STRAIGHT FLIGHT OF AIRCRAFT EQUIPPED WITH RADAR-OPERATED PILOT'S INDICATOR

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ABSTRACT

The ranges of an aircraft to two radar beacons on the ground are supplied to an instrument which indicates to the pilot the departure of that aircraft from any one of a series of predetermined straight and parallel lines of flight. These lines of flight may be spaced any desired distance apart and oriented in any direction with respect to the radar beacons. From data recorded on flight tests, the sensitivity of the indication was found to be sufficient for the pilot to control the flight of the aircraft to within a maximum departure of 0.05 mile from a straight line. Such control of flight has advantages for aerial surveying.

INTRODUCTION

CONSIDERABLE work has already been done in investigating the use of radar for aerial surveying both in the United States (1, 2) and in England (3). The type of radar that has been most extensively used enables the position of the survey aircraft to be determined at any desired instant by a measurement of the distance from the aircraft to a pair of radar beacons installed at known ground points. The same radar equipment can be used as a navigational aid to enable a series of controlled paths to be flown. For example, each path may be one of a series of concentric circles about either radar beacon. However, a straight flight path is preferable, both from the point of view of the pilot, who must keep the aircraft level during each vertical photograph, and the surveyor responsible for laying the photo mosaic.

As part of its program of investigation of the suitability of radar aids for surveying, the Commonwealth Scientific and Industrial Research Organization undertook the design and construction of an instrument which, in conjunction with suitable radar equipment, would enable an aircraft carrying out a photographic survey to be flown along a series of straight and parallel tracks oriented in any desired direction. The instrument that was developed and the results obtained on flight trials performed in April, 1949, are described below.

DESCRIPTION OF STRAIGHT-LINE FLIGHT INDICATOR

The instrument was designed for use with Shoran radar equipment AN/APN-3 (4), but could be readily adapted for use with any other radar equipment in which the range from the aircraft to each of the beacons can be presented in the form of a shaft rotation proportional to that range.

The operator of the Shoran equipment, by rotating a pair of handwheels, keeps reply pulses from the radar beacons aligned with a marker pulse displayed on a cathode-ray tube. When the pulses are correctly aligned, the range dials and counters which are connected to the handwheels indicate the radar distances to the two beacons.

To avoid mechanical interconnections, and so that range information could be fed simultaneously to a number of instruments, including the straight-line flight indicator, the Shoran equipment was modified by providing electrical transmission of the range dial rotations. The Admiralty M-type step-by-step transmitters and motors were adopted for this purpose.

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In the design of the instrument, the useful area of the aircraft for surveying was considered to be limited by (a) the operational requirement of the radar equipment that ranges should lie between 50 and 250 miles, and (b) the accuracy requirement that the estimated range errors would cause excessive errors in position fixing unless the angle subtended at the aircraft by the two beacons lay between 30° and 150°. These limitations are shown graphically in Figure 1. The maximum ranges are governed by the maximum height of the aircraft and by the sites of the beacons since the radar operates on a radio frequency at which propagation occurs along paths that are almost straight lines.

The instrument is a mechanical model, to a nominal scale of 40 miles per inch, of the positions of the radar beacons, the aircraft, and the desired flight paths. A photograph of the instrument is shown in Figure 2. At the two beacon positions, range arms in the form of lead screws are pivoted. These lead screws are rotated by M-type motors through reduction gearing so that the displacements of nuts on the lead screws represent the radar ranges to the beacons. The nuts are coupled together and carry an electrical probe which represents the position of the aircraft. This probe moves in a plane that is very close and parallel to the surface of a metallized glass grid which is engraved with a series of parallel flight tracks. The probe and metallized grid are part of an electrical circuit by which the deviation of the probe from the center of the nearer engraved flight track is indicated on a center-zero microammeter.

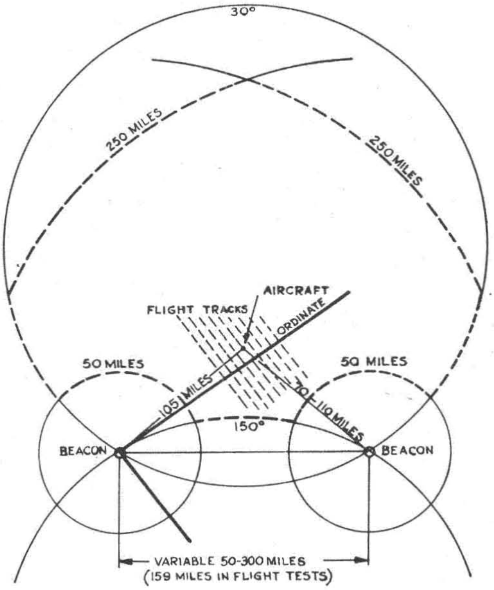

FIG. 1. Boundary of operational area of aircraft under radar control taken into account in designing the instrument. The area in which flight tests were performed and the coordinate system used in reducing the results are also shown.

The spacing of the parallel tracks is governed by the height that the survey aircraft is to fly, the vertical camera to be used, and the overlap of the photographs. Thus, if a change in the survey program involves any one of these factors, a different grid must be fitted to the instrument. However, several different grids would make it possible to fulfil most survey requirements.

The probe and metallized grid form part of an alternating current bridge circuit which is in balance when the probe is centered over an engraved track. The degree of electrical unbalance of the bridge is amplified, fed to a phase-sensitive detector and displayed on a center-zero indicating instrument to the pilot of the aircraft. Thus, if the probe representing the position of the aircraft is closer to strip A than to strip B of the grid (Figure 3), the pointer of the pilot's indicator will be deflected towards A by an amount depending on the departure of the aircraft from the desired line of flight. The pilot is thus shown how to regain the desired line of flight and, after this has been done, the pointer on the indicator will return to center-zero.

A second purpose of the instruments is to provide facilities for automatically operating the vertical camera at selected equal ground intervals. A second probe

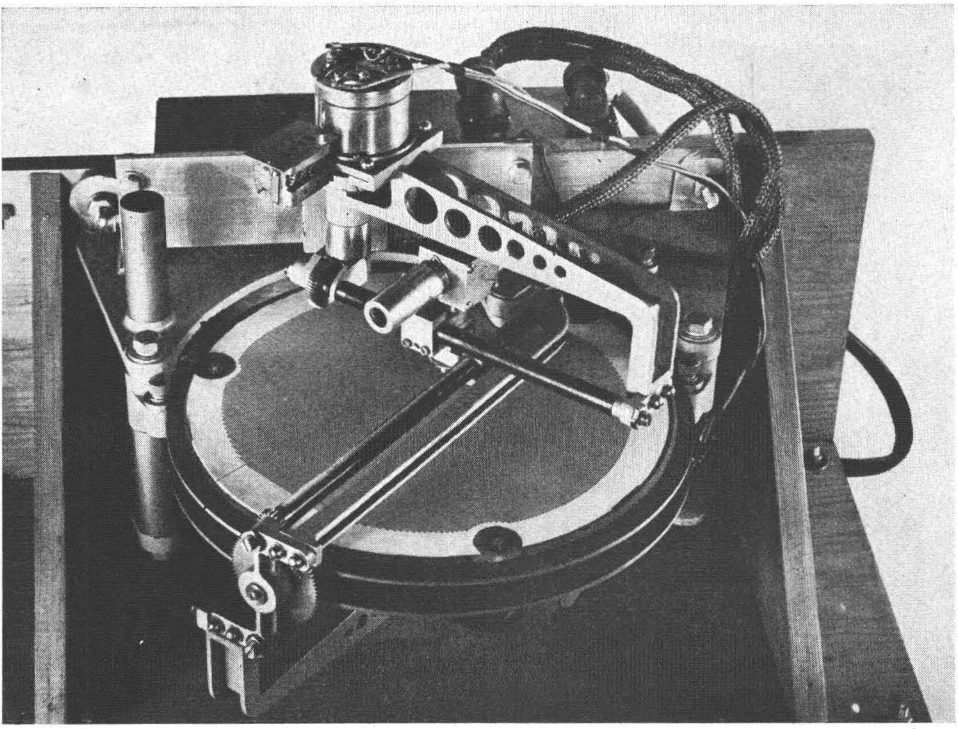

FIG. 2. Straight-line flight indicator mechanism.

is arranged vertically beneath the one described above, and moves in an identical manner over a second grid system which is aligned at right angles to that defining the aircraft tracks. The spacing between the engraved lines on the grid represents, to scale, the ground interval at which it is desired to take vertical photographs. As described before, the probe and grid form part of a bridge circuit, of which the electronic detector has been designed to produce pulses for operating the relay of the vertical camera at each instant that the probe crosses the center of a gap between adjacent strips of the grid.

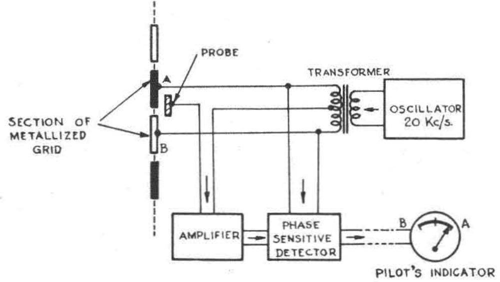

FIG. 3. Schematic diagram of electronic circuit.

The instrument can be adjusted for working with beacons from 50 to 300 miles apart. This adjustment is made by shifting one of the lead screw pivot bearings along a guide plate and clamping it in the desired position.

Each of the grids is mounted on a separate index plate which may be rotated about its central axis and clamped in position. Thus the grids may be oriented in any direction relative to the baseline between the beacon axes.

When the instrument has been set up and adjusted for a particular survey flight, its operation is entirely automatic. Once the pilot is flying along a track with the aid of the center-zero indicator, he may turn the aircraft around so as to fly in the opposite direction along either adjacent track without losing an indication of the position of the tracks.

A more detailed description of the instrument will be given in a paper (5) that is being prepared for publication.

FLIGHT TESTS

The instrument was installed, together with the radar and associated equipment, in a Douglas C47B aircraft. Flight tests were made at an altitude of about 10,000 feet, with ground beacons 159 miles apart at Sydney and Canberra. The aircraft was flown, with the aid of the instrument, on a series of straight and parallel tracks 1.7 miles apart. This choice of flying height and track separation was made as being typical of medium-scale photographic surveying. The sensitivity of the center-zero indicator was arranged so that full-scale deflection corresponded to a deviation of 0.3 mile. In practice this sensitivity proved to be the most suitable of several values tried.

So that a permanent record could be obtained of the performance of the aircraft and equipment, a photographic recorder was used to record the readings of the radar range counters and cathode-ray tube display, together with a compass, altimeter, air speed indicator, clock and a second center-zero meter giving the same information as that presented to the pilot. With this recorder, photographs of the above readings were taken at intervals determined either by a clockwork timer or by the instrument. In the latter case the recorder operated at times corresponding to those at which vertical photographs would be taken. In a survey operation, these photographic records would be used to determine the position of the plumb-point of each vertical photograph.

REDUCTION OF OBSERVATIONS

The cathode-ray tube display in the photographic recorder was used to monitor the performance of the radar operator and enabled correction to be made for any errors that he introduced through inaccurate tracking. These corrections were applied to the readings of the radar range counters. The corrected figures of radar distances from aircraft to ground beacons were used to compute the position of the aircraft. These distances were taken to the nearest hundredth of a mile since the radar equipment was incapable of an accuracy of better than ±0.01 mile for an individual reading.

In order to simplify the computing procedure, it was assumed that the Earth is flat, and that the correction necessary to reduce the slant range from aircraft to ground beacon to horizontal distance is a constant for any given height and independent of the slant range. The error introduced by these assumptions does not exceed a few thousandths of a mile for the conditions under which these experiments were performed.

In presenting the results, one beacon was chosen as the origin of coordinates, as shown in Figure 1, the abscissa being taken parallel, and the ordinate perpendicular to the flight paths given by the instrument. Ordinates were calculated to determine the departure of the aircraft from the chosen track and abscissae to determine the intervals at which vertical photographs were taken.

RESULTS

The results obtained during typical flights over two adjacent paths of about 40 miles in length are shown in Figure 4. This shows the position of the aircraft at 5-second intervals, at which instants a photographic record was taken, along two parallel flight tracks 1.7 miles apart. It should be noticed that the distances along the track which were obtained by multiplying the time interval by the aircraft air speed are only approximate. It will be seen that in the lower graph of Figure 4, the maximum departure from a straight track is only 0.04

mile wide, and the average departure 0.01 mile. In the upper graph in Figure 4, these figures are increased to 0.07 mile and 0.016 mile respectively. Some of this variation may be due to inaccuracies in the radar equipment itself, the remainder being due to the instrument and to the pilot, as the radar operator errors are negligible.

Tests of the instrument under laboratory conditions have indicated that the imperfections of the mechanism and the grid tracks may produce an average error of less than 0.01 mile. This error was obtained by setting the range counters of the instrument at a series of pairs of ranges which were computed to give points along a straight-line track, and then determining from the reading of the pilot's indicator the departure of the probe tip from the grid track.

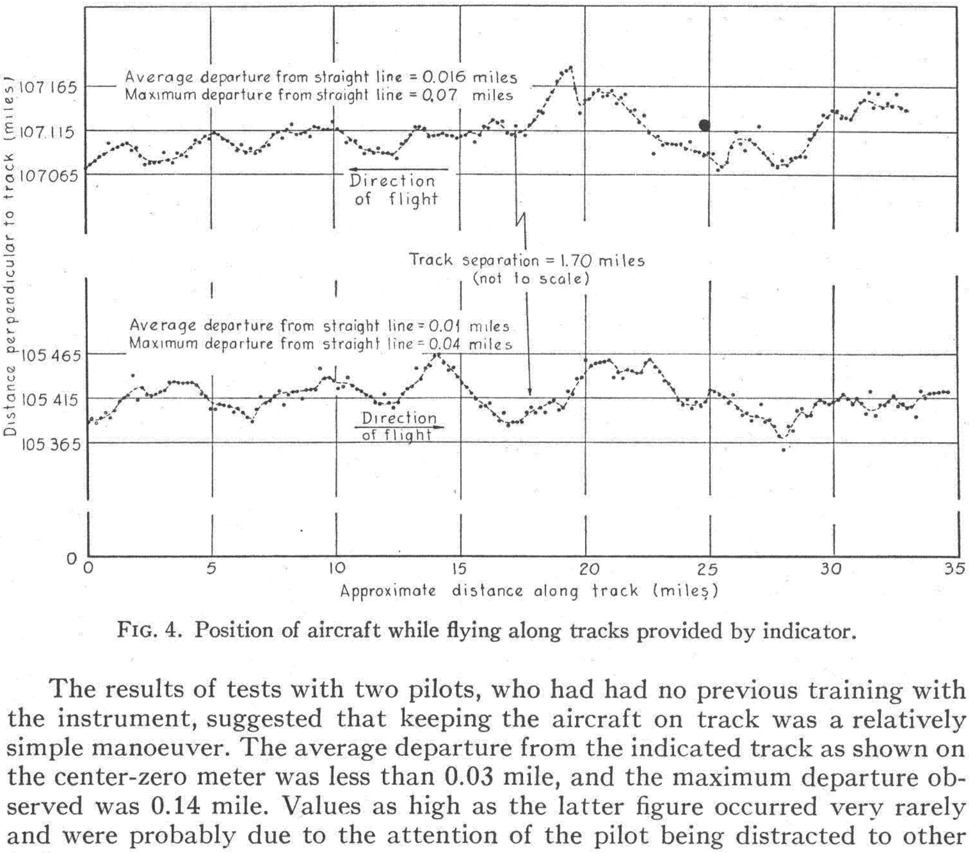

FIG. 4. Position of aircraft while flying along tracks provided by indicator.

The results of tests with two pilots, who had had no previous training with the instrument, suggested that keeping the aircraft on track was a relatively simple manoeuver. The average departure from the indicated track as shown on the center-zero meter was less than 0.03 mile, and the maximum departure observed was 0.14 mile. Values as high as the latter figure occurred very rarely and were probably due to the attention of the pilot being distracted to other tasks.

It was found that errors due to the radar operator not following accurately the movement of the aircraft were small. The maximum error observed during the flight tests was 0.03 mile and the average was less than 0.01 mile.

In the time available for testing, comparatively few parallel tracks were flown, but in those in which results were obtained, the mean separation was always very close to the design figure of 1.704 miles.

When the interval between photographic records was determined by the instrument itself, the mean of 120 intervals, calculated from records of aircraft position, was 0.76 mile compared with the design figure of 0.757 mile. However, in this case there was considerable variation from one interval to the next, the average variation in interval from the mean being 0.06 mile. To some degree this was undoubtedly due to insufficient care in first setting up the instrument when a check was not made for equality of voltages on the two halves of the grid network, as was done in the case of the grid defining the parallel tracks. This resulted in alternating long and short intervals along the track. It is likely that the average variation of interval would be halved under correct operating conditions.

CONCLUSION

The experimental model of a straight-line track indicator proved sufficiently accurate to allow an aircraft to be flown along paths which approximated to predetermined lines with a maximum error of 0.05 mile and an average departure of 0.01 mile. In addition, signals were provided for operating a vertical camera at constant distance intervals along the desired track. It was found that the average deviation of the interval obtained from that chosen was 0.06 mile, but it is likely that this would be considerably reduced by a better adjustment of the instrument.

Experience that has been gained in the construction and operation of this first experimental model should enable an instrument with a better performance to be designed. Particular care needs to be taken with the engraving of the grids, machining of the lead screws, which should be as free as possible from pitch errors and eccentricities, and the fitting of the component parts so as to reduce backlash to a minimum.

Advantage may be taken of radar equipment installed in a survey aircraft for operating this straight-line track indicator. With its aid an accurately spaced set of vertical photographs may be obtained with resultant economies in flying time and photographic materials. Also, with such a system, the photo mosaic strips may be laid either along or at right angles to the aircraft's track.

ACKNOWLEDGEMENTS

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