Secondly, atomic energy is now a source of useful new materials produced by transmutation. It promises to supply us with heat and power, available in large quantities wherever needed, and thus to open new economic frontiers. New advances in medicine, in industry and in science are on the horizon.

Thirdly, as the most recent great step in the long progression of advances in science and technology, the advent of atomic energy is forcing mankind along the difficult road to greater humanity. Growing co-operation, education and spirit of service are evident trends.

In the fierce competition between social systems in the atomic age, the need for strength demands that we enable every citizen to contribute to the common welfare as his abilities may permit. Permanent peace can now be secured if we will work for it. Increased prosperity, with broader horizons, lies before us. Greater development of the human spirit is the inevitable consequence of the increased responsibility for using our new powers. These are among the greatest of human goods.

RADAR FOR CIVIL AVIATION

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THE story of the development of radar during the War is now well known—how it started as a defensive measure to give warning of the approach of enemy aircraft to the coasts of Britain, and grew finally to take an important offensive role in almost every form of warfare. An outline of the history of this remarkable development has been given in *Nature* by Sir Robert Watson-Watt*. One of the fields in which radar technique has made very large contributions is that of air navigation. In war-time, aircraft must fly in all kinds of weather, by day and by night, and the development of radio aids to replace those visual aids available in clear weather was of paramount importance. In peace-time it is just as important that aircraft should be able to fly with safety in all kinds of weather if aviation is to give regular and reliable passenger and freight service. It is still true, however, that the weather is the main limitation on flying, and although much has been accomplished, much remains to be done.

Advances made in war should become available at once for use in peace. It is therefore to be expected that radar should quickly begin to contribute towards safe and reliable civil aviation. That the immediate application of radar to civil flying has been slower than some would have hoped has been largely due to essential differences between civil and military flying. In order to understand the application of radar to the former, we must examine the most important of these differences. The most obvious difference is that of 'pay-load'. One may be prepared to spend a lot more to deliver a load of bombs on a vital objective than to deliver a load of passengers or freight. Again, one will be prepared to sacrifice a considerable portion of bomb-load for radio equipment if this will ensure that the remainder of the load falls on the target. In civil flying, however, weight and bulk of radio equipment must be kept to a minimum, otherwise flying will become uneconomic. Military aircraft must be able to navigate at will over most of the country at home and over enemy territory, expecting not co-operation but hostility over the latter. Civil aircraft are expected to keep rigidly to well-defined routes along which they can expect active co-operation from the ground most of the way.

* *Nature*, 156, 319 (Sept. 15, 1945).

It is not surprising then that much military equipment is not suitable for civil aviation. The fundamental scientific and technical principles learned during the War are, however, applicable, but some time must elapse before they can be used to create equipment specially designed for civil aviation. Nevertheless, there are several radar equipments in the navigational field which are immediately applicable to civil aviation and, if not now in ideal form, can at least be employed until more suitable versions are developed.

Advantages of Radar

It must not be supposed that only radar technique can provide answers to the problems of radio navigation. Indeed, in many cases ordinary continuous-wave (C.W.) techniques will provide a simpler solution than radar. Radar has, however, two outstanding characteristics which may enable it to succeed where continuous-wave technique would fail. The first is its ability to measure distance simply and accurately ; and when this is required, radar has no serious competitor. The second arises through the fact that if short pulses are used, reflexions from the ionosphere and local objects near the transmitter may be separated from the direct pulses and so may be ignored. With continuous-wave systems, such reflexions frequently destroy the accuracy of the information obtainable from the system. Thus we shall see that for precise long-range navigation, radar techniques alone are likely to provide a satisfactory answer.

Radar Beacons

Very soon after radar had been developed for use in aircraft, mainly to detect ships (ASV) and hostile aircraft (AI), it was realized that by the use of repeaters to send back an amplified and coded form of the pulses received from the radar, an excellent navigational aid would be obtained. The radar set measures the range of the repeater, or 'responder beacon' as such devices are called, and by means of directional aerials enables the aircraft to home to it. This type of radar is known as secondary radar, primary radar being dependent on energy reflected from the target. When two beacons are within range, the aircraft may find its position by means of range cuts.

So successful was this form of navigation that it was desired to use it for aircraft which would not carry search radar. This is quite possible because the high-power transmitter of the search radar is unnecessary for navigation by responder beacons, since the 'echo' received is the retransmitted pulse from the responder and not the weak reflexion as from an aircraft or ship. Thus the radar beacon system of navigation was developed in its own right in the form known as *Rebecca-Eureka*. It became the basic radio aid for dropping paratroops, and its vital role on D-day has been told elsewhere. Thereafter a wide experience of the use of the system grew up in Transport Command and, as a result, its immediate application to civil aviation is possible.

One of the outstanding requirements for civil aviation is the measurement of distance along an air-route. The radar beacon system supplies this at once. In addition, homing to an airfield is simple and the facility is available for 'holding' a circular 'orbit' around the airfield while waiting to land. Since VE-day, a considerable amount of research has gone into adapting this system to the special needs of civil aviation. Cathode ray tube displays have been replaced by meters enabling the distance and orbiting information to be given direct to the pilot. Developments in miniature technique have been applied to produce a light and compact equipment.

Of all radar equipment, the interrogator and responder is the simplest and is likely to be the first to be widely used for civil aviation.

The scientific problems in this field are now well understood and there only remain the engineering problems of designing light and reliable equipment to meet the needs of civil aircraft.

Gee System

The need to develop a system of radio navigation to enable British bombers to operate at night over Germany became acute soon after it was apparent that our bomber offensive was likely to develop on a large scale. Out of this need grew the *Gee* system, perhaps the most extensively used of all radar equipments. Depending as the system does on the precise measurement of the time difference in the arrival of pulses sent out from three or more ground stations, *Gee* set a completely new standard of accuracy in radio navigation. In time, the whole of Britain and the surrounding sea was covered by the lattices laid down by several *Gee* chains, and although the coverage of enemy territory was seriously reduced by his jamming before we landed in Europe, large tracts of Europe are once again covered by *Gee* lattices. The system is such that any number of aircraft can use it, and the large raids staged by Bomber Command would have been impossible had *Gee* not been available to guide the bombers to their target and to get them back to their bases.

However, there are difficulties in using a system such as *Gee* for civil purposes. Large military aircraft carry a navigator who can take the *Gee* readings and plot his fixes. Civil aircraft plan to use as few members of crew as possible, and the desire is strongly expressed that all navigational aids should be presented direct to the pilot. Again, civil aircraft are required to fly along predetermined routes, and the navigational information should tell the pilot simply whether he is on the right or left of the track which he desires to fly. Undoubtedly electronic computers could be designed to enable *Gee* information to be presented in this form, but the system is already somewhat complex and this addition would almost certainly rule out its use for civil aviation.

In the meantime, however, owing to lack of suitable alternatives, it is likely that *Gee* will be used over large parts of Europe for a considerable time to come, even by civil aircraft. At present, the *Gee* ground stations each require a crew of two or three to keep them serviceable and in exact synchronization. Considerable steps have been made, however, towards making the synchronization completely automatic. In removing the need for large operating staffs, this would make the system more attractive for civil use.

Loran System

Loran, the American variant of the British *Gee* system, was developed principally as a long-range aid over sea. In order to achieve long ranges over sea, *Loran* uses the low 'high-frequency' band in the region of 2 Mc./s., whereas *Gee* works in the 'very high-frequency' band (20–80 Mc./s.), and so is limited in range, especially at low altitudes. All long-range aids previously developed had suffered from adverse effects due to reflexion of waves from the ionosphere. Since *Loran* is a pulse system depending, like *Gee*, on the timing of the arrival of pulses from ground transmitters, the ionospheric waves can be sorted out from the direct waves. Using the techniques of time measurement evolved in the process of radar development, a dependable accuracy is achievable at long range with *Loran* which is much higher than in any previous radio system. *Loran* is therefore likely to play an important part in trans-oceanic air navigation.

The equipment is unfortunately somewhat complex, but the facilities it gives are likely to justify its being carried by the large aircraft likely to operate on ocean crossings. There is no doubt that if an accuracy comparable with that given by stellar navigation under the best conditions is required at all times at long range, some pulse system like *Loran* must be used [see also p. 166 of this issue].

Ground Radar

Although it is an extremely attractive thought that the track of any aircraft approaching Britain may be plotted by means of the chain of radar stations, it must be appreciated that this involves a large and expensive organisation. Though this is justified in war-time, it is unlikely that civil aviation could afford to maintain its own complete radar cover. Such radar cover as is maintained by the military authorities would, of course, be available for civil purposes and would provide a valuable aid to aircraft in distress. One special application is, however, certain to be extensively used. In the vicinity of a busy airport, control of aircraft will normally be carried out visually. In dark or fog, however, this is impossible ; but radar can supply the controller with much of the information he requires. Radar has, in fact, already been used for this purpose with some success.

Two outstanding problems require to be solved before full advantage may be taken of the facilities provided. It is well known that reflexions from fixed objects spoil the radar picture for the first few miles from the set. It is just those few miles that are most important for airfield control. This difficulty may be overcome to some extent by careful siting of the equipment, but this imposes severe limitations. The second outstanding difficulty is that of identifying each aircraft seen on the radar screen. There is little point in giving instructions to an aircraft if the controller does not know to which aircraft he is talking ! Some progress has been made towards a solution of this problem by using direction-finding technique on speech from the aircraft, but this is unlikely to provide a satisfactory answer at busy airports. The ultimate solution is likely to be found through the use of secondary radar. By coding an airborne responder suitably, identity and other information such as altitude could be obtained. Trouble from reflexions from local objects could also be overcome as the responder normally is made to operate on a frequency slightly different from that used by the interrogating radar. The weakness of the system lies in the fact that aircraft would have to carry extra equipment which must be extremely reliable. The advantages to be gained, however, might well make this desirable, especially for scheduled aircraft. The main scientific and technical problems in this application are now well understood, and such a system has been tried experimentally, including automatic decoding. The remaining problems are largely engineering.

An extremely high precision form of ground radar has been developed in the United States (*GCA*) and applied to landing of aircraft in conditions of poor visibility. The track of the aircraft, and also its altitude, are observed with high accuracy and the pilot is 'talked down' to the end of the runway by a controller. This system has the great advantage that no equipment other than a communication set is required in the aircraft. The ground equipment is, however, very complex, and this may limit its peacetime use.

Track Guides and Instrument Approach Systems

Existing continuous-wave systems used for track guides and instrument approach are not wholly satisfactory. If they are operated in the 'medium frequency' band, they suffer badly from static interference. If they are operated in the 'very high-frequency' band they suffer from site effects due to reflexions from local objects. This can only be overcome by clearing sites of all obstructions over a wide area. Airborne radar has been used during the War as an aid to landing military aircraft. The metric *AI* and *ASV* systems, as well as *Rebecca*, were operated in conjunction with special ground beacons which laid down an equisignal track (*BABS*).

The additional radar information given to the pilot in the form of his distance from the end of the runway proved of great value. The use of the system in its present form involves display on a cathode ray tube, and an operator must pass the information received to the pilot by voice. The transformation of the radar landing information to a form suitable for meter display as required by civil aviation has been achieved experimentally, but is much more difficult than the meter display of distance or homing information. The resulting equipment is so complex that it cannot compete with continuous-wave systems, in which the information is readily applicable to meters. Nevertheless, ultimately one may be forced to a pulse technique in order to overcome siting troubles, which are a very serious weakness in all continuous-wave systems in use.

The need for radio ranges laying down a multiplicity of tracks radiating from a centre has increased the troubles due to site obstructions. One of the first new problems tackled by radar research workers in Great Britain specially for civil aviation was the provision of such a 'multi-directional range' using radar techniques. Experimental systems have already been demonstrated, and it has been shown that excellent straight courses can be laid down using very short pulses even when no special precautions have been taken to clear the site. The same technique may ultimately solve the problem of laying down landing beams free from bends due to siting troubles. Much research, however, still remains to be done.

Airborne Microwave Radar

One of the most interesting and spectacular radar developments has been the use of centimetre wavelengths to produce in an aircraft a radar map or plan of the terrain over which the aircraft is flying (H_2S). With present technique the map is somewhat of a skeleton, only the main features such as towns, lakes and large rivers standing out clearly. It is not, however, unreasonable to assume that with further advances in technique, more and more detail will be discernible. At first sight this would seem to offer the ideal radio aid to navigation, being a direct replacement for contact flying and requiring no ground organisation. At the present moment, however, the equipment is heavy and complex and is mainly carried in heavy bombers. The major part played in the bombing operations by the Allied air forces by this equipment is now well known. It seems unlikely, however, that there will be any immediate application to civil aviation, as the weight and cost would be prohibitive.

Nevertheless, considerable advances in the technique of miniaturization have been made and it is not unreasonable to hope that equipment of this type weighing about 100 lb. will be possible in the not very distant future. Even so, it is unlikely that any but very large civil aircraft would be justified in carrying it. This field of research must, however, be one of the most important, for in addition to navigational information, microwave airborne radar may provide the solution to one of aviation's most pressing problems—warning of collisions.

Collision Warning

With the great increase in civil flying likely to take place, especially the increase in bad-weather flying, the danger of air collisions may grow to an alarming extent. Three types of collision are well known already, namely, collision with high ground, with dangerous clouds and with other aircraft. Undoubtedly, the danger will be much less when accurate and simple air navigation is available to all aircraft flying in bad weather and direct control is exercised by means of radar in the vicinity of busy airports. The ultimate solution, however, is likely to be found in equipment carried by the aircraft itself.

Warning of high ground and dangerous cloud is already well known to those who have operated microwave equipment in the air. There is still, however, much to learn about the reflexion of centimetric radio waves from clouds and rain. Interesting new data have recently been obtained, and it seems that radar may make a significant contribution to the understanding of the formation of rain clouds and other atmospheric phenomena. A great deal of design work on the display of warning information to the pilot has still to be done. The fact that echoes are seen on a cathode ray tube is but a first step.

The problem of collision with other aircraft is much more complex. Warning of the approach of enemy fighters was obtained with the microwave equipment in use during the War, but it is a long way from that to giving the pilot such information on the position and course of aircraft with which he may collide, and only those, in such a way that he can take appropriate avoiding action in the very short time which would normally be available. Any device which gave warning of anything but potentially dangerous aircraft would be a menace and would needlessly worry and distract the pilot. Here then we have one of the most interesting but difficult radar problems. It is likely to need new technique and much ingenious invention for its solution.

There are many other unsolved problems, but enough has been said to show that there is still much scope for research in the field of radar, and that one of the most important and interesting applications of this still new technique will be to making civil flying safe and sure. British research has led in the radar field in war—it must not lag in the peace.