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CHAPTER I

INTRODUCTION

RADAR can be described as the science of locating distant objects by radio. Many of the techniques used are as old as radio itself ; others have been developed under forced draught to meet the urgent demands of war and it is these which will be described in this book.

Radar depends on two fundamental processes neither of which is essentially new—the use of short pulses for the measurement of distance and the scattering of radio waves by material bodies.

The first use of radio frequency pulses was in 1925 when Breit and Tuve[1] used them as a means of investigating the reflecting regions of the upper atmosphere. They radiated pulses of approximately 1/1000th second duration in a vertical direction, which after reflection at the ionosphere were received on a receiver adjacent to the transmitter. The time of transit of the radio waves was observed and, their velocity of propagation being known, a direct measurement was obtained of the equivalent height of the ionosphere. In the years which followed this became the standard method of conducting such investigations in nearly every country in the world.

The scattering of radio waves was first observed by Hertz during his classical experiments in 1886. On many occasions since, the suggestion has been made that such scattering might be used for the location of obstacles but it was never demonstrated in practice. The next reported observation of interest was by a team of British Post Office engineers[2] who in 1932 observed the reflection of radio waves scattered from an aircraft in flight.

[1] G. Breit and M. Tuve, " A test of the existence of the conducting layer," *Physical Review*, Vol. 28, September, 1926, p. 554.

[2] F. E. Nancarrow, A. H. Mumford, F. C. Carter and H. T. Mitchell, " The further development of transmitting and receiving apparatus for use at very high radio frequencies," Post Office Radio Report No. 223, June, 1932.

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It was the combination of this observation with the use of pulses for measuring distance which, in the years between 1930 and 1940, gave rise to the remarkable techniques which have since become known as radar.

Historical Development

These events were part of the normal process of scientific research, the results of which were freely published and discussed throughout the world. But when their vital importance was realised, a cloak of secrecy fell on the work and obscured its subsequent history. It is known, however, that the broad path of scientific development leading to radio location was followed in England, America, France, Italy and Germany, and in many of these countries the years 1934 to 1936 saw the culmination of experimental work and the emergence of embryonic radar systems.

In England it is interesting that radar was not so much the result of a happy inspiration as the consequence of a deliberate and carefully planned policy. In 1935 there was apathy in the land and the danger of an impending air attack went unheeded except by a small minority of people. Prominent among the few who recognised the danger was Sir Henry Tizard, who formed a committee of scientists to investigate the problem of the defence of Great Britain against air attack. They studied all forms of defence—fighter aircraft, anti-aircraft guns and the passive methods of air raid precautions—and arrived at one outstanding conclusion : that unless there was at least twenty minutes warning of the approach of enemy aircraft, practically all forms of defence were useless. Tizard and his committee were therefore able to postulate the basic problem, and once it was stated in a simple form, the solution was soon forthcoming from another source. Putting together his experience of the pulse method of investigation of the ionosphere and his knowledge of the observation of the reflection of radio waves from aircraft, Watson Watt (now Sir Robert Watson Watt) was able to suggest the radio method

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which not only provided the necessary warning but gave precise location as well. Following this proposal, Watson Watt and a small team of co-workers succeeded in receiving pulsed echo signals from a distant aircraft for the first time in June, 1935.

In America[3] the search for methods of obstacle detection began much earlier than in Britain and there is record of work being done at the Naval Research Laboratory, Anacostia, in 1922. As a result of these efforts, pulsed radar detection equipment appeared in the United States at about the same time as in England. A remarkable feature of these efforts was that in spite of the fact that there was no communication between the participants, there was striking similarity in the final equipment. The first American air warning equipment for use on board ship operated on 200 megacycles per second, a frequency identical with that of a British ground-based equipment. The aerial system consisted of the same number of elements mounted on a similar reflecting mattress, while the transmitter and receiver were almost indistinguishable in each case.

War Application

The first application of radar in war was as a defensive weapon. Because radio waves can propagate farther than visible light, at night or through adverse weather conditions, the primary function of radar was to deny the enemy that element of surprise which is normally a potent factor in offensive operations. With later development, the wider potentialities of radar were recognised and it finally proved as effective in offensive operations, on land, on board ship and in the air. Its applications can best be described in terms of the objects from which echoes are obtained when radar equipment is used in various locations.

As shown in Fig. 1, a radar set on the ground obtains echoes

[3] "Radar—A report on science at war," released by the United States Joint Board on Scientific Information Policy, August, 1945.

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from distant aircraft at moderate or high altitude. This is its air warning function, detection of the approach of hostile aircraft being used to alert the defences and to scramble fighter

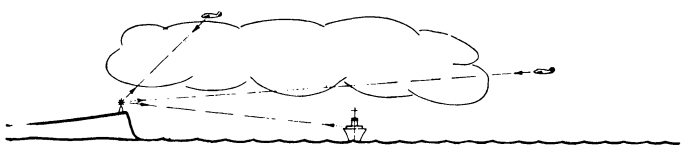

Figure 1.—The reception of echoes from ships and aircraft on a ground radar set.

aircraft. It is followed by the active defensive phase during which other radar equipments fix the position of individual hostile craft more accurately and use the information for the control of fighter aircraft, for searchlight direction and control of gunfire against seen or unseen targets. In addition, ground radar obtains echoes from ships at sea, the information being used for control of fire from coastal batteries.

The use of radar on board ship is similar to that on land, as shown in Fig. 2. For tactical reasons the division of functions is into air warning, sea search and fire control, the last being against both surface and air targets. In addition, the

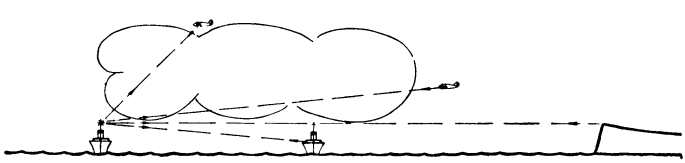

Figure 2.—The reception of echoes from other ships, aircraft and land targets on a shipboard radar set.

ship's radar equipment obtains echoes from nearby coastlines, a feature which has proved useful for navigation in coastal waters.

Perhaps the most varied uses of radar are in aircraft, because echoes are received from a greater variety of targets, as shown in Fig. 3. Echoes are received from other aircraft in the

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sky, enabling air interception to be carried out at night and in certain cases, air-to-air blind firing. Ships or surfaced submarines, in fact anything protruding from the surface of the sea, can be detected and attacked by blind bombing methods. Coastlines and hills provide massive echoes which

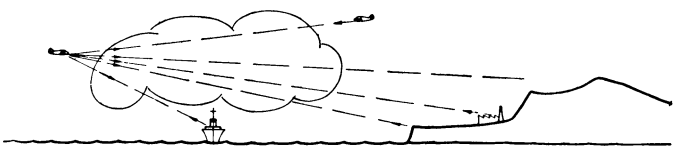

Figure 3.—Airborne radar equipment can receive echoes from other aircraft, from ships or surfaced submarines, the ground or built-up areas.

are detected at extremes of range and have proved invaluable for navigational purposes. Finally, built-up areas may be recognised by the larger signals which are reflected from them compared with those from open country, and attacked without the pilot seeing them by eye.

The first great test of radar in war came during the Battle of Britain. The Hurricanes and Spitfires of the Royal Air Force Fighter Command were superior to the aircraft against them and their pilots were without equal ; but their numbers were small against a huge attacking force. The use of radar so enabled them to conserve and direct their available strength that the attack was finally beaten back with disastrous losses to the enemy.

There followed the Battle of the Atlantic which was notable for the use by the enemy of every technical trick to an extent which exceeded that in any other phase of his war effort. Initially enemy submarines had the advantage. They were free to cruise at will and at considerable speed on the surface at night and were obliged to submerge only during the hours of broad daylight. Soon after hostilities commenced radar changed this set of conditions in a startling manner, since it provided patrol ships and aircraft with means of spotting submarines at night or in any weather. The submarines were forced to remain submerged for long periods to preserve themselves from crippling attacks and this so reduced their mobility that they were prevented from making effective

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attacks on our shipping. So passed the first great wave of shipping losses and the submarine menace was temporarily reduced to a low level.

The submarines collected their forces and came back with a countermeasure which again gave them virtual freedom of the seas. It was the use of listening receivers which gave warning of the approach of radar-equipped ships or aircraft. Shipping losses rose to a new peak, but for reasons not in any way connected with submarine warfare, the solution was ready in the form of microwave radar detection equipment which had been developed for other purposes. Not only did it have a performance superior to that of earlier equipment but it could not be received on the submarines' listening gear. The installation of the new equipment was carried out with all possible speed and it was instrumental in restoring the ascendancy to our ships and aircraft. Shipping losses were once more reduced while enemy submarine losses mounted to a greater height than at any other period. The waves of measure and countermeasure continued with the scales weighted heavily in the Allies' favour, until in 1943 a situation existed in which there were a greater number of submarines at sea than at any other time, but the intensity of our patrols and attacks was so great that shipping losses were negligible. The "one single weapon" to which Hitler attributed the failure of his submarine warfare was at once an admission of the superiority of Allied equipment and a tribute to the scientific way in which it was used.

Finally in the air offensive operations which were of such importance in the later stages of the war both in the European and Pacific theatres, radar was effective in overcoming the limitations of weather which at one time threatened to cripple the scale of our effort. The number of occasions on which aircraft could leave their base in clear weather and find their target also clear was surprisingly small; in Europe this would have restricted useful air operations to some six days a month. By providing aids to navigation, new target finding methods and blind bombing techniques of startling precision, radar

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unshackled the bonds of cloud and weather and allowed the final attack to be launched at its full intensity.

The Special Features of Radar

The features of radar which make it outstanding are its ability to measure distance, its use of radio frequencies which propagate over considerable distances, and the extraordinarily sensitive methods it incorporates for detecting minute quantities of electromagnetic energy.

The measurement of distance is accomplished by determining the time of transit of a radio wave from its point of origin to the target and back again. The velocity of propagation being known, the distance to the target can then be determined in miles. The precision of the observation depends on the timing accuracy and our knowledge of the velocity of propagation of electromagnetic waves in the lower atmosphere. Using refined methods, the timing may be as good as 1 in 10^9 (or a few feet in a million miles), but the final accuracy is at present limited to 1 in 10^5 due to variations in atmospheric propagation. In practice it has been found relatively easy to measure distance to an accuracy of a few hundred yards, while for special military purposes a precision of $\pm$ 20 yards has been achieved over a distance of 200 miles. It is now known that this can be improved by a further factor of 3 or 4.

The frequencies which have come into widespread use for radar purposes are in the region between 100 and 10000 megacycles per second, within which band atmospheric attenuation is negligible. The range of detection therefore extends to the line of sight which in the case of high flying aircraft is considerable. This line of sight performance is almost invariant, but is sometimes improved by abnormal refraction around the earth's surface.

The sensitivity of radar receivers is extraordinary. The pulse transmitted power averages about 10^5 watts, while the received energy from a target at maximum range may be as little as 10^{-14} watts. The overall operating efficiency is therefore 10^{-19} and it is a great tribute to the pioneers of

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radar that they persisted in their efforts to attain apparently impossible ends.

The techniques which have made these achievements possible are sometimes new and original, sometimes an extension of those common in radio practice. The first tendency was to press the upper limit of frequency of operation well beyond that found in radio. This process was assisted by the fact that operation under pulsed conditions allowed existing valves to operate at excess voltage levels and still with low dissipation. As a result, many early radar sets were designed to operate at frequencies up to 200 megacycles per second when the highest frequency in use for radio purposes had scarcely gone beyond the 50 to 75 megacycles per second region.

The demands of war for still more refined techniques to combat a new threat or meet a new tactical situation accelerated this process until it culminated in the development of entirely new methods of operating in the centimetre wave region. In this field the resonant magnetron stands out as perhaps the most brilliant single invention since radar itself. It made power outputs of 10^6 watts available on wavelengths of a few centimetres, whereas some years previously 1 watt was a notable achievement. Associated with it was the klystron, a modified version of which played a great part in all manner of radar receivers.

Other interesting developments arose from the necessity of displaying the received information to the radar operator in an easily readable form. In ordinary radio practice, signals are reproduced aurally. In radar, the small time intervals involved—pulse durations of millionths of a second and measurement of echo delay times of a thousandth of a second—are beyond the scope of human senses, and instrumental aids must be invoked. The instrument most used for the purpose was the cathode ray tube, on the face of which distance and bearing or height of the target was displayed in pictorial form. The plan position indicator gave simultaneous distance and bearing indications and stands out as the most elegant of a number of brilliant conceptions. It was followed by others such as the

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range-height display which in meteorological work can give results of great practical importance and incidentally of surpassing beauty.

Those displays are being continually improved and as picture resolution increases, it is becoming possible to appreciate outlines of a target on the radar screen. With further development, precise details of form and configuration will ultimately be revealed. The process is leading inevitably to complete radar vision in which pictures of surrounding objects equal to those seen by eye will become possible through any weather conditions.

Further Applications

Until recently applications of radar have been predominantly of a military character but the techniques can also be applied to the peacetime activities of mankind.

Its use as an aid to aviation and marine navigation is obvious and substantial developments in these fields have already taken place. Not so well known, perhaps, is its application to the study of fundamental meteorological processes. Its ability to "see" raindrops and ice and snow particles in regions normally inaccessible to visual or direct observation is opening up new methods of investigating the physics of the formation of cloud and rain, whether occurring naturally or stimulated by artificial means.

The military methods of blind bombing which depended on the exact location and control of aircraft from points at a home base revealed that the accuracy with which the position of an aircraft could be fixed was often in excess of that with which points on the ground were then known by the ordinary methods of survey. A substantial re-survey of parts of the European theatre was therefore necessary before this type of bombing could be employed to full effect. The methods have a direct peacetime use in the survey of undeveloped or inaccessible terrain and in the determination of the figure of the Earth.

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The precision attainable in the measurement of distance by radar means is very high and it was the use of such methods over accurately surveyed baselines which first drew attention to the fact that the velocity of electromagnetic waves is some 16 kilometres per second greater than the previously accepted value. Two recent determinations, one of which is based on the use of radar techniques, have substantiated this higher value (299,792 kilometres per second) for the velocity of propagation in free space. Activity in many other branches of physical science is similarly being stimulated as the application of radar methods of experiment and instrumentation becomes more widely known.

The successful reception of radar echoes from the Moon by the United States Army Signal Corps in January 1946 is noteworthy as the first step in sounding the universe, a step only made possible by the extraordinary instrumental developments which are an essential part of radar. The application of the same general techniques has opened up an entirely new field of astrophysical investigation, the study of the Sun and the stars by means of the radio-frequency radiation of thermal and electro-dynamic origin which they emit. This is the province of Radio Astronomy, a new branch of science which has already produced something of a revolution in astronomical ideas and which may well lead to a reconsideration of the philosophy upon which our theories of the universe are based.

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