missions which were entirely visual. The other three missions were run by radar, above a solid undercast, and no bombs fell on friendly troops. Each of these five missions was a maximum effort, and the misplaced bombs on the visual missions can probably be attributed mostly to the difficulty of picking out aiming points amid the dust and smoke raised by the bombs of preceding aircraft. Radar, of course, had no such trouble. While its accuracy in the form of B. T. O. is definitely less than visual bombing can afford under the best conditions, it is unaffected by visibility considerations.

B. T. O. was at its best for tactical purposes in the D-day bombing of the beaches. The target, a shoreline and installations just beyond, was admirably suited to show itself well and unmistakably on B. T. O. The job to be done was important and difficult; for 25 minutes beginning at H-30 minutes a rolling barrage of bombs was to be planted ahead of the landing craft of the assault forces—and not very far ahead, for a man can recover from the paralyzing effects of heavy concussion in half an hour. With less than a week to make final preparations for the possibility that the mission would have to be run by radar, the Eighth lifted from its bases before dawn on 6 June 1944, and found solid cloud clear across the Channel. Every bomb dropped was aimed by radar, not a single allied man was killed or hurt by the Eighth's bombs, and the effectiveness of the attack won letters of commendation from the ground commanders.

A tactical air force, in addition to bombing and beating up ground targets, has a big job to do in transporting and supplying airborne troops. United States troop carriers in Europe and Italy have for some time been using a microwave ASV radar to guide them to the drop zones and the landing zones by showing the radar picture of the ground below. Not all troop carrier aircraft are so equipped, and a Pathfinder scheme is used to confer on the aircraft of the main force the navigational benefits of the radar they do not have.

Pathfinder planes, equipped with the ASV (special radar equipment meant specifically for use in troop carrier operations is now going into use) drop, on the various areas which have been selected as drop zones for paratroopers or landing zones for gliders, specially equipped Pathfinder teams of paratroopers. These teams set up and operate a variety of signals which can be " homed on " by aircraft of the main force, including special lights, panels, and " radar beacons," the last being radio transmitters which send out coded groups of pulses when they are challenged properly by a very simple radar set with which all troop carrier aircraft are fitted. The radar beacons, because of the fact that their signals cannot be visually detected either from the ground or from the air, except by the use of the correct challenging equipment, are the most popular form of signal so far as the paratroopers are concerned. Pathfinder teams which had the misfortune last June to land on the Cherbourg Peninsula in the midst of German troops there on maneuvers found that they could not use their visual signals at all. The bulk of the paratroopers were brought to their DZs by means of the radar.

These radar beacons are also very useful in arranging for supply drops to be made at night. There are obvious virtues, during a hotly contested phase of an air-borne operation, in sending the unarmed, slow, and low-flying resupply aircraft out by night; but pin-point dropping is essential. Correct use of the beacons make blind " biscuit bombing " just as feasible as any other kind of blind bombing, and the low altitude from which it is done makes it a whole lot more accurate.

As the war in Europe ended, radar was finding its way into every phase of tactical air operations, and the ingenuity and skill with which our air forces used it were increasing daily. They will carry into the war with Japan—if extended ground warfare proves to be necessary—the same ingenuity and skill and experience, teamed up with greatly improved radar equipment.

11. Radar in Naval Warfare

THE USE of shipboard radar by the fleet in dealing with air attack and in convoy escort work has already been covered. The variety of shipboard radars in use, both longwave and microwave, have been mentioned, and a limited picture has been given of the functioning of CIC in air defense. It is our purpose in this chapter to show the other ways in which radar and CIC have revolutionized fleet tactics and made possible a new flexibility in surface-ship warfare.

In modern task forces, large numbers of ships cruise at high speed in relatively tight formations with all lights blacked out. This not only provides protection against possible enemy submarine attack, but provides a concentration of fire power against possible air attack, helps prevent detection by snooper planes, and has numerous other advantages. Before this war, however, such a formation presented a problem in station keeping, and few officers-of-the-deck were ever absolutely sure where their neighbors were. The situation was particularly fraught with danger for every man on board when the whole formation was executing simultaneous zig-zags. If a single OOD made a mistake and "zigged" when he was supposed to "zag," or even if he forgot to execute the turn on time, collision was a probability.

Today, however, watching the whole situation on a PPI he can maintain his proper station in the formation throughout zig-zags, course changes, and emergency turns solely on its information. Even without the repeater, CIC relays to him periodical ranges and bearings on the guide and on the ships nearby which may themselves be out of station. And not only are the individual OOD's able to handle their ships in perfect safety, but the officer in tactical command of the force can see at a glance the disposition of the formation for which he is responsible.

On the basis of this radar information, but supplementing it, a summary plot is kept of all ships in the disposition and the officer in tactical command can be advised, for example, which destroyer is leaving the screen for picket duty, which one is returning from investigation of a sound contact, the position of the carrier which has left the formation to launch and land planes, the composition of the carrier's screen and literally scores of kindred items.

In addition, the same information is available concerning other friendly forces within radar range—providing sufficient intelligence information has been made available. With surface radar, IFF, and the latest operational information at his side, a CIC officer can report something like the following to the Captain, even in the middle of the darkest night:

"Several ships—probably five, two large and three in the screen; lead ship bearing 030, range 39,000, showing IFF; course 220°, speed 18 knots, no zig-zag; believed to be two CVE's on ferry duty with three cans in screen, as they are approximately 3 miles west of the supposed position of ferry group; should pass them to starboard with 2,000 yards between screens at 0137; will advise any change in course, speed, or our evaluation."

This is not a trumped-up situation for the sake of example. This is being done every day on almost every ship in our Navy.

If such information can be furnished about friendly forces, it can do the same with enemy forces. Then the report above might be the same except for the statement:

" No IFF, evaluation—enemy; could be task force reported to have sortied from Tokyo Bay, consisting of one BB, one CL, and 3 cans." And at this point CIC would be feeding information to the gunnery department. The target's bearing and range, course and speed are fed into computers as the huge main battery directors swing swiftly into position. Gun crews stand ready to load powder bags and shells.

The two forces continue to close. New ranges and range rates automatically reposition the mighty guns. Finally the radar indicates that the enemy is within range. Word is given to " Commence firing!" the Master salvo key is closed, and with a roar nine 16-inch shells go hurtling through the night. So sensitive is the radar that the operator can " watch " the shells move across his screen toward the target " pip." Then he sees indication of their splashes and can quickly read off how much correction must be made. Again the guns boom forth, and this time the salvo appears to land squarely on the leading ship. Sure enough, as the operator watches, the " pip " slowly fades from the screen. The ship has been discovered, identified, tracked, fired upon, and sank without a man seeing it visually.

This is not an imaginary incident. It has happened many, many times in the history of the present war.

One of the first times was late on the evening of 4 November 1942, among the Solomon Islands in the South Pacific. One of our new warships was out looking for the enemy. The sea battle for Guadalcanal was in its final phase, the issue still undecided. Aboard the American vessel, radar, like an invisible searchlight, probed the darkness and discovered the presence of an enemy vessel more than 8 miles away. The big ship lifted its gun muzzles towards the stars. They flashed and thundered. The second salvo, despite both darkness and extreme range, landed squarely on the target, which disappeared from the radar screen.

Last fall, at the battle of Suriago Strait, the captain of a destroyer leading a column of destroyers was on the bridge when the enemy fleet was sighted and action was begun. The commodore of the destroyer force was in the CIC, watching the radar screens and plots. It was a spectacular surface battle at fairly close range, and the gunfire and the blaze of Japanese ships which had been hit made an unforgettable spectacle.

" Come up here, for the sight of your life! " the captain called down to the commodore.

Replied the commodore: " No thanks. I can see it better from here."

A technique has been worked out for shore bombardment with the aid of radar that is perhaps even more remarkable than the technique of sea battle. It has played an increasingly important role in the advance of our amphibious operations across the Pacific and in the working over the Jap home islands. In the black of night or through the thickest fog our warships can pinpoint a target.

Obviously, if such precision of gunfire is possible by means of radar readings of short targets, radar is an everpresent, invaluable aid to navigation and piloting in dangerous waters. This, of course, will be its major peacetime use for shipping and passenger liners. A captain can bring his ship safely into narrow harbors, avoiding navigational hazards, detecting landmarks, lighthouses, buoys, rocks, coast line and other dangers. He can detect other ships going in or out and avoid collision, though the harbor be fog-bound. The contour of a shore line can usually be seen almost as accurately as if it were drawn on a chart.

Rather early in the war, the ultimate potentialities of radar began to be apparent when the following incident took place. A formation of cruisers was ordered to steam into an archipelago in the Solomon group to bombard some enemy shore installations. The time chosen was on the blackest of black nights, and the waters had been charted only sketchily, yet the formation set out, relying on their radar to bring them through. They took column formation, steaming at 25 knots, and kept formation perfectly. They cruised confidently through the intricacies of the unfamiliar archipelago to the point to be bombarded. Reaching that point, they successfully evaded several mine-sweepers engaged in sweeping operations in the immediate vicinity. They found their objective and carried out their assigned bombardment. Still at 25 knots, they turned and countermarched in the narrow waters and steamed back out. And on their arrival back at base, they were able to report that one of the reefs on their crude charts was in error by about six miles. All this was done in zero visibility.

Again and again in this war, it has been necessary for United States Navy ships to approach strange harbors in the dead of night—harbors about which only the sketchiest information is known. In the Aleutian campaign we operated for two winters in waters of the most perilous kind which had never been charted. Farther out in the Pacific it has enabled our largest battleships to come closer to strange shores in the dead of night than they would ever have dared before. This has afforded point-blank fire against shore batteries. In the same way, transports and cargo ships are permitted to unload closer to the beach, lessening the danger to their small craft and saving immensely on unloading time.

The other ways in which the Navy has used radar to speed the end of the war are literally too numerous to mention. Many of them are still bound in security. But it is safe to say that the speed with which our overwhelming naval might has driven the Jap from the seas and brought our land forces within the shadow of Tokyo would have been much more difficult and costly in men and ships without radar.

12. The Electronic Navigation

EARLIER DISCUSSION of the use of radar in ships and aircraft has made it clear what an important bearing radar has on navigation. The RAF's pulse navigation system, designed to guide its bombers out and back on their raids over Germany, has been more or less universally adopted for air navigation, either in its original form or in a United States version which goes by the name of Loran (for Longe Range Navigation).

This system, while based on the same principles as the British system, was developed independently by the Radiation Laboratory. Work on it was commenced by the beginning of 1941, and by the end of 1942 the first of the ground stations which were later to lace the world with the electronic lines of position were operating. The original British system works on a shorter wave length; and is consequently limited to straight-line propagation and line-of-sight ranges. It is of little use for the navigation of surface vessels for this reason—before they are many miles from the ground stations they are over the horizon and out of range.

Loran, on the other hand, works on a longer wave length which is not radically different from the range of wave lengths used for long-range radio communications. Its waves are reflected from the ionosphere and therefore follow around the curvature of the earth just in the way that radio broadcasting waves do. Loran fixes can be taken either by aircraft or ships at distances of several hundred miles—sometimes more than a thousand miles—from the ground stations. The accuracy of these fixes is just as good as a celestial observation would provide, and they are much easier to take and interpret than celestial fixes are. They are available whatever the weather or the visibility. This system has become the basic navigational scheme for the long-range ships and aircraft of the United Nations, not only for combat craft, but for transport ships and aircraft as well.

We have also seen how airborne radar, such as B. T. O., or the ASV used by troop carrier aircraft, will permit navigation by radar pilotage, in which radar check points which may be cities, lakes, islands, or characteristic stretches of shorelines, are used in place of the visual check points so essential to conventional air navigation. Such radar pilotage cannot be used over empty expanses of water, of course; here Loran is the only reliance. And it must not be depended on, alone, for truly reliable navigation, but must be supplemented by full-time dead reckoning. Radar check points, however, permit constant and reliable dead reckoning to be done over land or within a hundred miles or so of land, and are a primary reliance of all aircraft which carry airborne radar.

Certain supplementary devices aid in navigation by airborne radar. Mention has already been made of the radar beacons which give a characteristically coded reply to a radar challenge; the world is now dotted with these unmistakable radar check points. And the labor of dead reckoning is being reduced by a radar attachment which will do automatic dead reckoning between the taking of radar fixes, obtaining its data from a compass repeater and a true air speed meter.

One last radar device deserves mention; this is the radar altimeter. Just as the range to an aircraft can be measured from the ground, so the range to the ground can be measured from an aircraft by radar means. Crude radar altimeters antedated the war, but the development in the radar art has made the present automatic radar altimeter a simple, reliable, and practical device. It is very widely installed and used.

13. Radar Personnel and Training

To APPRECIATE fully the remarkable nature of the growth of radar and of its use in the war, we can compare it with the development of the airplane.

In terms of the elapsed time between the reception of the first pulse radar signals in the history of the world and the outbreak of war, it is as though a war had begun in 1907 and the Wright Brothers' airplane, having made its first faltering flight in 1903, had been developed by 1910 into a powerful weapon of which thousands were in constant use.

There is nothing magical about radar. Much of its effectiveness depends on the techniques that have been evolved to make maximum use of its information. And its work depends ultimately on the training, native skill, and intelligence of its operators, and on the degree to which radar's capabilities have been integrated into tactical planning and combat operations.

The development of radar moved so rapidly all through the last years before the war and the early years of the war itself that only the radar specialist had any real knowledge of its behavior and its capabilities. Yet the immediate demands of war made it necessary to expand suddenly and tremendously in all directions at once.

Probably no scientific or industrial development in the history of the world has expanded in all phases simultaneously, and on such a scale. Research, development, production design, actual production, field trials, training of thousands of operators and installers—all these had to go on at the same time, and they did. Most significant of all, the use of radar with the armies and the air forces in the field, and the ships at sea, was so widespread that nearly every responsible commanding officer had to be educated to an appreciation of the capabilities and the limitations of the new weapon which was being put into his hands. Having gained this appreciation, officers in the field had to work out the tactical employment of this new equipment through the trial and error of combat operations. Further, they had to communicate the experience and knowledge thus gained to all other field commanders. All this was made more difficult by the necessity of maintaining the strict secrecy which must surround a new and important development.

The Army and the Navy set up a huge program to fill the ever-growing needs for operating and maintenance personnel by recruiting men with radio experience, and establishing special pre-radar and radar schools.

The earliest training of Army personnel in radar techniques was informal and was carried out at the Signal Corps Laboratories concurrently with the early development work. It was effectuated by such steps as having a detachment of antiaircraft troops stationed at the laboratories for several years beginning in 1937. A course on Radio Set SCR-268 for Coast Artillery noncommissioned officers was conducted at the Signal Corps area on Fort Hancock in the fall of 1940, and these men served afterward as the nucleus for an antiaircraft artillery radar school.

On 2 June 1941 the Signal Corps School at Fort Monmouth set up an Aircraft Warning Department which, by early 1942, was operating on a three-shift basis to provide the many operators and maintenance men needed for the greatly increased numbers of radar sets coming from the factories. In June 1942 Camp Murphy was opened at Hobe Sound, Fla., to house the Signal Corps Radar School, later renamed the Southern Signal Corps School. During the ensuing 2 years, this school trained thousands of enlisted men and officers of the Signal Corps, Coast Artillery Antiaircraft, Air Corps and Marine Corps, as well as a limited number of Allied Army officers, in the operation and maintenance of various types of radar equipment.

Special technical training in ultra-high-frequency techniques associated with radar was given Army and Navy officers at Harvard University and the Massachusetts Institute of Technology, beginning in June 1941. These schools gave the armed services the advantage of the most advanced electronic training facilities at two institutions whose faculties also were connected with major research projects in the electronics field.

The Navy, of course, was having similar personnel problems early in the war, and at first it fell to the Naval Research Laboratory to furnish most of the technical know-how. The Radar Section, which now numbers more than 600 people, at that time consisted of only a handful of scientists. These few had to double and triple in brass, supplemented where possible by field personnel of contractors for radar equipment. Their presence was required in the Laboratory itself to solve the urgent development problems that faced them. But if the equipment was to be installed and operated, they were required elsewhere as well. They were required in navy yards to teach the Radar Divisions the entirely new art of installing radar. They were also required to go aboard ship and explain the operation of the new equipment to the radiomen and other bluejackets who had been hurriedly pulled from other stations to become radar operators. They were required to write manuals and instruction books. And finally they were required as teachers in the newly-set up radar schools.

To simplify the geographic problem, the first Navy radar school was established at the Naval Research Laboratory. Later, a second school was started at Treasure Island, a third at United States Navy pier, Chicago, and still others in several universities. Laboratory personnel was required to assist in most instances.

The story of radar training in the Pacific Fleet illustrates the point.

In the spring of 1941, the Commander in Chief, U.S. Pacific Fleet, took steps to meet the problem of training the Fleet, and a few dozen officers were returned to the Naval Research Laboratory.

The time and distances involved as well as the limited capacity of the laboratory made necessary the establishment of a school at the Fleet base in Hawaii. A request was made, and plans for this advanced school were under way before the outbreak of hostilities. From the beginning, the school, although staffed mainly by Navy personnel, taught the maintenance of all types of radar—landbased, airborne, and shipborne—so that when the school began formally in March 1942, it was attended by Army, Marine and Navy personnel.

By the end of 1942, the situation had become more complex, for the supply of experienced radio repair men was nearing exhaustion, many new types of radar were appearing, and the numbers involved were rapidly increasing. In order to meet these new demands, specialized training was instituted, and a preradar course was begun in order to give more background to the less experienced students.

Since the early radars were air search radars, the problem of training fighter direction officers arose at an early date, and a school was started in San Diego in 1941, which moved to Hawaii in the spring of 1942 and occupied part of the same building as the maintenance school. The fighter director school was also an interservice school teaching controllers from all branches of the service. In addition to teaching, this school developed the tactics of fighter direction which were to prove so successful in later battles.

The Fleet Radar Gunnery School was founded in November 1942 to teach fire-control tactics. In the spring of 1943 it was decided that steps should be taken to coordinate all Fleet radar training and development in one organization to be known as the Pacific Fleet Radar Center with the mission of training radar maintenance men, radar operators, CIC and Fighter Director Officers, and of instructing senior officers in radar tactics.

Today, training of Naval radar operators and technicians is organized on a vast Nation-wide scale. Training aids of every kind have replaced the highly personal, verbal instruction that served in the early, critical days. More than 125,000 officers and men have gone through advanced radar training at Navy schools within this country.

With the initial phase of Air Corps radar training—in the use of ground sets for the Aircraft Warning Service—handled by the Signal Corps in the early days, the first problem of Air Corps training concerned itself with the use of ASV, and other sea search equipment, used by the Antisubmarine Command. A school was set up at Langley Field, headquarters of the First Sea Search Attack Squadron, where training mehods were pioneered, usually under operational conditions. The growth of the radar training program in the AAF is seen in a comparison between the 818 graduates of all radar courses for the first 6 months of 1942 and the 23,175 graduates for the first 6 months of 1945. In the interim radar schools had been set up in all the Technical and Flying Training Commands. With the introduction of B. T. O., the difficulty of training increased, for a potential radio operator or bombardier who would use the equipment in combat could be taken on only a limited number of operational flights over simulated target areas. Many ingenious training devices have been developed to simulate, for students, the performance of airborne radar equipment, and thus cut down the flying hours required for instruction.

In April 1941—a month after passage of the Lend-Lease Act—British authorities offered to provide training for American officers in the radiolocation system which already was in operation against the German air force and U-boats. An agreement was made by which hundreds of qualified United States Army Signal Corps officers were to be sent to the United Kingdom for radar training in British schools, and a period of operational duty with the British armed forces. The United States Army's ranks were combed for officers and men with the requisite education or experience in radio engineering or electronic physics. Enlisted men and civilians with the necessary qualifications, who volunteered for overseas duty at a time when the United States was still at peace, were appointed second lieutenants in the Signal Corps Reserve with assignment to the Electronics Training Group.

The recruiting campaign began 30 June 1941. The first section of the Electronics Training Group—consisting of 1 first lieutenant and 30 second lieutenants—was assembled at Fort Monmouth on 11 August 1941. After 3 weeks of preliminary instruction on American-type radar equipment, the officers on 12 September left Fort Monmouth for England. They were classified as military observers, and headquarters of the Electronics Training Group was established at the American Embassy in London. The American officers were given theoretical and laboratory training in British schools and then assigned to British Army and Royal Air Force operational units. By the end of November 1941, a total of 209 Signal Corps officers were on duty in England. The next group of 50 learned only upon their arrival that the United States had been attacked at Pearl Harbor while they were at sea.

America's entry into the war accelerated the return of some of the ETG officers, and by March 1942 a total of 58 had been brought back for reassignment to aircraft warning duties with AAF Fighter Commands along the coasts of the Continental United States and at overseas bases. Many of those remaining in England after the completion of their instruction took over active positions in the British aircraft warning service as well as on airborne radar patrols against German submarines. Four members of the group were reported killed or missing as a result of airplane flights during their service in England.

When the overseas electronics training program was ended in 1943, a total of 907 Signal Corps officers had completed their training in England—457 in British Army radar, and 450 in Royal Air Force equipment. On various occasions thousands of British troops served under the command of these American officers, at a time when combined military operations under supreme allied headquarters were still in the future. As United States operations expanded in the European theater, many of these Signal Corps officers were taken over by AAF units.

From the British viewpoint the ETG provided qualified personnel during a period when both the British Army and the RAF were short of officers with the necessary technical background. From the American point of view the arrangement was valuable because a number of these officers obtained training and experience under operational conditions, during a phase of the war when the United States had not yet undertaken full-scale offensive expeditions.

Under various auspices, important civilian assistance was rendered to the Army and Navy. In the Navy, an Operational Research Group working on the antisubmarine problem was concerned with operational matters touching radar. Under the sponsorship of the Navy's Bureau of Aeronautics, the Airborne Coordinating Group sent to the field civilian radar experts concerned with maintenance. Many radarwise civilians have been working with the Army, mostly the Army Air Forces. The AAF had Operations Analysis Sections which were, as part of their work, concerned with the operational performance of radar.

The Signal Corps had, in the Office of the Chief Signal Officer, an Operational Research Group concerned with the impact of operational experience on equipment problems. The Signal Corps and Air Service Command sent to the field civilian Technical Observers, on contract from industrial firms, to deal with maintenance and other radar problems. Civilian consultants in the office of Dr. E. L. Bowles (who was the first secretary of the Microwave Committee and has served since April 1942 as Expert Consultant to the Secretary of War) were sent to the field to serve as expert advisers on the operational use of radar. This group also assisted in planning the Army's radar program, integrating the scientific and industrial effort with the military needs.

The Radiation Laboratory set up a British branch which helped with the field modification of radar equipments to fill operational needs, gave maintenance help, and in some cases advised on the operational use of radar. The Office of Field Service of OSRD, operating through the War Department General Staff, sent civilian experts to the theaters to advise and assist in the operational use of new equipment.

Whatever the formal auspices on which civilians reached the field, once there they were welcomed by most commanders. Because of their special knowledge of the new and rapidly-developing field of radar, these men could often be useful in connection with operations; and they were able to bring back to design and procurement agencies an up-to-date picture of radar's current performance and of the directions in which new developments were most urgently required. As radar became more of a routine part of military operations, the Army and Navy to an increasing extent provided specially trained detachments to introduce new equipment systematically into combat.

14. Radar in the Peacetime World

THERE has already been a great deal of rather uninformed speculation about the peaceful uses of radar. It will be clear from what has gone before that the direct and immediate use of radar will be to make air and sea navigation entirely continuous and foolproof, regardless of night or weather. Its use in land transport, during the immediate postwar years, is more dubious. In the forms in which it exists now, radar is not a very useful attachment to an automobile or a railroad locomotive.

The biggest influence radar will have after the war is indirect. The thousands of man-years which have gone into the improvement of the detailed components which make up a radar set—many of these components being identical with those of a radio or television set, or hearing aid, or other electronic device—have made obsolete many of our prewar ideas about what could and could not be done in electronics.

Furthermore, radar has made the electronic industry one of America's major ones, now comparable in size to the pre-war automobile industry. This new industry, through its enormous laboratories, can be expected to find innumerable applications in a wide variety of fields.

If television is still around the corner after the war, nothing but economic factors, not technical ones, will have kept it there. Communication, especially radio communication, will have a tremendous flowering based largely on the opening up of the microwave field.

Individual radio communication is even beginning to appear a practical matter, subject to certain limitations.

The number of men who have been trained in the techniques of radar operation and maintenance by the Army and the Navy is colossal; we can expect these men, in large part, to make feasible the greatly expanded use of electronic equipment of all kinds, because of their preparation to enter the industry or to set up in the parts and repair business.

Altogether, it is fair to say that radar, as radar, will have a mild immediate beneficial effect on all our lives, by making it safer to travel by sea or by air. But the impact on electronics generally of techniques developed during the war because of radar will have profound and far-reaching effects on the shape of our daily life.

Appendix. Technical Description of Radar Systems

PRACTICALLY every radar set is made up of the following major parts or components:

1, A modulator; 2, A radio-frequency oscillator; 3, An antenna with suitable scanning mechanism; 4, A receiver; and 5, An indicator.

While the physical form of each of these components may vary widely from one kind of radar set to another, each radar must have this complement of parts in order to function.

1. The *modulator* is a device for taking power from the primary power source (which may be the commercial power line, a special engine or motor-driven generator, or storage batteries) and forming suitable voltage pulses to drive the r-f oscillator in its bursts of radio frequency oscillations. In other words, it is the modulator which turns on the radio frequency oscillator to oscillate violently for a millionth of a second or so, turns it off sharply and keeps it in repose until time for the next burst.

2. The *radio-frequency oscillator* is a vacuum tube of suitable design, or a group of such tubes, which will oscillate at the desired radio frequency and give the desired bursts of radio frequency power when connected to the modulator. The development of suitable oscillator tubes has been one of the major achievements of the radar art. It is a relatively simple job to produce a radio frequency oscillator which will give oscillations of any desired frequency provided one is satisfied with a power of only a few thousandths of a watt. In the receiving part of a radar circuit this amount of power is adequate. A practical radar transmitter, however, must generate during its momentary bursts of oscillation a power which may run into hundreds of kilowatts. Since the oscillator is turned on a small fraction of the time, the average power is usually hundreds of times less than the peak power, but even the average power may run up to the order of one kilowatt. Thus, practical radar equipment requires extremely high frequency oscillators running at powers thousands of times greater than was thought possible a few years ago.

3. The problem of *antenna* design is also one of the major problems in radar, incomprehensible as this may seem to the operator of a home radio receiver, who finds a few yards of wire strung up on his roof adequate for his purpose. A suitable radar antenna must have the following characteristics:

> *a*. It must be directional; that is, it must concentrate the radio energy into a definitely defined beam, since this is the method by which the direction to the objects detected is determined;
>
> *b*. It must be highly efficient. All of the generated power must go into the beam and none must leak off into " side lobes " in other directions, since such side lobes may often be fatally confusing; and,
>
> *c*. The radar antenna must be capable of being directed or scanned from one point in space to another, and on shipboard and in aircraft it must frequently be stabilized to take out the motions of the ship or airplane itself.

An antenna may be made directional either by building it up of an array of small antennas or dipoles, suitably spaced and phased to concentrate the energy in one direction, or it may be built on the searchlight principle of spraying the energy into a large parabolic " mirror," which focuses the energy into a beam. In either case, the larger the antenna, the sharper the beam for any given wavelength. Sometimes antennas may be longer in one direction than the other, giving a beam which is sharper in the first direction and thus fan shaped.

The *scanning* of the portion of space which the radar set is intended to cover must usually be done by mechanical movement of the antenna structure itself. This means that the structure, whatever its size, must swing around or up and down to direct the beam in the necessary direction. In certain cases where one needs to scan only a small sector, techniques have been worked out for rapid electrical scanning not requiring the motion of the whole antenna structure itself. So far, however, there has been no method for extending this rapid electrical scanning to cover more than a relatively small sector. Radars for directing guns which need accurate and fast data in a small sector are making use, however, of this valuable technique.

To carry the radio-frequency energy from the oscillator to the antenna, and the echo from the antenna to the receiver, wires and coaxial cables are used at ordinary wave lengths. For microwaves, however, it is more efficient to use wave guides, which essentially are carefully proportioned hollow pipes—and the transmission system hence is often called " plumbing."

4. The problem of the *receiver* for radar is also a complex one. In practically all radars the superheterodyne principle is employed, which involves generating at low power a radio frequency fairly close to that received, and " beating " this against the received signals, forming an intermediate frequency, which is then amplified many times. Curiously enough the crystal, used as a detector and mixer, has again come into its own in microwave receivers. The peculiar characteristics of pulse signals require that receivers be built with extremely fast response, much faster even than that required in television. The final stages must prepare the signals for suitable presentation in the indicator. The receiver normally occupies a relatively small box in the complete radar set, and yet this box represents a marvel of engineering ingenuity. A particularly difficult piece of development is concerned with a part closely connected with the receiver. This is a method of disconnecting the receiver from the antenna during intervals when the transmitter is operating so that the receiver will not be paralyzed or burned out by the stupendous bursts of radio frequency energy generated by the transmitter. Within a millionth of a second after the transmitter has completed its pulse, however, the receiver must be open to receive the relatively weak echo signals; but now the transmitter part of the circuit must be closed off so it will not absorb any of this energy.

5. It is the *indicator* of a radar that presents the information collected in a form best adapted to efficient use of the set. Nearly (but not quite) all radar indicators consist of one or more cathode-ray tubes. In the simplest or " A " type of presentation the electron beam is given a deflection proportional to time in one direction—say, horizontally—and proportional to the strength of the echo pulse in the other—say, vertically. If no signals are visible, then one sees a bright horizontal line (the " time base ") across the tube face, the distance along this line representing time elapsed after the outgoing pulse. A returning echo then gives a **V**-shaped break in the line at the point corresponding to the time it took the echo to come back. The position of the " pip "

along this line measures the distance to the reflecting object. There are many variations of this type of indicator for special purposes, but most radars have an A-scope, even when other types are also provided.

Many types of radar whose antennas " scan " various directions employ the PPI tube. Here the time base starts from the center of the tube and moves radially outward in a direction corresponding to that in which the antenna is pointing. This time base rotates in synchronism with the antenna. The returning signal, instead of causing a break in the time base, simply intensifies its brilliance for an instant. Hence each signal appears as a bright spot of light at a position corresponding to the range and bearing of the target. Thus a maplike picture of all reflecting objects appears in the cathode-ray tube face.

Since the antenna can usually be rotated only slowly (e.g., from 1 to 20 r.p.m.) and since the light from an ordinary cathode-ray tube fades away almost instantly, one might expect not to see a " map " at all, but only bright flashes at various spots as the antenna revolves. Some way had to be found to make the brightness of these flashes persist for many seconds after they were produced. Special screens were developed which continue to glow for some time after being lighted by a signal. Thus the whole map is displayed at once.

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