THE APPLICATION OF RADAR TO GEODETIC SURVEYING

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[*Manuscript received August 19, 1949*]

Summary

One of the most important applications of radar to surveying is its use in geodesy for precise measurement of long lines. The results of a large number of radar measurements of six distances varying from 160 to 310 miles in length using a modified "Shoran" radar equipment, indicate that an accuracy of about 7 parts in 100,000 can be achieved. Equipment errors constitute the immediate limit to accuracy, but reasonable modifications would yield a figure of 2 parts in 100,000. Radar measurements using the technique described can be completed in a fraction of the time required by normal ground survey methods since a measurement of upwards of a hundred miles is made in a single step.

I. INTRODUCTION

Radar has already been used extensively abroad as an aid to the surveyor (1, 2). One of its most important applications is to geodesy in the precise measurement in a single step of lines upwards of 100 miles in length. The tenfold increase in distance that can be obtained in one measurement, compared with present ground triangulation methods, allows a considerable reduction in the time required to survey an extensive area. Moreover, large water barriers may be crossed without loss of accuracy.

As a preliminary to the possible use of radar by the Australian survey authorities, a series of investigations has been carried out to determine the suitability of a modified "Shoran" radar equipment for precision distance measurement. The sides and diagonals of a quadrilateral, with sides about 200 miles in length as illustrated in Figure 1, were measured with the radar equipment and, in order that the accuracy of the technique could be found, these measurements were compared with the distances computed from a first-order ground triangulation.

This paper does not purport to describe the applications of radar from the viewpoint of a surveyor. However, it does describe the method of measurement, the equipment used, the method of reducing the observations, the errors involved in the measurement and computational procedure, and the possibilities of obtaining increased accuracy in sufficient detail to give a clear picture of the problems involved. Detailed descriptions of various aspects of the project are given elsewhere (3-7).

The results of over 100 measurements spread over the six lines gave an overall accuracy of about 7 parts in 10^5. The scatter of the individual

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measurements on any one line was about one-third of this. Systematic equipment errors proved the main limiting factor in obtaining higher accuracy, and suggestions are made for methods of eliminating or reducing them.

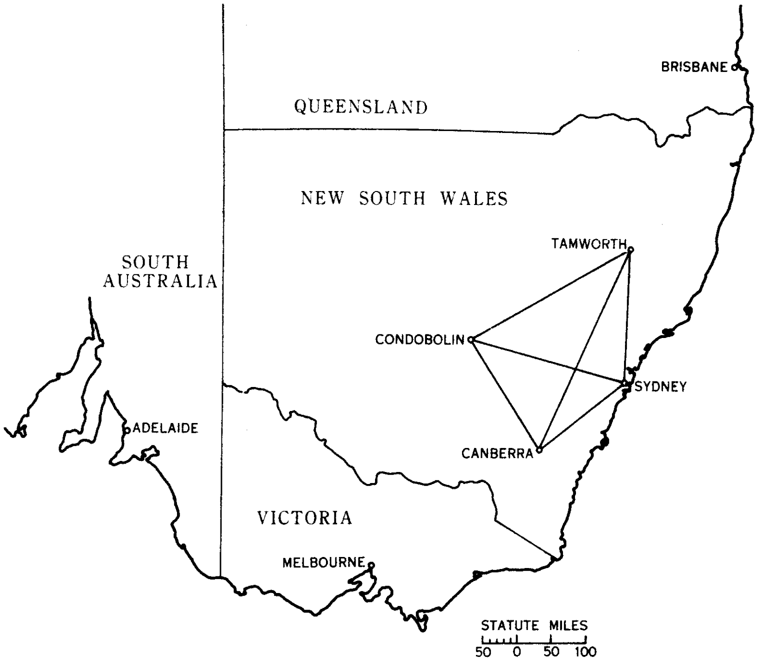

Fig. 1.—Area in which radar measurements were made.

II. Method of Measurement

The method of measurement, which will be referred to as the line-crossing technique, can be explained by reference to Figure 2. The technique has been used extensively by Col. Carl I. Aslakson (8) of the 7th Geodetic Control Squadron, United States Army Air Force. An aircraft carrying a radar interrogator unit is flown across the line joining the two points whose separation is to be measured, and where responder beacons are situated. The aircraft is flown straight and level for a few miles either side of the line between the beacons and at such a height that there is no obstruction in the radio line-of-sight between aircraft and beacons. All measurements are made from the aircraft end of the radio links. A continuous record is taken of the distances from the aircraft to the beacons, measurements being made using normal pulse-radar techniques. The sum of the two distances is plotted against time as the aircraft crosses the line and the minimum sum obtained. It is clear that if the altitude of the aircraft and height of the ground stations are known, then these values combined with the radar measured distances at the crossing point and the earth radius will enable a calculation to be made of the geodetic distance between the two ground beacons. It can be shown readily that, provided the sum of the two radar distances is known accurately, a rough indication of the two individual distances is sufficient for an accurate calculation to be made. The maximum distance that can be measured using this technique will be limited by the maximum operating height of the aircraft and the

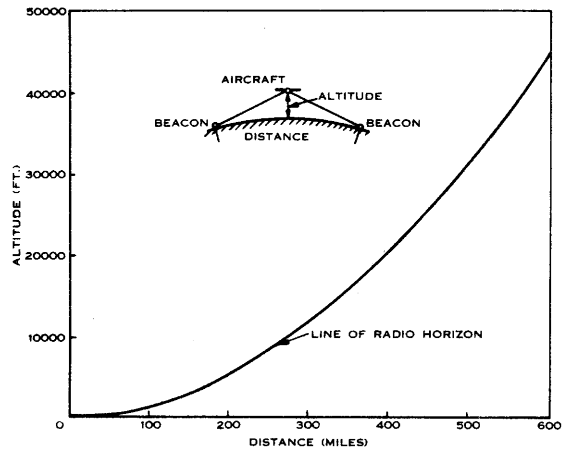

Fig. 2.—Method of distance measurement and maximum distance that can be measured by radar from an aircraft.

siting of the ground stations. Figure 2 shows the maximum distance that can be measured at various aircraft heights for the beacons at sea-level on a smooth earth. Obstructions near the ground beacons will, of course, reduce these values, and siting of the beacons on high ground will increase them.

III. Equipment Used

The work was carried out in a Douglas Dakota C47B aircraft flown and maintained by the R.A.A.F. This aircraft is very convenient for experimental work of this type, as there is ample room for equipment and the reliability of the aircraft is excellent. The ground beacons were installed in trailers initially, one subsequently being installed in the back of a covered truck. Power for the ground stations was obtained in all cases from supply mains, though provision was made for operation from a petrol-electric set carried with the equipment.

(a) *Aircraft Equipment*

The equipment used for making the distance measurements was fundamentally an American Shoran AN/APN-3 radar. However, in order to record automatically the sum of the two radar distances, to simplify the task of the radar operator, and to keep track of operator errors, additional equipment was constructed and installed. A radar altimeter,

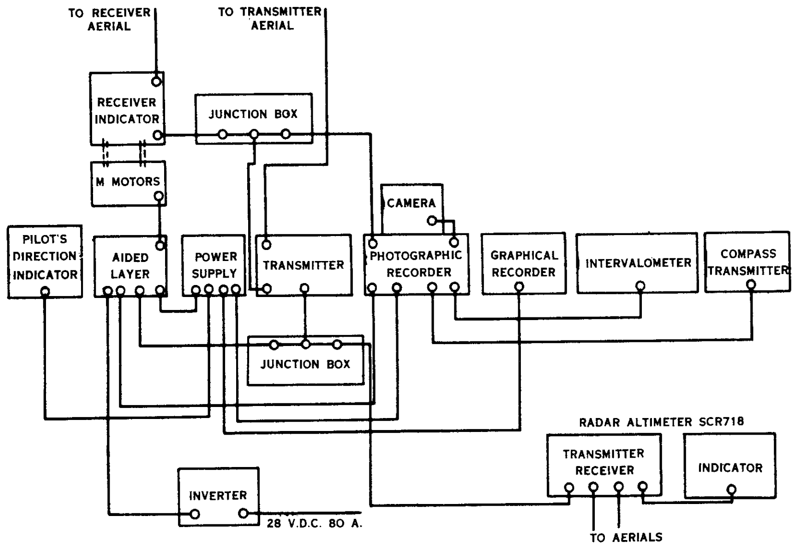

Fig. 3.—Block schematic aircraft installation.

type SCR718, and equipment capable of measuring meteorological conditions, were also installed in order that an accurate aircraft height determination could be made, and that corrections could be made to the measured distance for the effect of changing atmospheric conditions on the velocity of propagation of the radio waves. The complete aircraft installation is shown in Plate 1, and Figure 3 is a block schematic of the aircraft equipment.

The radar equipment performs a distance measurement by sending out pulses to the ground stations which receive them and reply on a different radio frequency. The time interval between transmitting a pulse and receiving a reply is measured, and from a knowledge of the velocity of propagation this is converted to a distance. By switching the airborne transmitter frequency at a slow rate, and having the two ground station receivers on different frequencies, it is possible to operate with both beacons almost simultaneously. The airborne set transmits pulses on a frequency of either 230 Mc/s. or 250 Mc/s., and receives reply pulses from the ground stations on a frequency of 300 Mc/s. The time interval is measured in the usual way by comparison with the period of a stable crystal oscillator of accurately known frequency. By a choice of oscillator frequency such that the period is equal to the time interval for a radio signal to travel out and back a distance of one mile, a direct calibration in terms of distance can be obtained to a close approximation. It will be, however, only an approximation, as the time to travel a mile will depend on atmospheric conditions over the distance.

The radar operator, by turning a pair of handwheels, one for each ground beacon, keeps aligned a marker pulse and the two reply pulses from the ground stations. When the pulses coincide, the degree of rotation of a pair of dials is a function of the distances to the ground stations. The dials are calibrated directly in terms of distance and are coupled to goniometers which shift the phase of the reply pulses to keep them aligned with the marker. Under operating conditions the distances to the ground stations are both changing so accurate tracking by the operator is difficult. To simplify his task an aided tracking device was designed and constructed and this is coupled to the "Shoran" receiver-indicator unit by means of M-type transmitters operating off the aircraft D.C. supply. Thus the handwheels turned by the operator control the rate and amount of rotation of a pair of M-type transmitters which are wired to M-type motors driving the radar dials.

In addition, wires are taken to M-type motors in the photographic recorder and graphical recorder, which are thus synchronized to the "Shoran" dials. At the photographic recorder the motors drive counters which indicate the two distances in the same way as do the "Shoran" dials. At the graphical recorder the motors drive a differential whose output is the sum of the two input rotations, and is used to drive a belt moving above the recording paper. A stylus can be clamped to the belt automatically at a predetermined sum distance as given by the "Shoran" dials, and it then records the variation of the sum distance as the aircraft crosses the line between the beacons. The recording paper is moved below the belt, and perpendicular to it, by a motor which starts simultaneously with the clamping of the stylus to the belt.

A further addition was made late in the progress of the project in the form of a Pilot's Direction Indicator. This consisted of a pair of counters, one recording the sum of the two radar distances, and the other the difference. These quantities were obtained by using another pair of M-type motors to drive two differentials, one giving a sum and the other a difference. The loci of constant differences in the two radar distances are a series of hyperbolae, which for small distances from the line between the beacons, and from its centre, are a series of straight and parallel lines perpendicular to it. Thus if the pilot flies the aircraft to maintain the difference counter constant he is keeping to a suitable track for the distance measuring procedure. Since the sum of the two distances is a minimum at the crossing point and increases on either side, the sum counter can be used to indicate to the pilot that he has flown far enough on either side of the line to permit a satisfactory record to be obtained. The sensitivity of operation of these two counters was adjusted by the use of suitable gear reduction ratios to make the instrument a satisfactory navigational aid. Its use enabled the operations to be carried out when the ground below was obscured by cloud.

The photographic recorder contains a cathode-ray tube which displays the marker pulse and two reply pulses that are also shown on the "Shoran" receiver-indicator cathode-ray tube. It can thus be used to check the performance of the radar operator in maintaining pulse alignment, and if warranted, corrections for operator error could be made to the graphical record during the reduction of the data. The camera on the photographic recorder is operated at intervals of about five seconds by means of an interval timer. The photographic recorder also contains various aircraft instruments such as altimeter, airspeed indicator, air temperature indicator, and magnetic compass to enable a check to be made on the aircraft operation during the measurement.

The radar altimeter was used in conjunction with the pressure altimeter and certain meteorological information, as will be explained later, to enable an accurate height determination to be made. It was necessary for the success of the operation for the aircraft height to be kept constant to about 100 feet and to be known to within 50 feet.

The meteorological instruments carried by the aircraft enabled measurements to be made of air temperature, pressure, and humidity, and a photographic record of these instruments could be taken at intervals determined by an interval timer. These quantities must be measured if the highest precision is required in a distance measurement, since they affect the refractive index of the air and thus the velocity of radio waves. Since the radar equipment measures only a time interval, variations of velocity will affect the indicated distance directly. For lower precision it is unnecessary to make these measurements, and in fact no measurements were used during the course of the project.

(*b*) *Ground Beacon Equipment*

The radar equipment at each ground station consisted of a monitor unit, which contains the receiver for picking up the aircraft transmitted pulse, and a transmitter. The monitor also contains a stable temperature-controlled crystal, which can be used for generating a train of pulses in addition to the normal reply pulses to the aircraft transmitted signal. These former pulses can be picked up in the aircraft to check the frequency of the oscillator used for calibration of the radar distance dials. The reason for this procedure is to eliminate the long warm-up time, necessary for the crystal oscillator to reach steady operating frequency, from the aircraft equipment where large time delays would be undesirable. This warm-up time is unimportant in the case of the ground stations as provision for it can be made readily in the operating procedure.

In addition to the radar equipment, the ground installations contained a communications equipment, type AT5/AR8, to maintain contact with the aircraft and with base. This was found to be a very desirable feature. The remaining equipment consisted of power facilities for the radar equipment and work bench space provided for maintenance. Power was obtained from the three-phase supply mains, although provision was made for the use of a small petrol-electric set in case of power failure, or in the event of power being unavailable at any of the ground station sites.

IV. Reduction of the Observations

After observations had been made of the variation of the sum of the two radar distances during a line crossing, the approximate individual distances, the aircraft altitude, and possibly meteorological data (obtained

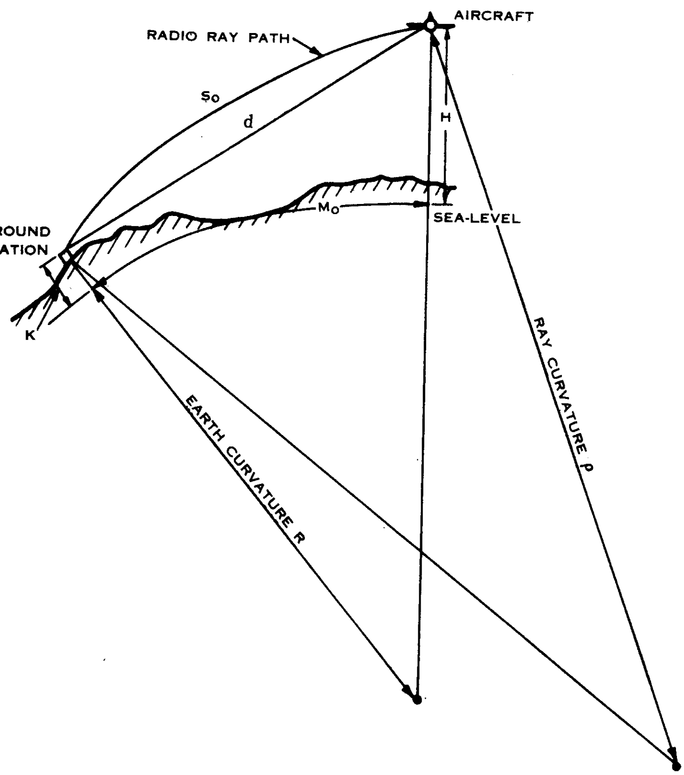

Fig. 4.—Geometry for reduction procedure.

for precise calculation of the variation of refractive index over the radio ray path), it was necessary to calculate the geodetic distance between the ground stations. The quantities necessary to make the reduction can be gauged from an examination of Figure 4.

It is first necessary to know the heights of the ground beacons above sea-level. In our case this was determined from existing surveys, but if these did not exist some procedure for finding the heights would be necessary. It is then essential to find the aircraft height more accurately than it can be determined from the aircraft altimeter. The error in distance caused by any given error in height is indicated in Figure 5. The method of accurate height determination that was adopted consisted of finding the height of a pressure level, at or near that to be used during line crossings, by means of a radar altimeter, and then calculating from a knowledge

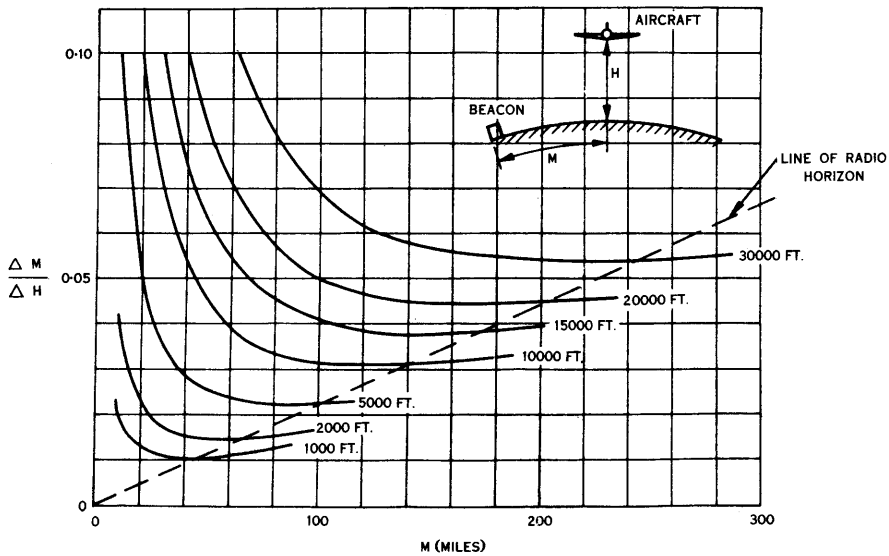

Fig. 5.—Error "ΔM" in distance "M" caused by error "ΔH" in altitude "H."

of wind data the change of height of the level between the check point and the operating point. The check was carried out over the sea, where the radar altimeter gave reliable readings. The pressure altimeter was used to indicate only the deviations from the chosen pressure level. A complete description of the technique and its probable accuracy is given elsewhere (9).

The distances indicated on the radar dials, which are really only time intervals, were next converted to true straight line distances between the aircraft and ground beacons. Due to changing refractive index with height the radio ray path is slightly curved with an increasing radius of curvature from ground level to the aircraft. It is sufficient to assume an average radius of curvature over the whole path, and to determine the

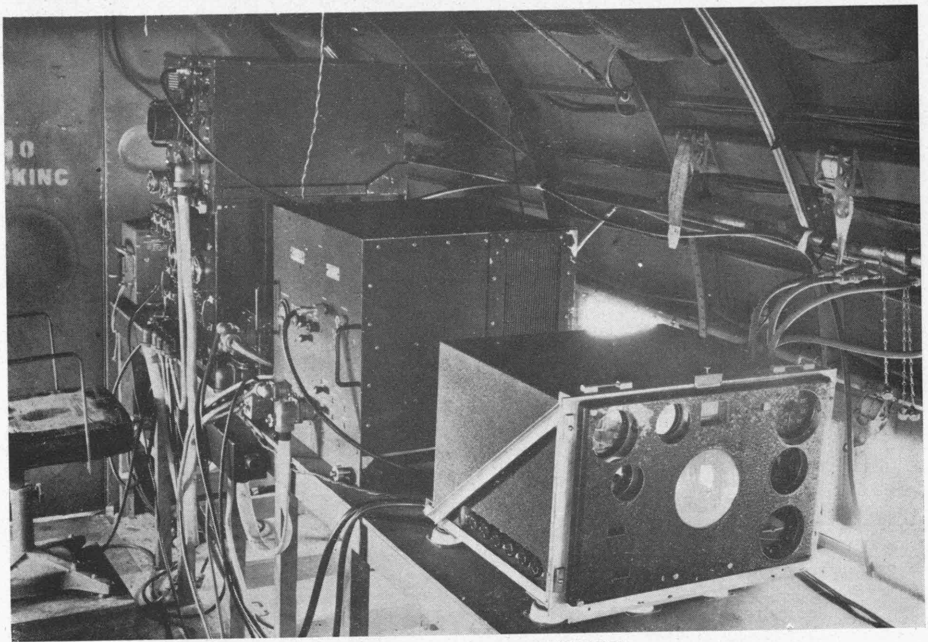

Fig. 1.—Starboard side of aircraft.

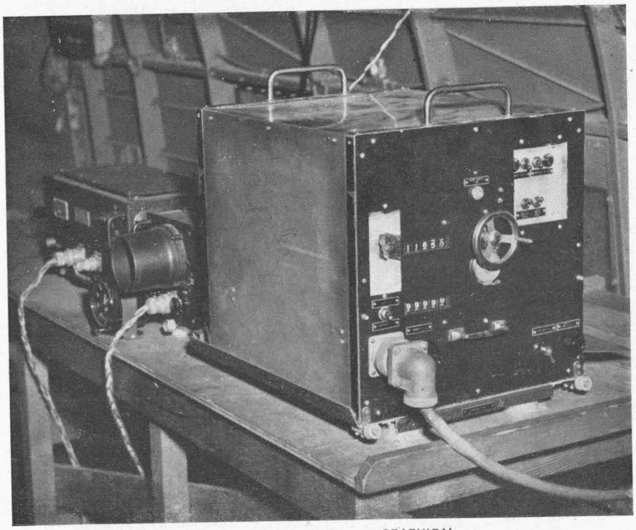

Fig. 2.—Port side of aircraft.

difference between the chord and arc distances, which in any event is very small, usually being less than five feet over distances of a few hundred miles. Further, the varying velocity of propagation over the path, due to changes of refractive index with meteorological conditions, must be taken into account. Unless actual meteorological conditions have been measured, average conditions must be assumed for the variation of refractive index with height. Calculations indicate that extreme variations of atmospheric conditions from the average will cause variations in the time to travel over a typical aircraft to ground beacon path of 100 miles, of the equivalent of about 20 feet.

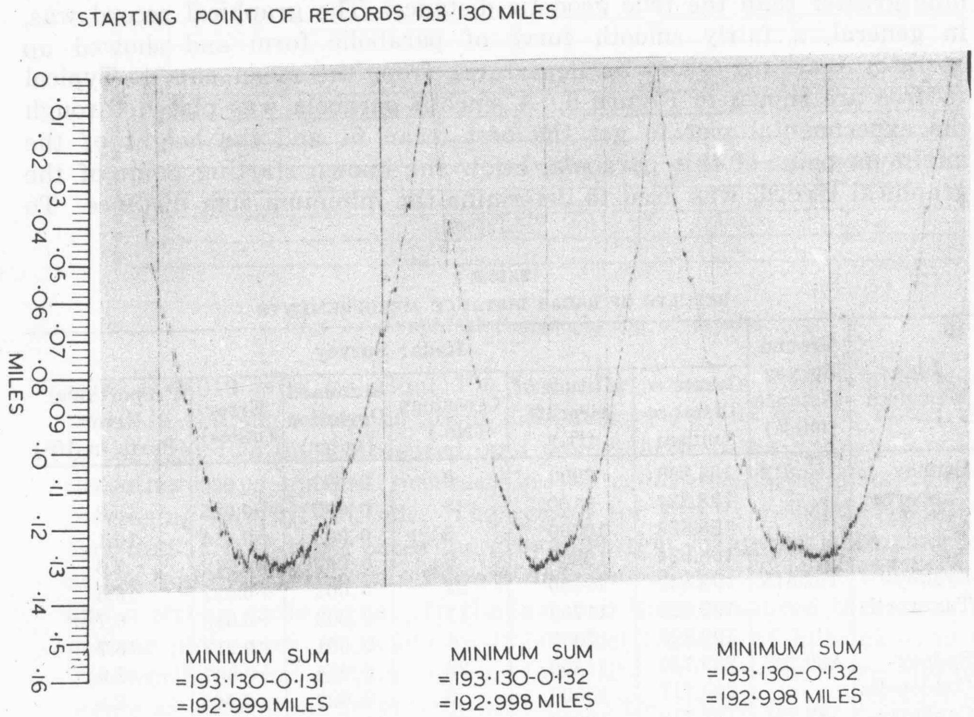

Fig. 6.—Typical records of the variation of the sum of two radar distances during a line crossing taken by the graphical recorder.

With the heights and straight-line distances known, it is a matter of geometry to determine the sea-level distance between the ground stations. Account must be taken of the earth's curvature, and the most accurate work will necessitate allowing for the changes of curvature with latitude.

Since all these correction factors are small, amounting at most to about a quarter of a mile, errors in the corrections are relatively unimportant. In some cases the distance to be measured was already known to about 1 per cent., and usually a trial crossing was made which determined it to 0.1 per cent. without worrying about corrections. Hence the corrections, and the way in which they varied with aircraft altitude and position along the line between the beacons, could all be computed before the main operation started and plotted in suitable form for rapid use later. This was found to be more convenient than calculating the corrections afresh for each line crossing, and resulted in less work.

The graphical record of the sum distance obtained from a line crossing starts from a predetermined value, which was usually about 0.3 mile greater than the true geodetic distance. The graphical record was, in general, a fairly smooth curve of parabolic form and showed up operator tracking errors as departures from the mean curve. Typical records are shown in Figure 6. A smooth parabola was placed through the experimental plot to get the best mean fit and the height of the minimum point of this parabola, below the known starting point of the graphical record, was used to determine the minimum sum distance. To

TABLE 1

RESULTS OF RADAR DISTANCE MEASUREMENTS

Line Measured	Ground Survey Distance (miles)	Radar Survey					
		Corrected Distance (miles)	Altitude of Aircraft (ft.)	Crossings (No.)	Standard Deviation (miles)	Error (miles)	Proportional Error (Parts in 10^5)
Sydney-Canberra	158.812	158.838	7900	6	0.002	+0.026	16.5
		158.837	9100	3	0.002	+0.025	15.8
		158.828	10600	5	0.003	+0.016	10.1
		158.824	18200	6	0.004	+0.012	7.6
Sydney-Tamworth	192.815	192.847	10600	22	0.003	+0.032	16.6
		192.828	11700	11	0.003	+0.013	6.7
		192.828	17000	6	0.001	+0.013	6.7
Sydney-Condobolin	239.723	239.730	11800	22	0.004	+0.007	2.9
		239.717	18500	8	0.002	—0.006	2.5
Canberra-Condobolin	187.234	187.219	10800	23	0.003	—0.015	8.0
		187.225	17200	7	0.003	—0.009	4.8
Tamworth-Condobolin	260.005	260.026	18500	19	0.005	+0.021	8.1
Canberra-Tamworth	311.301	311.334	19500	20	0.003	+0.033	10.6

this minimum sum distance corrections were applied as described above in the form of velocity, curvature, and geometrical corrections. The final result is the radar measurement of the distance between the ground stations.

V. Results and Discussion of Errors

The results obtained are summarized in Table 1 and in Figure 7. The mean error of all the results on all lines, taken without regard to

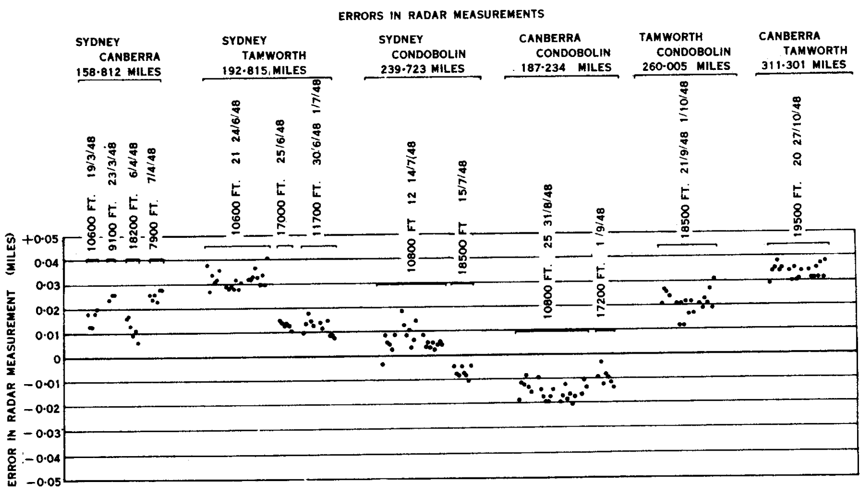

Fig. 7.—Graphical representation of results.

sign, is 0.019 mile, or about 100 feet. The average proportional error, taken in the same way, is about 8.5 parts in 10^5. It will be noted that in the first two lines measured, and particularly in the Sydney-Canberra line, there is a marked decrease in the radar measured distance with increasing aircraft altitude. The reason for this is associated with the fact that in both these cases the ground station siting was such that only at the highest altitude was there a clear line-of-sight path to the aircraft and a strong radio signal. In the last two lines measured there was not a clear path, even at 18,500 or 19,500 feet because of hills close to the Tamworth ground station. It was impossible to perform these measurements at a significantly greater altitude as the ceiling of the aircraft was about 20,000 feet, and it was difficult to fly an accurate track much above 19,000 feet. If we take only the high-altitude readings in the first two lines the average proportional error is about 7 parts in 10^5.

The reason for an error that varies with aircraft altitude is associated with equipment design. This error is a function of signal strength, and provided the signal strength is constant, as it is during any series of measurements at a constant altitude and fixed locality of aircraft and ground stations, the error itself is constant. If any of these factors changes, the signal strength changes, and the error changes. An experimental investigation indicated that a total variation of about 0.08 mile, or 400 feet, was possible under extreme conditions. The normal variation to be expected, however, would be about a third to a half of this amount, going from about —0.01 to +0.03 mile, which were about the limits observed in the six lines measured.

Since this source of error was so large it was not thought justified to push to the limit the elimination of other sources of error. For instance, all the above results are based upon the assumption of an average atmosphere derived from published meteorological data and radiosonde observations for Sydney. As mentioned earlier, this assumption could give rise to maximum errors of about ±40 feet for a 200-mile line. The consistency of the day-to-day results, as is indicated by the standard deviation, indicates that it is unlikely that errors as great as this have occurred owing to changing meteorological conditions.

Systematic errors in aircraft height would affect the accuracy of the result; the magnitude of the error in distance is roughly one-tenth to one-fifteenth of the error in height, as is shown in Figure 5. The technique adopted for accurate determination of altitude was such that the probable error should be within 50 feet. The errors in distance arising from this source are then clearly insignificant compared to other sources of error.

It was mentioned that all the measurements, which consist essentially of time measurements, are based upon the period of a highly stable quartz-crystal oscillator. Although this crystal was adjusted to within 1 part in 10^6 of its nominal frequency, there was a drift of about 1 part in 10^5 during the course of the work. This is equivalent to about 10 feet in 200 miles, which again is small in comparison with the signal intensity error. There are also a number of other equipment errors of magnitude about 5 to 10 feet which have been ignored. It was felt that, until such time as the signal intensity error itself could be reduced, it would be largely a waste of time to consider the other errors in the technique.

VI. Some Operational Aspects of the Use of Radar in Surveying

One of the most important aspects of the use of radar for geodetic surveying is that concerned with the manpower requirements and the time and flying hours necessary to perform a given measurement. The experimental work that has been performed over the last year and a half can serve as a guide to the requirements of a full-scale field survey. A better use of available time would almost certainly be achieved if more than two ground stations were in use simultaneously, since much time is wasted in moving ground stations and in flying from base to the point of operation.

It has been found necessary to have two operators in the aircraft in addition to the normal aircrew, one at each ground station, and one at base. Since the programme was primarily an experimental one it was decided to use qualified technical men as operators in all cases, but it is likely that a field operation could be carried out satisfactorily with non-technical staff at the beacons, and at base, and with only one technical man in the aircraft. It is desirable that the latter should have a sound understanding of both survey and radio aspects of the operation if the best results are to be achieved.

Although the programme described was an experimental one it is considered that the time spent in flying, and the time taken to move the ground stations to new sites, are some indication of what would occur in a field operation. An analysis has been made of these factors which showed that an average of eight flights was made for each line measured and that an interval of 11 working days occurred between measurements of successive lines. Only about 60 per cent. of the flights were devoted to line-crossing measurements, the remainder were used for intensity error investigations or demonstrations of the equipment. Each flight lasted on an average about three hours, most of which was spent in flying from the base aerodrome to the crossing point and back. Flights occurred on about six days in every 10, this being regarded as normal since many factors can prevent a flight occurring, bad weather being the most frequent.

In a field operation all the time would be devoted to line-crossing measurements and it is expected that the number of working days required for each line measured could be reduced to nine, on five of which flights would be made. It is considered that a minimum of three flights is necessary for each line measured. If meteorological soundings are made the duration of the flights would be longer than our average of about three hours, probably by one or two hours. Such soundings would be necessary if an accuracy better than about 3 or 4 parts in 10^5 were to be achieved.

VII. Conclusions

The method of distance measurement using the line-crossing technique that has been described gave an average accuracy of roughly 7 parts in 10^5 when measuring lines of 160 to 310 miles in length. The greatest source of error is in the radar equipment that was used and is associated with signal strength. It is considered that by suitable modification to the equipment, in particular to the receivers, this signal intensity error could be reduced to within ± 0.002 mile. If this were done it is likely that the overall accuracy of the technique would improve to about 2 parts in 10^5. An improvement on this latter figure would be impossible without extensive improvements to the radar equipment, particularly to the phase shifting goniometers and the display. In addition a thorough investigation of problems of atmospheric refraction would be necessary.

VIII. Acknowledgments

The author would like to acknowledge the active cooperation of those members of the R.A.A.F. Aircraft Research and Development Unit who were responsible for the operation of the aircraft used throughout this project. The author also wishes to thank the members of the Division of Radiophysics who assisted him in the work, in particular, Mr. R. C. Baker, Mr. D. C. Dunn, and Mr. H. E. Miller, who operated the ground stations, assisted in the flying, and did much of the testing, maintenance, and organization inseparable from a project of this type. Thanks are particularly due to the Property and Survey Branch of the Department of the Interior which supplied the ground survey information used to check the accuracy of the radar distance measurements.

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