RADAR IN WAR AND IN PEACE

By Sir ROBERT WATSON-WATT, C.B., F.R.S.

It is customary, but not invariably wise, to preface an account of a new subject with some attempt at a definition. There being no part of the problem more difficult than accurate and condensed definition, this custom makes the whole subject look more difficult than it really is. For this reason the immediately following section of these notes on radar might well be annotated, as in some prescribed text-books, with the remark "May be omitted at a first reading".

On Defining 'Radar'

To devise, and to interpret, an adequate definition of 'Radar' would be more laborious than profitable. The group of varied and flexible but intimately related techniques which have grown from a common stem of R.D.F. or radiolocation in Great Britain and radar in the U.S.A. have it in common that they involve essentially a measurement of distance, inferred from a relative time-delay and an assumed or known speed of travel of radio waves. But they have much more in common, and they are far from being merely radio range-finding systems. They might not have been achieved without Appleton's classical range measurement on the ionosphere; they would not have been practically useful without Breit and Tuve's powerful tool of the radio pulse, which carried Fizeau's method out of the optical laboratory into the upper air.

At the least, a radar system must provide an unambiguously associated pair from the three co-ordinates required to specify the position in space of the material object to be located by radio means, and must present these co-ordinates in a form convenient to the user. It should and normally does measure the third co-ordinate (usually stated as flying height) in the case of aircraft, and it frequently gives additional information about identity, numbers, speed in line of sight, and so on.

It would be pedantic, unrealistic and unhelpful to restrict 'radar' to the "location of an object without active co-operation from that object". The radiolocation of friends will, happily, be a far more general practice than the search for enemies, and active co-operation from the friend should not be ruled out as 'not cricket'. Nor should the emphasis be on 'an' object. The very essence of radiolocation, alike for war and for peace, is that it began with a determination to achieve something more practical than one of several possible systems which could locate 'an' aircraft alone in space, or could continue to locate an aircraft once an initial position was known, to the neglect of all the other aircraft in the sky and of the initial pick-up problems.

It would be artificial and misleading to confine the adjective 'radar' to systems involving the reflexion of radio energy from the object to be located, or even to the return of energy from the object towards the primary radiator. The most generally installed radar equipment of all was the 'Gee' receiver, which enabled the air navigator to determine his position by measuring the relative times of arrival of radio pulses emitted synchronously from three ground stations. The techniques involved in this 'one-way traffic' system of pulses, travelling from ground to aircraft or from shore to ship but not back, are quite inseparable from the techniques used in the 'H' and 'Oboe' systems, in which the primary radio pulses 'interrogating' the mobile craft automatically release from it a series of reinforced, coded, and conveniently frequency-displaced reply pulses, which travel back towards the primary radiator. And the techniques of all these, and of the I.F.F. system from which 'H', 'Oboe' and radar beacons grew, are in turn quite inseparable in general conception and broad execution from those which are used to extract somewhat lower accuracies at somewhat shorter ranges from the somewhat less informative radio echoes returned from a non-co-operative aircraft.

So in practical life radar is a group of techniques which enable the position of one object among many to be measured by radio means, involving essentially the measurement of relative time-delays and thence the total paths or difference of paths, in the travel of suitably labelled radio waves between the object to be located and the radio station or stations (which may be transmitting, receiving or receiving-and-retransmitting stations) which provide reference points for the location. The 'labels' attached to the radio waves may be a controlled change of frequency, as in the Appleton foundation experiment in radio range-finding, or a controlled change in amplitude, of which Breit and Tuve's pulse technique is the almost universal application.

The Pulse Technique

The pulse technique has attained this universality because it satisfies a number of special needs simultaneously. The beginning or 'leading edge' of the pulse marks a packet of energy which can be re-identified after the vicissitudes of travel, thus permitting accurate measurement of time of travel, and the end or 'trailing edge' marks the beginning of an invaluable clear period in which the radar echoes or response signals can be received free from the overlaying and interfering effect of the primary signal. In modern pulse technique, pulses which may be very brief indeed are sent out at a very accurately controlled recurrence frequency, and displayed on the equally accurately synchronized time-base of a cathode-ray oscillograph. This gives a cumulative preference to the slowly changing pulse-responses over the random noises occurring along with them, since the successive responses are more or less accurately superposed while the noise is spread more or less evenly over the background. The interval between primary pulses is preferably made just greater than the time-delay of the response from the greatest distance to be sounded. The time base then becomes a range-scale, with its zero at the leading edge of the primary pulses, and it can be made linear in time and range. Care must, however, be taken that echoes or responses received after a time-delay greater than that between primary pulses are not read as coming from a distance less by one or more whole pulse-periods than their true path. Finally there is a considerable advantage in discrimination to be attained by using the pulse-recurrency frequency as a coding characteristic of the stations concerned, and by additional coding by pulse-width or multiple pulse-spacing, or both. These advantages of the pulse system are bought at that price in increased width of frequency channel occupied which is the inescapable price of high information-carrying capacity.

The superposed successive pulses returned from any one reflecting or responding object can be treated as a continuing signal coming from that object, unmixed with others of different time-delay, and can thus be subjected to standard processes of direction-finding, in azimuth and elevation, independently of the corresponding series of responses from more or less adjacent objects. And if the responses come from closely spaced objects, such as a tight formation of aircraft, the beating which results from their incomplete separation can be used as a means of estimating the number of objects thus incompletely resolved.

The First Steps

When it became distressingly obvious that it would be important to detect and locate enemy aircraft while they were still far from our shores, the high probability that a single aircraft could be located at a hundred miles, and the possibility that it could be detected at two hundred miles, was readily demonstrated by simple arithmetical process, supported by a crude experimental demonstration at short range. The arithmetic was easier than the consequent decision, for it pointed to an engineering efficiency, in a single determination, of the order of one in 10^{17}. The joint operational and technical decision that it was alike worth while and practicable to utilize this low-efficiency process transformed an idle dream, often conceived and always dismissed, into a decisive weapon of war.

But there were many technical difficulties in the transformation. No distances less than thirty miles had ever been measured by radio range-finding; targets separated by less than fifteen or twenty miles would not be resolved by the then existing technique. These two profound and indeed prohibitive limitations must be removed by a very drastic shortening of the emitted pulse, from the then current durations of about half a millisecond to durations of five or ten microseconds. This shortening must be accompanied by a great increase in the peak power emitted, and by a 'squaring' of the pulse shape. A sharp leading edge was vital to accurate range-finding; a long trailing edge was fatal to echo separation. The receiver and its associated aerials must give good response over the wide frequency band occupied by such short steep pulses, and it must also be immune from paralysis by the enormously powerful impulses from a transmitter a few yards away; many other defects in senders and receivers had to be cured. No direction-finder of adequate sensitivity existed; it had to be developed. The effective measurement of flying height depended on specially favourable topography; sites with a favourable foreground must be combined with accessibility and bearing capacity for heavy towers. Even on the most suitable sites the resulting data had to be corrected against calibration flights and had, after correction, to be put in a form convenient for immediate communication to the user. How the technical problems were solved must be told in detail elsewhere; the broad operational results have already been outlined in the daily Press. Here it is important to emphasize the milestones in radar technique, and how they were set up.

Milestones

When the more obvious of the difficulties just enumerated had been surmounted there remained those due to interference between the rays propagated directly between ground station and aircraft, and those reflected, with an almost complete reversal of phase, from the ground. It was the presence of the reflected ray that made height-finding practicable; but this one convenience was a part compensation for great inconveniences. The phase reversal meant that the interference pattern between direct and ground-reflected ray had a minimum in the horizontal direction, so that low-flying aircraft could come close inshore before detection. The only cure for this was the adoption of much shorter wave-lengths, so that the bottom lobe of the vertical polar diagram could be pushed lower without the use of prohibitively tall aerial systems.

The higher minima in the interference pattern were still at such angles that there were inclined lanes down, or to some extent across, which aircraft could fly unlocated, and these gaps in coverage had to be filled by the use of aerials of different height, with a non-coincident interference pattern, and by switching frequently from one aerial height to the other.

The attainment of high powers and adequate receiver gain on one-and-a-half metre wave-lengths allowed low cover to be established; but it permitted also the setting up of the third milestone in radar. The aerial system for such wave-lengths could now be rotated mechanically, and gave a comparatively narrow beam. By electrical beam-swinging the beam could be moved by a few degrees, and by matching amplitudes of response with the beam in its two positions the target could be located in azimuth with an accuracy some twenty times greater than by the previous methods. The inaccuracy of bearing fell from one or two degrees to five or ten minutes of arc. This was indeed a landmark in the history of precision measurement by radio.

Concurrent work on improved accuracy in the time-delay measurement was in train, and it was soon (in fact in 1938) established that the operational range-accuracy of the monostatic radio range-finder was, against quick-moving aircraft targets at least, higher than that of the monostatic optical range-finder. Errors of about twenty-five yards at heavy anti-aircraft gunnery ranges became standard.

One of the greatest steps in radar technique was the development of the Plan Position Indicator. Initially the time-base of the cathode ray oscillograph had been a fixed diameter of the tube-face, and the radio response or echo made an indentation (or 'blip' !) transverse to this line. But when the rotating antenna was introduced, and the radiation was confined to a comparatively narrow rotating beam, it became practicable to make the time-base a radial one, with its zero at the centre of the tube-face, and to rotate it synchronously with the antenna. If now the received signal were used to give brightness modulation of the cathode-ray beam, a response was displayed as a bright, though not very small, sector of a circle, the inner edge of this sector measuring the range and the mid-angular point of the sector the bearing; the width of the sector was of course governed by the sharpness of the radio beam. Thus automatically the rotating radial time-base gave in map form a plan display (with slant range used instead of horizontal range) of the positions of responding objects. This device, first used in the controlling from the ground of night-fighters, was of the utmost importance in the airborne and shipborne radar of the war against the U-boat, and in the aids to the bombing of invisible targets which were variously called 'H2S', the 'gen-box', 'Mickey' and the 'Magic Eye'.

The greatest revolution of all, however, was the success of the campaign for centimetric wave-lengths. It had long been clear that the major defects of airborne radar, and many of those of ground radar, were curable only by the use of an extremely fine pencil of radiation scanning the area to be explored. Such a pencil could only be formed by an antenna and reflector system having an aperture of many wave-lengths, and this could only be fitted in aircraft if the linear dimensions and weight were kept down by the use of wave-lengths less than ten centimetres. The precision with which individual targets could be located, the clarity of display, the separation of responses from two or more targets, and the reduction of the very serious overlaying effect of responses from fixed objects were all immediately dependent on the attainment of centimetric working. There were some associated advantages in reduction of the enemy's power to interfere with the full enjoyment of radar facilities.

How centimetric radar came is so closely associated with the general story of the organization of scientific effort on radar that it is desirable to look next at that story.

The Spiritual Ingredients

The most important thing about the British development of radiolocation as an instrument of war is not that it happened, but that it happened at the right time. The essential difference between the British effort and the most nearly corresponding effort in other countries is to be sought in those intangible factors which assured to us, at each stage in development, an adequate (though often a no more than adequate) margin of time for meeting the successive crises of the War.

It cannot be too often or too firmly stated that the victory over Germany was essentially a victory of the spirit. No technical devices can turn the scale of war save as tools of the spirit. Nor is there, indeed, any real gap between spirit and material, though the very mechanical perfection of our new technical devices may hide the vital fact that they are not only the tools but also the products of the spirit. Radiolocation is perhaps the best of all examples of the interaction of spirit and technique in the forging of a decisive weapon of war. But its origins in the spirit of science may be temporarily lost to view behind its successes. The curiosity-value of its devices, the wealth of its applications to all forms of warfare, and its spectacular victories may dazzle the casual observer.

Radiolocation was the direct, but in no wise the predestined and inevitable, fruit of pure research. Its beginnings lay in the work of those who laboured to understand more of the things that happened in the earth's atmosphere. Its later developments, and much of its technique at all times, were due to those who sought the inner secrets of the structure of matter.

Britain was a prominent leader in those pure researches into the physical processes of the ionosphere and of the lightning flash which were, indeed, directed towards the improvement of radio communications, but which were of an enlightened width and depth, not closely trimmed to immediate practical ends. These researches were State-aided, but most generously and most lightly State-controlled. The Department of Scientific and Industrial Research had, through the vision of its first Minister, A. J. Balfour, and of its successive administrative heads, Sir Frank Heath, Sir Henry Tizard and Sir Frank Smith, established a unique position for its Radio Research Board, founded and nurtured by the gentle wisdom of Admiral of the Fleet Sir Henry Jackson. Among the Board's contributions to the international stock of fundamental knowledge and to the international store of radio technique, none was more important than those due to Dr. E. V. Appleton, whose radio researches it supported from its foundation until the time when he succeeded Sir Frank Smith (himself a dominant figure in the scientific work of the Board) as Secretary of the D.S.I.R., and became Sir Edward Appleton. It is morally certain that without the peaceful pursuits of the Board in general, and of Appleton and his colleagues in ionospheric research in particular, radiolocation would have come too late to have any decisive influence in the War.

The Radio Research Board had trained a team of young research workers encouraged to see and explore the wide open spaces between the Morse key and the loud-speaker. They were to remember the needs of the radio user, but to probe to the heart of the processes rather than to apply palliative dressings. They were to be pathologists rather than physicians; to be physiologists and even morphologists rather than pathologists. Their vision and imagination were to be turned in the general direction of application, but they were to take neither narrow nor short views.

The scientific staff of the Air Ministry reviewed in 1934 the prospects of aerial warfare. They were profoundly disturbed by the lack of any effective means of defence against the fast military aircraft of the day. On their advice, the Secretary of State for Air sought the counsel of three distinguished 'outside' scientific workers of deep knowledge and wide experience. They in turn suggested that one aspect of the problem should be discussed with a member of the Radio Research Board's team.

As an official document has recently said: "This contact between a user Department with a great need, and a Department which had fostered scientific discovery not wholly directed towards specific needs, was perhaps one of the most important events in our history, and illustrates the need for fostering scientific research in all fields and for making the needs of the State known to those who are engaged on scientific research".

It was a characteristic and natural step in this train of enlightened reviews of general needs rather than particular prescriptions, that the radio researcher brushed aside the problem directly posed, replacing it by a quite different and far from novel problem, for which he proposed a novel solution. The solution was novel, not because it had not been glanced at qualitatively on other occasions, not because it contained any intrinsically novel element, but because it was a quantitative synthesis, a judicious mixture of old ingredients, each ingredient to be modified and refined for the new purpose, and adapted to the complexities of an operational problem far more involved than those of the laboratories—even of the open air laboratories—in which the ingredients had been evolved.

But again it must be said that the basic ingredients of radiolocation were in fact the spiritual ingredients, the wisdom that integrated the scientific advisers into the Air Staff in the handling of its day-to-day worries, the judgment that assessed the relative priority of these worries, the courage of all the participants—courage in the small band of "good but not first rank" (the description is their own) men of science who made firm promises out of their exact knowledge and their imaginative enthusiasm; courage in the men of science who recognized the scientific and operational validity of promises made on a one in 10^{17} basis, courage in the officers who staked some millions of pounds of public money and revised the air defence system of the country on the paper promises of a "bunch of scientists", the exploits of a "rather ancient lorry" near Daventry and the not unqualified successes attained in a few tentative air exercises.

That success—a success which even in the first trial of strength in 1940 made the difference between a free and an invaded Britain—was achieved was due to those same influences which governed the acceptance of the gamble. The most significant factor in the story of radiolocation was not the technical skill packed into its boxes, was not the operational skill with which they were used. It was the unprecedented and unprecedentedly productive interplay between scientific and operational minds, which carried the basic technique from its first defensive application in an early warning system through more actively defensive phases to a wealth of offensive applications which had a decisive effect in every major phase of the War.

When radiolocation has taken second or third place to future novelties in the military art, this intimate co-operation of scientific and military minds will remain as the real secret weapon in the British armoury, as something which grew to full vigour with radiolocation, at once a source and a product of that successful development. Nowhere in the councils of the United Nations or of their enemies—and those concerned in developing radiolocation have been at some pains in recent months to verify this last point—has there been a parallel to the practice followed from the first days of radiolocation research. The Air Marshal took advice from the junior scientific officer on how to make war, and the laboratory assistant was told by the Admiral why physics has sometimes to give way to psychology in the planning and conduct of operations. The soothing fiction of an operational requirement stated by an all-wise staff, and unquestioningly satisfied by a docile and technically expert developer, has no place in the history of the most versatile technique of the War. The proud and affectionate title of "Boffin" conferred on the scientific developer by his military colleagues and co-workers is earned only by a man in whom technical expertize is matched by operational understanding and indomitable zeal, allied to the peculiarly scientific virtues of inquisitiveness, impatience, intolerance and insubordination.

The fruitful co-operation was not confined to the origination and development of technical equipments and systems. It extended to the selection and training of personnel to operate and maintain the systems, to the evolution and practising of tactical methods based on the systems, and to the whole complex of technical, tactical and logistic problems involved in introducing new scientific devices into heavily engaged operational formations.

The over-riding demands of secrecy limited the size of the team and the facilities that could be devoted to radiolocation in the 1935–39 period. Not the least of the merits of that limited team were their technical restraint and their ruthless objectivity, their refusal to explore at once the innumerable avenues of development opened by the new art, their insistence on the sacrifice of refinements, elegances and versatilities to the one desperate need for "something to be going on with". They never turned aside from their cult of the third best—"the best never comes, the second best comes too late".

Easter 1939 saw the opening of a continuous watch—sustained unbroken for the next six years—by the radar stations of the east and south coast; it saw also the reinforcement of the research and development teams by the cream of the physical research laboratories of the country. The ninety physicists who spent the spring and summer of 1939 in the coastal stations devoted their first war-time efforts to meeting the needs and exploiting the possibilities which suggested themselves in their first scrutiny of radar at work. Further strengthened by transfers from other groups, the greatly augmented team brought to the work intellectual qualifications, research experience, depth of fundamental physical knowledge, imagination, initiative, versatility, enterprise and enthusiasm, inquiring and critical faculties, of quite unique order. The dreams and aspirations of the 'founder members' were rapidly fulfilled and surpassed, new dreams were converted to achievements, and the traditions of constructive debate between General and junior scientific worker and of inextricable interweaving of contributions from operational officer and boffin were cherished, maintained and extended.

The newcomers, knit into a large and powerful organization, with facilities better proportioned to their needs than ever before in research for military purposes, came from other fields besides pure physics. Chemists, physiologists, general biologists, dons and schoolmasters were united by certain basic characteristics common to all branches of science. The habit of measurement, classification, comparison, and orientation in the light of defined principles, the isolation of those changes in behaviour which are due to the variation of one identified factor from those due to other factors, the stringent assessment of statistical validity in measurements, are of the creed of all men of science in all fields. A sturdy refusal to take refuge behind chance and accident, a firm hatred of the creed of the 'magic box', make the boffin the sworn enemy of the 'gremlin'. A stern exclusion of emotion from the method of science is allied with a fierce flame of emotion as the motive power behind the application of that method. Above all, a religious conviction that all facts are good facts, that suppression of the known and measurable truth is the supreme sin, governs and explains the determination of the man of science to drag every strategic and tactical skeleton out of the cupboards of the Commands, so that it may either be reclothed and revivified or be decently interred.

From this fervent objectivity, backed by the highest technical skill ever organized into a single team, and by a remarkable organization for quick production, came the successive devices that turned the tide of battle in successive phases of the War. They were vital to the defeat of the day bomber and the night bomber attacking London and other British cities and towns. They drove the enemy surface ship from the Straits, the North Sea and the oceans of both hemispheres. They beat the U-boat in the Bay of Biscay and in the Atlantic. They foiled the 'flak' gunner in the Ruhr. They penetrated the fog and cloud cover that was the best anti-aircraft aircraft defence the German cities ever had. They baffled the night fighter which strove to make good these lost defences. They silenced the coastal gunner on the Normandy shore. And, by aiding the airborne forces and the tactical air forces supporting the armies of liberation, they contributed to the defeat of the last Panzer and infantry defences of the crumbling Reich.

The Centimetric Revolution

The demands for adequate transmitter power and receiver sensitivity on centimetric wave-lengths had grown more and more insistent from the time they were first voiced by the radar team of 1935, and the ninety 'scientific observers' on the chain in 1939 included those best qualified to perceive the intensity of the need and to devise the means for meeting it.

Under the inspiration of Prof. M. L. Oliphant a team at the University of Birmingham provided the essential element in the solution. Dr. J. T. Randall applied the resonant-cavity technique to the relatively ineffective magnetron of pre-war days, and made of it a radically new and immensely powerful device which remains the heart of every modern radar equipment. Dr. R. W. Sutton, of the Admiralty Signals Establishment, matched it with an equally novel receiving valve, the Clarendon Laboratory team made a vital contribution to the efficient use of a common aerial system for transmission and reception of radar pulse signals, and centimetric radar for ground, ship and airborne use was at hand. Floodlighting and wide-beam systems remained an essential part of the whole radar complex; but the fine pencil scanning systematically and point by point the whole area of search alone sufficed to paint the fine detail of target areas, to avoid the smudging over of each element by the response from adjacent or more remote elements, to give adequate 'illumination' of the extremely low flier or the surface ship by coast-watching stations. And apart from permitting fine-beam formation, the very high frequency permitted a corresponding improvement of discrimination in depth, by allowing pulses of duration much under one microsecond to be formed by the transmitter and reproduced comparatively faithfully by the receiver. Only at frequencies of, or above, three thousand megacycles per second does the bandwidth occupied by such short pulses constitute a sufficiently small percentage of the central frequency for good pulse-shaping at sender and receiver to be attained.

These were the foundations of the techniques which gave the night fighter an A.I. set in which the returns from the ground no longer overlaid those from the bomber under pursuit whenever its range from the fighter exceeded that of the nearest ground, so that the maximum effective range of the A.I. set was no longer, as before, the flying height of the fighter. They gave the searcher for the surfaced U-boat, in destroyer, corvette and aircraft, the means of locating a periscope at several miles and a normally surfaced U-boat at tens of miles, and prevented the U-boat from getting, before he was driven from the sea, that early warning of pursuit which he derived from listening sets on metric wave-lengths. They gave the anti-aircraft gunner a higher precision and an almost complete release from the limitations of site and obscuration by 'ground-clutter' which had crippled his tactical freedom in using metric-wave GL sets. They were applied by our American collaborators in ground installations of considerable elegance and high adaptability which made great contributions to the defeat of the flying bomb and to the close air support of ground forces in the liberation of Europe.

Bombing by Radar

Perhaps the most picturesque, and certainly one of the most valuable, of the centimetric radar devices is the 'H2S' airborne aid to the bombing of invisible targets. The 'P.P.I.' picture in which seas, lakes and waterways remain black because they give substantially specular reflexion of the scanning pencil away from the aircraft projecting it; in which coastlines, with their cliffs, bays and inlets, show up clearly as outline map features because they scatter radiation back towards its source; in which the inland landscape is of a nondescript intermediate tone; and in which the 'works of man'—camps, hangars, and above all towns and cities—stand out brightly, the towns reasonably clearly defined in outline at tens of miles and in some detail at ten miles and under; this fascinates everyone at first acquaintance and never ceases to impress even the hardened boffin.

It has no competitor in this grip on the imagination, save perhaps the other blind-bombing device, of higher precision but limited coverage, called 'Oboe'. That two controllers sitting in vans on English soil should each know with an accuracy of a few yards each way—certainly within fifty yards—the position of an aircraft over Essen is a surprising thing, no more and no less surprising when one reflects that they know it much better than do the occupants of the craft. Yet in principle it is ridiculously simple; one ground station, *A*, knows the deviations of the craft from a circular track of constant distance from *A*; the other, *B*, knows when the craft flying a circle about *A* is at any desired distance, including zero distance, from the intersection of that circle with another of known radius about *B*. And this point of intersection was selected, in the relative comfort of the English ground stations, to be the bomb-release point, arrived at by applying up-to-the-last-moment corrections for the local wind conditions over the German target. *A* and *B* are pulse-interrogator stations, the aircraft has a responder of constant and accurately known delay-time, and meticulous calibration and adjustment assure an accuracy in radar range finding of one in ten thousand or so at some two hundred miles.

Radar in Peace

Radar in war fell into three convenient categories, each of which has come to stay in the peace.

Primary radar is that form of radar which "does not require the co-operation of the object to be located". It is useful against icebergs and enemies generally; it is an extravagance when used against friends.

Secondary radar requires that small measure of co-operation which is involved in the fitting and switching on of an otherwise automatic responder. The responder sends back, when interrogated by radar pulses, reply pulses on a different wave-length—so that 'ground clutter' disappears from secondary radar—coded with information about the 'personal identity' of the craft carrying the responder, and about its flying height if it is an aircraft.

Radar navigation does not depend essentially on the return of an echo, amplified or unaltered, from the craft to be located. It may in some special cases like 'Oboe' find that convenient; in some other and more frequency cases like 'G-H' and 'Babs' (Blind Approach Beacon System) and 'Rebecca-Eureka' utilize coded responses sent back by a ground responder-beacon in reply to pulses from an airborne or shipborne interrogator. And in 'Gee' and 'Loran' and related systems it will depend on a measurement in the craft of the time-difference of arrival of primary pulses from synchronized ground stations in accurately surveyed positions.

In a well-ordered world—which includes, but goes beyond, a world at peace—primary radar would have no place in aviation save as an airborne means of avoiding dangerous high ground and dangerous clouds and as a 'last resort' ground system for locating aircraft whose responders had failed, as they may on occasion do even in a well-ordered world. In the shipping world it would have a corresponding role, save that all ground is then dangerous high ground and the iceberg is the equivalent of dangerous cloud. In land transport primary radar should have no place at all; but primary radar on the ground will help the meteorologist in his still difficult task of forecasting. The world has still some way to go before even an optimist will regard it as well-ordered, and so ships will sail and aircraft fly with primary radar performing other duties which will ultimately be better confided to secondary radar.

The aim of the radar aids to civil aviation which were discussed at the recent Third Commonwealth and Empire Conference on Radio for Civil Aviation (C.E.R.C.A.) in London is to give from a generous provision of ground installations and the minimum of equipment in the aircraft, sufficient information (without the intervention of communications from ground controllers) for the pilot to know at every moment where he is, how to fly to his destination by the shortest or safest route, and how to land safely whatever the visibility. These provisions will be supplemented by radar aids which will keep the air traffic controller fully informed of the traffic pattern around his airport and on his designated routes. It will not be done cheaply, but independence of the weather has never been cheaply bought.

The simpler problems of marine transport find simpler radar solutions, and the sea and air transport without which our great Commonwealth and Empire cannot hold together in its service to civilization need radar services with an urgency second only to that which produced radar services in war.

Of railroad radar no one will at this date speak with equal confidence. But it is surely reasonable to believe that the simple elements of secondary radar in cab, cabin and caboose will at last banish the primitive detonator from this fog-girt isle! Romance cannot wholly dispense with radar in its noble task of bringing up the eight-fifteen—especially in the not infrequent conditions in which it is not romance alone that is 'all unseen'.

SCIENCE IN THE U.S.S.R.*

ASTRONOMY AND TERRESTRIAL MAGNETISM

By Sir HAROLD SPENCER JONES, F.R.S.
Astronomer Royal

RUSSIA has played an important part in the development of astronomy since the foundation of the Pulkova Observatory by Czar Nicholas in 1839. Under the direction of F. G. W. Struve, this observatory was built regardless of expense. It has made notable contributions to fundamental astronomy, its instrumental equipment for such observations being more varied and complete than that of any other observatory. The Pulkova observations have always been characterized by their great accuracy. At the beginning of the present century, the work was expanded to include astrometry and astrophysics. Its great refractor, of 30-inches aperture and 45-feet focal length, was one of the finest in the world. In 1908 an astrophysical observatory was established at Simeis in the Crimea. There were, at the time I visited Russia in 1914, several other observatories, but for the most part their equipment was modest and their staffs were small. Since the Revolution a great expansion in astronomical work has occurred. Additional instrumental equipment has been installed, including the 40-inch reflector at Simeis: new observatories have been constructed in Abastumani (Georgia), Stalinabad (Tajikistan), Yerevan (Armenia), Poltava (Ukraine) and Alma Ata (Kazakhstan), the last of these during the war years. Astronomical institutes have been established in Moscow and Leningrad, for computational and theoretical work in the fields both of astrophysics and of celestial mechanics. The total staffs have been increased about ten-fold.

* Continued from page 285.

In the pre-Revolution days, each observatory worked alone, and its resources were generally insufficient to enable large programmes of observation to be undertaken. In the Soviet years an Astronomical Council has been constituted by the Academy of Sciences which co-ordinates the work of the various observatories, including both those which come directly under the Academy and those which are attached to universities. Thus, it has been possible, by pooling of effort, to undertake fields of work which are beyond the scope of any single observatory and also to avoid unnecessary duplication. For example, observations of selected minor planets and of the positions of some 16,000 red giant stars have been undertaken at several observatories for the improvement of the fundamental system of star places. Special attention has been given to solar phenomena and their terrestrial relationships. The paths of totality of the total solar eclipses of 1927, 1936, 1941 and 1945 have crossed Soviet territory and extensive programmes of observation were planned. For the last three of these eclipses some fifteen to twenty expeditions were organized and were distributed along the line of totality—valuable results being obtained.

The time service has been extended, and its accuracy considerably improved. A Nautical Almanac is published to meet the needs of navigators and surveyors as well as astronomers. The computations for its production are made at the Astronomical Institution in Leningrad.

Soviet astronomers have made important contributions to the theory of the structure of comet tails and heads, to the problems of the variation of latitude, to the study of the atmospheres of stars (including the discovery of heavy isotopes of carbon), to the problems of novæ, and to cosmogony.

Astronomy in the U.S.S.R. has suffered a serious setback through the destruction of, or damage to,