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Operational Research Group (W. and E.) Report No. 327

The Development of Unseen H.A.A. Fire Control 1940-45 with Special Reference to the work of A.O.R.G.

Communicated by Supt. O.R.G. (W. and E.)

Requested by C.P.R.S.D.

I. Principles of A. A. Gunnery.

1. The problems involved in the development of unseen fire control methods can only be appreciated in the light of the essential principles of A.A. Gunnery. Briefly, it is first necessary to fix the position in space, at a given moment, of the aircraft to be engaged; this involves the determination of three quantities. These are usually slant range (or sometimes height), angle of elevation, and angle in aximuth *[sic]* (bearing). Secondly, owing to the fact that the target is moving, it is necessary to predict a point in space at which it will be possible for a shell fired from the gun in use to meet the target (the "future position" of the target); besides knowing the ballistics of the shell, therefore, we must also know both the course and speed of the target, or some equivalent quantities, and assume that they will not change before the shell has reached the target.

II. A.A. Fire Control Before the Advent of RADAR

Direct Fire.

2. Accurate fire control methods were based on the assumption that the target would be visible. Slant range was measured by an optical range finder (coincidence type in Great Britain, stereoscope type in U.S.A. and Germany), but owing to the inaccuracy of the individual determinations, it was usual to combine the slant range measurements with those of the corresponding angle of elevation, and to deduce the target's height; since, in general, aircraft fly at a relatively constant height, these individual height determinations could be averaged over a suitable period of time, with considerable increase in accuracy.

3. This process whereby a number of individual observations, each of inadequate precision, are averaged over a period of time, can only be performed if the quantity under observation is sensibly unchanged during the averaging period; in other circumstances, the value of the average will be "stale". Increase in precision by averaging observations of relatively invarient quantities became of great importance in the early days of Unseen A.A. Fire.

4. Angle of elevation, and bearing were measured visually by laying telescopes on the aircraft. This laying was performed at the predictor, which, in German practice, was combined with the range-finder; in British and U.S. practice, however, the range-finder was a separate instrument from the predictor, and was layed in elevation and bearing by separate operators.

5. In the predictor, also, were mechanisms for determining the course and speed of the target (or equivalent quantities) from the bearing, elevation and height set into it, and mechanisms for performing the rather elaborate computations necessary in order to evaluate the firing data to be supplied to the gun. The predictor was thus, in effect, three instruments in one, performing the operations of tracking the target, deducing its course and speed, and evaluating the future position and firing data, respectively.

6. At the outbreak of war in 1939 two types of Heavy A. A. predictor were in service use in Great Britain: (a) the Vickers (No. 1) predictor, in which the future position of the target was estimated in terms of the rates of change of bearing and elevation, and the course and

speed did not appear explicitly; and (b) the Sperry (No. 2) predictor (of U.S. origin) in which the course and speed of the target were estimated in Cartesian co-ordinates (rates of change of northing and easting). Both predictors assumed that the target would maintain a constant height which had to be set before beginning engagement.

7. At night, direct fire could be brought to bear if the aircraft to be engaged was illuminated by searchlights and the graticules of the telescopes, and necessary dials and scales of the predictors could be illuminated by internal lighting arrangements. The Searchlights were directed on to the aircraft by means of sound locators which deduced its approximate position from the noise made by the engines.

8. The Operational Limitations of this system were roughly:-

(a) No engagements were possible in conditions of bad visibility.

(b) The optical range-finder was a serious handicap in conditions of only moderate visibility. Since a mean height had to be obtained, and set into the predictor before fire could be opened, observations with the range-finder had to be made as soon as, or before, starting to track at the predictor; on the other hand range finding was more limited by poor visibility than simple tracking and lack of height measurements delayed, or prevented, the opening of fire at times when the system could otherwise have been operated.

(c) At night, the sound locators were not very efficient in obtaining illuminations of the aircraft engaged, and as the height and speed of the targets increased, the efficiency became less. Moreover, in a gun defended area (G.D.A.), sound locators became practically useless once the guns had opened fire. During an attack on a coastal target, such as a port, from the direction of the sea, only the first few aircraft of the attacking force could have been illuminated. This limitation was of less consequence in inland G.D.As. since, in theory at least, the searchlights could be placed outside the G.D.A. in order to initiate the engagement, the target being then handed over from one searchlight to another until it reached the G.D.A.

Indirect Fire

9 When indirect fire is employed, the shells are not directed continuously at any individual aircraft, but are fired into a region of space which is believed, or suspected, to contain aircraft. In its most elementary form “barrage fire,” it consisted in estimating the most probable height of the attack and the direction from which it would arrive, and firing shells fuzed to burst in the volume of sky through which the aircraft should pass at a time when the attack was believed to be in progress. A number of refinements were made, however, in which the direction of the attack, and the time at which the aircraft would cross the "barrage line" were estimated from observations made outside the G.D.A. These observations could be made on sound alone (by means of sound locators, or less precisely, from Royal Observer Corps reports), so that "Predicted Barrages" could be fired in conditions of poor visibility. Such schemes involved elaborate communication networks, and in terms of actually destroying hostile aircraft were extremely ineffective.

III. The First RADAR Equipments

10 The first RADAR equipment for use with A.A. Guns (G. L. Mk. I) was not designed to provide complete fire control information; it was intended primarily, as a range-finder, in order to eliminate the operational limitations of the optical range-finder described in para. 8(b). In this, it was extremely successful, since the accuracy with which the ranges were measured was independent of the range (out to all ranges then necessary) or visibility of the aircraft. No heights, however, could be determined unless and until visual measurements of angles of elevation were possible, and fire could thus be opened only in conditions of reasonably good visibility.

11 As a secondary, but quite important function, G.L. Mk. I acted, in the terminology of more recent days, as the "putting-on" equipment for the visual layers at the predictor. Means were provided by which the RADAR could determine the bearing of an aircraft, though not its elevation, so that the predictor operators could be looking in the right direction before the aircraft became visible; much time in getting "on target" was thereby saved.

The Height Computor Gear

12. As an ancillary to the G.L. Mk. I, an additional box was developed for fitting to both Vickers and Sperry predictors. This enabled slant ranges and bearing to be received from G.L. by electrical transmission and followed by the predictor operators; provision was also made for the reception of elevation, but this was not used until the advent of G.L. Mk. II. In addition there was a drum which was rotated through angle of elevation, by the layer for elevation, and the pointer moved, parallel to the axis of rotation by the operator who followed the slant range received from the RADAR. On the drum were lines of constant height, so that the height of the target at any moment was indicated by the line which was under the tip of the slant range pointer.

IV. The Beginning of Fully Unseen Fire Control.

13. In September 1940, air attacks on London began to take place regularly in conditions when the attacking aircraft was invisible from the ground, even with the aid of searchlights. In the early days of these attacks attempts at fully unseen fire were made, a G.L. Mk. I providing slant range and bearing, and a sound locator angle of elevation. These, however, were by no means successful, chiefly owing to the difficulties inherent in operating a sound locator in the neighbourhood of a battery of guns; other reasons were the lack of facilities of G.L. Mk. I for "constant following" in bearing (see para. 14), and the lack of a sufficient supply of height computor gears, without which the RADAR data could not be transmitted electrically to the predictor, but had to be passed by telephone.

The Elevation Finding (E.F.) Attachment for G.L. Mk. I

14. Earlier in 1940, however, the possibility of this situation arising had been foreseen. G.L. Mk. II had been designed to provide full Unseen Fire Control and was then in development. It could not be in the service until 1941, however, and in the meantime Mr. Bedford of Messrs. Cossors Ltd., designed and had produced, the "E.F. Attachment" (also known, by its function, as the "switching pre-amplifier") for G.L. Mk. I; based on the same principles as those employed for G.L. Mk. II this enabled G.L. Mk. I to measure angles of elevation, and, of equal importance, to provide constant following in bearing. In G.L. Mk. I the bearing of the target was determined by rotating the cabin and aerial system until the signal received was a minimum; when the equipment was not on bearing, therefore, there was no indication as to the direction in which it should be rotated and this had to be discovered by trial and error, or "bracketting". The E.F. Attachment provided a display by which bracketting was rendered unnecessary, and a reasonable smooth measurement of bearing was supplied to the predictor. This made the operation of the predictor in unseen conditions really possible for the first time.

15. No provision was made for transmitting the measurements of elevation to the predictor. Owing to the method by which these were obtained, the dial on which the elevation was read did not rotate linearly with the angle of elevation and a more or less arbitrary scale was used. Simultaneous readings of slant range and of elevation were therefore taken, the height calculated and passed to the predictor by telephone. In this respect, therefore, the drill was identical with that using an optical range-finder.

16. In one other respect, however, the drill was very different. Under visual conditions, the predictor made use of the three parameters, height, bearing and angle of elevation; under unseen conditions, height and bearing were available, but no angle of elevation. This

difficulty was got over by making use of the RADAR slant range, and by operating the height computor gear backwards, as it were. The slant range operator traversed the pointer along the drum through slant range while the layer for elevation rotated the drum so as to maintain the line corresponding to the ascertained height opposite the pointer, thereby setting in the appropriate angle of elevation. Unfortunately the lay-out of the height computor gear was not designed so that the layer for elevation could see the height computing drum; on the Vickers predictor, operation was just possible if a tall man with long arms was employed; on the Sperry predictor a mirror had to be attached and even then the layer for elevation had to work in a very awkward position. (The mirrors not infrequently fell off when the guns fired).

The Development of Prediction Systems for Unseen Conditions

17. In bearing, the inherent "discrimination" of G.L. Mk. I (E.F.) was not very high and even in the best circumstances, careful observation of the display system was required in order to detect that the equipment was as much as 1 degree off target. It was thus quite impossible to prevent the operators wandering quite appreciably about the true point of lay. In elevation, the "follow-the-height-curve" (F.H.C.) system described in para. 16 should have given results of reasonable accuracy; the slant range output of G.L. Mk. I was more accurate than that of any previous range-finder and the operation was easy; the height used was a mean of several observations so that even though the accuracy of the elevation measurements was no greater than that of bearing measurements, the errors should have been smoothed-out. The large number of manual pointer-following operations in the chain, and, above all, the extreme difficulty of accurately following the height curve ordered in the awkward lay-out necessary, resulted in the appearance of large errors. (in the Sperry predictor, for example, the chain consisted of: (i) manual following of the RADAR echo in the RADAR cabin; (ii) manual pointer following of slant range at the predictor: (iii) manual following of the height curve by the layer for elevation; (iv) manual following of the angle of elevation by the ground range operator).

18. The result of these wanderings about the true values of bearing and elevation was that, effectively, the apparent course and speed of the target, as supplied to the predictor wandered about the true values, and the guns were layed ahead of the target in almost every direction except that in which it was flying. (The word "wandering" is used deliberately, rather than "oscillation" or "fluctuation", in order to emphasise the fact that the errors changed in magnitude and sign relatively slowly; the predictors were often technically "steady", in that a solution had been found for the "A.A. Balance", but the prediction was wrong in both magnitude and direction.)

The Amputated Sperry Predictor

19. Professor Blackett, in the Autumn of 1940, realised that this behaviour could be largely eliminated if the course and speed of the target could be determined over much longer periods of time than the few seconds used by the Vickers and Sperry Predictors, and proposed the "amputation" of the Sperry Predictor. With this modification, the Cartesian co-ordinate rates were not measured automatically within the predictor, but were measured on a plotting board over as long a period as was desired, and set into the predictor manually, by a mechanism already present and intended for setting in wind corrections.

20. It is emphasised that the value of this proposal lay in the concentration of the smoothing processes in quantities which were invariant (compare para. 3) and smoothing of the co-ordinate rates has been included in every heavy A.A. predictor developed since 1941. Some attempts had previously been made to increase the accuracy of prediction by instructing the G.D. bearing operators to lay smoothly. It was found, however, by the A.A. Command Research Group (fore-runners of A.O.R.G.) in a series of tests of operational RADAR operators, that such attempts at smoothing led to the true changes of bearing, and more

particularly of rate of change of bearing, being entirely missed; the bearing output was often remarkably smooth, and the predictor would doubtless have been steady, but the actual values of bearing supplied to the predictor were grossly in error (in one test, the error reached 25 degrees). As a result of these tests, the Report on which was not issued generally, smoothing of the RADAR was discouraged, and operators were instructed to lay as accurately as possible, even if this meant a loss in smoothing.

21. The A. A. Command Research Group carried out a number of trials on the first Amputated Sperry Predictor, and compared the accuracy of the output with that of the normal Sperry; these were largely carried out indoors, signals being fed to a G.L. Mk. I receiver from the experimental model of Mr. Bedford's trainer (Trainer A.A. No. 5). These trials fully confirmed the expected great increase in the accuracy of the output of the predictor, and the results were written up in two Interim Reports of the A. A. Command Research Group. A third report considered the effect of the wandering of the plotted track of the aircraft, on the accuracy with which the co-ordinate rates could be measured, and the optimum length of track to be used; all three Reports were given only a very limited distribution. One very important factor, however, was overlooked in these trials. It was assumed that there would be no difficulty in estimating the co-ordinate rates in action, whereas it was subsequently found that very substantial errors and mistakes were frequently made (compare A.O.R.G. Report No. 312). Indeed, by and large, the Amputated Sperry Predictor was a failure until the advent of the Automatic Rate Measuring Gear, which enabled the co-ordinate rates to be determined on the predictor itself and set in with less risk of error; the Mechanical Smoothing Gear, introduced shortly after, further simplified the process, but by this time the Sperry Predictor was obsolescent.

Smoothing at the Vickers Predictor.

22. This was a more difficult problem, since the principle on which it works does not result in the appearance of any invariant quantities. The angular deflections, however, are set in manually, by operators turning handwheels in such a way as to prevent needles from rotating in either direction; those needles are each driven by the difference between the deflection sot and the deflection required to make the "A.A. Balance". On the lateral (bearing) side, therefore, it was possible to devise a drill making use of the fact that the lateral deflection required for a target flying on a constant course at a constant speed, varies with time in a characteristic and relatively simple manner; indications by the rate needles consistent with this general character were to be followed, those in opposition to it were to be ignored. Knowledge of the moment at which the target reached crossing point was also required, but this was provided readily and accurately as the moment at which the slant range reached a minimum value. On the vertical side, no such simple rules could be devised, owing to the complexity of the changes in vertical deflection. Indeed no method has been devised for increasing the accuracy of the Vickers Predictor on the vertical side, and good results can only be obtained by using highly skilled operators and when engaging targets on courses and at speeds with which they are familiar. The trials on which the lateral smoothing drills were based were described in A.O.R.G. Reports Nos. 3 and 41.

Indirect Fire - Plotting Control

23. During Autumn, 1940 and Spring, 1941, owing to the inadequate supply of RADARS, height computor gears, and to some extent, predictors, much of the A.A. fire was controlled by plotting procedures. The principle of these procedures was that the height of the target was measured and its position in ground plan plotted on a map, or gridded board at regular intervals of time (usually 10 seconds). As soon as enough plots had been made to establish the course and speed, a moment for engagement was decided t secs, (where t was usually about 60), ahead of the last plot on the board. The expected position of the target at this moment was ascertained by extrapolation of the meaned plotted track, the; guns layed on

this point, and fired at a moment (t-T) secs. after the last plot, where T was the time of flight of the shells to the point of engagement. This procedure had the great advantage that the fire of a number of neighbouring gun positions could be controlled by one master position which was equipped with radar. Plotting however, with the inadequate facilities available, was difficult, and not very accurate, and the timing of the moment to open fire was subject to considerable error. On the whole, much valuable shooting was performed with its aid; analysis of sample engagements were made in A.O.R.G. Reports Nos. 6, 23 and 35.

24. It was fairly generally held at this time that predictors could not be made to work satisfactorily on data from G.L. Mk. I, and that plotting procedures would be essential. A.A. Command put in hand, therefore, provision of the Semi-Automatic Plotter. This instrument was specially designed for its purpose, and permitted greater accuracy of plotting. More important, however, it gave a continuous presentation of the ground plan position of the target, so that the Back-timing procedure of 26 A.A. Brigade could be used. The Back-timing procedure differed from the Forward-timing procedure described in para. 23 in that the point of engagement was not chosen so as to be a definite time interval ahead, but was chosen arbitrarily at any point on the extrapolated track sufficiently far ahead. The guns were layed on this point and the time of flight read from the range tables; fire was then opened when the target reached a point distant v.T from the point of engagement, where v is the speed of the target and T the time of flight to the point of engagement. This procedure clearly reduced considerably the errors in estimating the moment to open fire, resulting from errors in the estimation of the t target speed. A further development, however, increased the accuracy still further. The greater part of the time that had to elapse between selecting the point of engagement, and opening fire was occupied in reading Q.E. and fuze from the gunnery data books, setting the fuze, loading the gun and traversing in bearing through possibly a large angle. The revised procedure, therefore, selected only a rough bearing to which the guns could traverse together with the ground range and height of the point of engagement, thereby fixing Q.E. and fuze. Some 10 seconds, only, before the target reached the point where fire was to be opened, a fresh mean course was drawn, and the final gun bearing given as the bearing of the point of intersection of this mean course with the circle representing the chosen ground range.

25 Various special pieces of equipment were developed in order to assist in the Back-timing procedure. The earliest of these probably was the "Spider" introduced by 6 A.A. Division; this consisted of a mask to be placed on the S.A. Plotter in the general form of a spider's web, the bearing of the point of engagement being read by means of the radial lines, and the range by means of the circles. 4 A.A. Division developed a vertical glass screen, on one side of which the target's position was plotted while on the other side, the course was meaned and the point of engagement selected. H.Q. A.A. Command developed the Prediction Linkage, which became the standard equipment. This consisted of two celluloid arms pivotted at the point of engagement; one arm was used for meaning the course, and reading the back distance, and the other was arranged to slide on a fixed pivot representing the gun position, so that the point of engagement could be correctly placed. The gun bearing was read on a large circular scale mounted on the S. A. Plotter. With all these methods, the back distance was read on a table which was entered for target speed, determined by measuring the distance travelled in 50 seconds, and for time of flight, as read on the Gunnery Data Book. A.O.R.G. developed an "Elastic Calculator" which could be set for speed, over any desired interval of time, and then used to measure back distance for any desired time of flight, thereby simplifying the procedure and reducing the number of operators. It was intended to be used with the "Spider" and could not readily be adapted for use with the prediction linkage; it was not used in the service.

26. It must be admitted that it is doubtful if this final procedure was responsible for much effective shooting, owing to its difficulty and the extreme speed with which it must be performed. A.O.R.G. personnel, under laboratory conditions obtained results which were no

less accurate than those given by predictors; in action however, circumstances were very different. The rate of fire, moreover, was very much less, and it was rare for detachments in action to fire more than one salvo per engagement, as against the 3-6 with predictors.

Fire Control for 3" A.A. Rockets.

27. The S.A. Plotter and the Back-timing procedure remained the standard fire control method for rockets. The virtual impossibility of firing more than one salvo at each target, owing to the time taken to load the projectors, made the disadvantage of this procedure, as compared with the use of a predictor mentioned in para. 26 of no importance. A.O.R.G. made an extensive study of the best methods of adjusting the procedure to suit the particular properties of the rockets and of the particular requirements as to radar information (Reports No. 4 and 48). The effect of rocket salvoes in causing hostile aircraft to take avoiding action was described in Report No. 226.

Initiation of the Development of New Predictors.

28. Early in 1941 the development of two new predictors and two new plotters was initiated; in those full account was taken of the experiences gained during the early days of unseen fire. The predictors were the Unseen Target Predictor (U.T.P.) and the Bedford-Cossor (No.9) Predictor. The plotters were the Plessey and the Service (A.R.L.). The latter was a more fully automatic and better engineered version of the semi-automatic plotter, and was never used in action. The former was initially a Plotter, in that the fuze to be fired was selected by extrapolation of a fuze-time curve, and the "A.A. Balance" was not made continuously; but it was subsequently modified for continuous prediction. It was later subjected to extensive trial and an experimental model was used on a few occasions in action. The principle and performance of both new predictors, and the Plessey Plotter, will be considered in somewhat greater detail in a later section (paras. 66-87).

Operational Limitations of the First Unseen Fire Control Systems.

29. These various systems were undoubtedly workable, and from November 1940 to the end of 1941 over ¾ of all rounds fired in A.D.G.B. were fired under their control, about 1/4 being under predictor control. There were, however, a number of limitations, some of them serious.

(a) The accuracy, even in the best conditions, was poor, and A. A. gunners who were used to visual methods were often shocked at the results.

(b) Targets could not be tracked when the angle of elevation exceeded about 45°. This meant that fire had to cease well before crossing-point in many cases, and engagement at the shorter ranges, where the fire would have been most accurate, was impossible. The advantages to be expected from increasing the maximum angle of elevation were assessed in an A.O.R.G. Report (No. 5) and the Double Slowcock Aerial System was devised which was capable of achieving this, although it was devised primarily with the object of defeating the clutter produced by ground objects and balloon cables (see (d) below). As a result of trials carried out by A.O.R.G. (Report No. 18) it was decided that it would be impossible to maintain the bearing alignment, and that too high a degree of skill was required on the part of the operator. The high angle requirement, however, was later met by the use of a lower aerial system (at 0.4 λ above the ground where λ is the wave-length in use), the reduced detection range inherent in the system being made up by the use of the more powerful Mk. II transmitter, which was then available, in place of the Mk. I transmitter (A.O.R.G. Report No. 17).

(c) The G.L. Mk. I equipments needed to be carefully aligned in bearing and calibrated in elevation. The methods for performing this alignment and calibration were not fully worked out until about mid-1941 or later, nor were the conditions in which the settings and adjustments would remain stable fully understood. It was the necessity for performing this alignment and calibration and for maintaining a constant check on the adjustments, that was responsible for the organisation of the Radio Maintenance Officers and to a large extent for the formation of the Operational Research Group.

(d) Considerable trouble was experienced with "clutter" -echoes from more or less permanent and stationary objects which filled up the display screen of the receiver and obscured the echoes from aircraft. These were of 2 main types: (i) Those due to ground objects such as hills, gasometers, electric power pylons and the like; they could be avoided by careful siting of the radar, but this could not often be achieved owing to the necessity for being close to previously sited gun positions, (ii) Those due to the barrage balloons and their cables; these were avoided eventually, by arranging that the balloons should be flown at the smallest height that was operationally acceptable. As already mentioned ((b) above) the Double Slowcock Aerial System was designed with the object of eliminating both ground and balloon clutter, but was not considered suitable for the service.

In addition, there was a third source of clutter which was never actually encountered, but which might have been a serious menace. If the enemy had mounted "mass" raids, with high densities of aircraft over the target area, there would have been so many aircraft echoes on the display screen that no single one could have been tracked; this was due to the very wide beam of the G.L. Mk. I equipment.

(e) It was possible, and even sometimes easy, for the radar operators to be "out of sense", i.e. to estimate the bearing of the target at 180° in error. This source of error was mitigated by the fitting of reflectors to the transmitter aerials, so that the power emitted was greater in the forward lobe, than in the backward, but very good drill and training - which were becoming increasingly difficult to ensure - were essential if it were to be avoided entirely.

(f) It was still necessary to assume that the target would fly at a constant height throughout the engagement.

V. The First Radar Equipments Designed for Fire Control

30. G.L. Mk. II (later officially known as Radar A.A. No. I Mk. II) was, from the beginning designed for complete fire control purposes. It was provided with a "split" system for continuous following in bearing, and with an elevation system, also provided with "split", whose non-linear scale (compare para. 15) was corrected by a cam, so that angle of elevation could be transmitted electrically to the predictor. It was hoped, therefore, that operation of the predictor in conjunction with G.L. Mk. I *[sic]* would be sensibly the same as its operation under seen conditions.

It is not intended, in this paper, to consider the problems raised by operational experience as to the design and construction of radar equipments, except in a very general way. More detailed and technical discussion will be found in the paper by Mr. J.S. Hoy.

F.A.P. vs. F.H.C.

31. The provision of facilities for supplying continuous measurements of angle of elevation to the predictor did not necessarily imply that the best results would be obtained by making use of them. This problem arose from the fact that the predictors then in use required that the height of the target should be pre-set; if the angle of elevation was continuously followed at the predictor - "Follow-angle-pointer" (F.A.P.) drill - inadequate use was being made of the accurate and consistent estimations of slant range now available from the radar. On the other hand, "follow-the-height-curve" (F.H.C.) drill, as described in para. 16, was a more awkward and complex procedure.

32. Preliminary investigations, under laboratory conditions, into the magnitude of the errors to be expected with the P. H. C. drill (A.O.R.G. Report No. 30) indicated that it was unlikely that the measurements of elevation in G.L. Mk. II would be so accurate that F.A.P. drill would be preferable. Further observations with the Sperry predictor were made during the course of the "Windsor Trials" (see para. 38 below) in which it become apparent, that, on the whole, the predicted future positions were more accurate with the F.H.C. drill than with the F.A.P. (A. O.R.G. Report No. 22). In a separate trial at Dartford, these conclusions were confirmed with the Vickers predictor (A.O.R.G. Report No. 41). In this type of trial, however, it is impossible to ensure that the comparison between the two drills was made under identical conditions as regards accuracy of tracking at the radar or straightness or general difficulty of the aircraft course. It was therefore decided to confirm the conclusions in a special series of trials with skilled operators, under reproducable conditions of input to the predictors. Such conditions could be realised with the aid of a course setter, devised by A.O.R.G., by means of which skilled operators could reproduce as accurately as was needed, the bearings, elevations and slant ranges actually layed by the G.L. operators when tracking an aircraft. In addition, the use of a course setter enabled the radar data obtained by tracking a relatively slow co-operation aircraft, at a relatively small height, to be "fudged" so as to represent observations on aircraft at more operational speeds and heights; this was done by multiplying all readings of slant ranges by a constant factor (usually about 1.5).

33. The trials were performed in conjunction with Coast and Anti-aircraft Experimental Establishment (C.A.E.E.) who supplied the skilled predictor detachment, and the results were described in A.O.R.G. Report No. 44. The superiority of the F.H.C. drill was abundantly confirmed and was estimated to be nearly twice as effective as the F.A.P. drill.

34. The F.H.C. drill was adopted for the service in spite of certain difficulties in procedure that it involved. The extremely awkward - even impossible - position which had to be adopted by the layer for elevation was a serious drawback, but this was overcome by fitting auxiliary elevating handwheels which were easily accessible. The computation of the height of the target presented some difficulty, however, since the lay-out of the G.L. Mk. II receiver cabin did not permit this to be done at all easily at the G.L. Arrangements had to be made therefore for two operators at the Command Post to read elevation and slant range, respectively, as transmitted from the G.L; the former of these had to be a special number, additional to the normal detachment. This drill was never satisfactory, owing to the inevitable errors made by relatively unskilled personnel when reading dials and owing to the extreme difficulty of ensuring precise synchronism in making the two readings. Later, in 1943, A.A. Command introduced the Mechanical Height Calculator for G.L. Mk. II which was a height computer drum inserted in the G.L. receiver cabin and allowing target heights to be read directly by one of the G.L. detachments thus solving all difficulties.

Smoothing of Radar Input.

35. The laboratory trials referred to in para. 32 above were primarily arranged in order to study the most effective way of smoothing the bearing input to the predictors. C.A.E.E. considered that useful smoothing could be performed by the layer for line when following the pointer which indicated the bearing layed at the radar, and developed a special drill to assist him in the process. A.O.R.G. doubted whether much useful smoothing could be done at this point owing to the long periods of the major wanderings, and considered that effective smoothing was not possible on the Sperry predictor (except by amputation) and was only possible on the Vickers predictor at the point where the lateral deflections were set in manually (see para. 22).

36. The results of the trial (A.O.R.G. Report No. 44) showed that with the Sperry predictor some increase in accuracy was achieved when the layer for line attempted to smooth, although the increase was small and of doubtful significance. Detailed examination of the results

showed, however, that the layer was apparently not able to perform the drill suggested, and was unable to smooth out the major wanderings of the input data; minor fluctuations of short period, however, were removed.

37. On the Vickers predictor the results at first sight indicated that smoothing by the layer for line (C.A.E.E.) was as effective as smoothing by the lateral rate setter (A.O.R.G.). Detailed examination of the results, however, again showed that the major wanderings were not removed by the layer for line, whereas the lateral rate setter was performing quite effective smoothing without being instructed to do so. This confirmed the earlier observations of A.O.R.G. when the smoothing drill was first introduced, that experienced rate setters were often capable of very effective smoothing without special instruction; the drill was intended for those rate setters who were less highly experienced, or who failed to develop the necessary facility. The smoothing drill for the lateral rate setter was adopted for the service and became the standard drill for unseen procedure with the Vickers predictor.

Tracking at High Elevations

38. As originally designed and put into production, the bearing aerials of G.L. Mk. II were at a height of 0.6 λ above the ground (λ being the wave-length in use); as in G.L. Mk. I therefore, no targets at angles of elevations greater than 45° could be tracked. The "Windsor Trials" referred to in para. 32 were in fact primarily arranged to test the possibility of lowering the bearing aerials to 0.4 λ and so removing the elevation limitation entirely.

39. The results of the trials (A.O.R.G. Reports Nos. 22, 25 and 55) showed, however, that this lowering of the aerials resulted in a loss of accuracy in bearing measurement which was quite inacceptable. A compromise of placing the aerials at 0.5λ was then proposed and tested by A.O.R.G. (Report No. 57). This put the bearing aerials in line with the range aerial (the system was known as the "3-in-line"); it was originally considered that there would be too much interaction between them. No difficulty was experienced, however, when the system was tried; the accuracy was unimpaired, as compared with the 0.6λ system, and targets could be followed with good accuracy up to elevations of about 60° and on some occasions were not lost even though the elevation at crossing point reached 80°. The "3-in-line" became the standard system.

40. With this system, angles of elevation could only be determined up to elevations of about 55°; this limitation was not serious, owing to the adoption of the F.H.C. drill, in which angles of elevation were only needed at intervals in order to make further estimations of height. An arrangement of aerials and a new correcting cam, were, however, developed, which allowed elevations to be measured up to about 80°; these were not required until the Bedford Cossor (No. 9) predictor came into the service and the F.H.C. drill was no longer desirable.

Training in Unseen Target Procedure

41. Trials by A.O.R.G. and other establishments showed that with skilled and inexperienced operators at both radar and predictor, reasonably satisfactory results could be obtained from the G.L. Mk. II - Vickers combination, and rather less satisfactory results from the G.L. Mk. II - Sperry combination. Observations on the results achieved in action showed, however, that the performance was very much less satisfactory, and it was apparent that the skill and experience of the normal site personnel were inadequate.

42. The origin of this state of affairs was largely in the hurried training necessary at the Schools and Practice Camps, and the lack of appreciation of the peculiar problems of unseen fire control and the shortage of radar equipments, which were urgently required for operations. The remedy lay in an increased amount of on-site training, but this was difficult to arrange owing to the shortage of aircraft and the consequent difficulty of arranging for adequate

amounts of co-operation flying; there was a demand for aircraft, also, for aligning and calibrating the radars.

43. In these circumstances much could have been done if an adequate supply of special training equipment had been available, which would have provided; (a) an artificial signal within the radar on which the operator could aly; and (b) an artificial input, simulating radar data, which could be supplied to the predictor. In addition, the training equipment should have provided a means of assessing the competence of the operators, and of indicating their faults to an instructor.

44. For the radar operators, A.O.R.G. designed and produced an experimental model of a trainer, intended to be attached, temporarily, to any G.L. Mk. I or Mk. II and which would fulfill, in part at least, the requirements set out in the previous paragraph. This was passed to A.D.R.D.E. for development and eventually became trainer A.A. No. 8; it did not reach the service, however, until the requirement for it had ceased, Mr. Bedford, also had previously designed his trainer which became Trainer No. 5, but this, although invaluable for use in schools, was unsuitable for on-site training. A.D.R.D.E., also, produced in relatively large numbers, the Trainers Nos. 4 and 4a; these were invaluable for setting up the G.L. receivers, but were not suitable for training the operators to lay.

45. For the predictor operators, it was clear that some form of course setter was required. The manually operated type used by A.O.R.G. in the trials was unsuitable and several types of full automatic course setters were designed. The only type to be produced in any numbers, however, was that designed by A.R.L., which become Apparatus A.A. Training No. 1; this undoubtedly served a useful purpose, particularly in exercising the whole command post personnel, although no easy means were available for assessing the competence of the operators.

46. G.I.A. also introduced the "Layer Trainer", which later became known as the "Artificial Visual Trainer". This was primarily intended to afford practice and training to predictor operators and L.A.A. gun numbers, in visual laying, and to score their performance both with respect to accuracy and to smoothness; a similar instrument, however, could also be used in training predictor numbers in "follow-the-pointer" operations. A.O.R.G. attempted the validation of the instrument as a trainer (Reports Nos. 112 and 174), but little interest was aroused and no Army requirement was stated.

4-7. Wherever recording vans were available, they were undoubtedly invaluable in drawing attention to the mistakes and inperfections of the detachments in action; they also provided a means of assessing the site's performance whenever co-operation aircraft were available. During the important period, however, (mid 1941 to mid 1943) recording vans were few and far between and could do little towards raising the general standard of skill and experience.

46. It should be recorded, however, that once it had become accepted that training of the radar operators should involve instruction in the art of laying the equipment, as well as, or even instead of instruction in the art of testing, adjusting and maintaining it, the standard of radar operation, on the whole, was satisfactory. The same, however, cannot be said of the standard of operation of the Command Post personnel (predictor and plotter operators).

49. On looking back, it is clear that any attempt to provide on-site training equipment, in the large numbers necessary, <u>after</u> the requirement for it has been discovered in action, is highly unrealistic; such equipment should be incorporated in the design of the parent equipment, if the operation is such as to require a high degree of manual dexterity, or of judgment, which can be obtained only by experience. In the absence of the necessary training equipment, the only solution was that adopted by A.A. Command, i.e. to press for the removal of the necessity for dexterity and judgment by making the equipment automatic.

Operational Limitations of G.L. Mk. II System

50. On the whole, the operational limitations of the first unseen fire control system, described in para. 28, were still present when G.L. Mk. II replaced G.L. Mk. I (EF), but were less marked.

(a) The overall accuracy was considerably greater although no reliable figures for action conditions are available; it was still far short of that attainable by visual methods, however.

(b) The high angle limitation was no longer serious, although tracking at elevations above 60° was extremely difficult and targets were usually lost.

(c) Alignment and calibration were still necessary, but better methods were being devised for checking them, and the adjustments were very much more stable.

(d) Trouble from "clutter" was reduced as a result of the narrower beam of the transmitter; it was still present, however, and at times could be serious.

(e) It was still possible for the operators to follow "out of sense" in bearing, although the beamed transmitter reduced the ease with which this could be done. Trouble was also experienced with the elevation operators following "out of sense"; owing to the non-linear characteristic of the elevation system, this resulted in an error of about 20° in angle of elevation.

(f) The constant height assumption was still necessary.

(g) An additional limitation appeared in that it was considered essential that every G.L. Mk. II receiver should be surrounded by a flat and level wire-netting mat, about 80 yds. in radius. The purpose of this mat was primarily to ensure the accuracy of the elevation measurements, which was very considerably impaired if the ground surrounding the receiver was not flat, level and of high electrical conductivity; considerable departures from level conditions also impaired bearing accuracy. These mats wore also highly desirable with G.L. Mk. I (EF), but owing to the lower precision of this equipment they were not so essential.

"Maggie"

51. The necessity for the provision of receiver mats with G.L. Mk. II resulted in there being a number of places in Great Britain where guns had to be deployed, but where the country was such that the mat could only be erected at great cost of time or labour, if at all. It was felt also, that abroad, i.e. in N. Africa, such conditions might not be uncommon although this fear was proved to be unfounded. G.L. Mk. II moreover, with its mat, was distinctly unsuitable for use in a seaborne landing.

52. It was decided, therefore, to adopt a small number of SLC equipment (Radar A.A. No. 2) for fire control purposes by adding a unit for measuring range (not required, of course, for searchlight control) and by fitting electrical transmission units for bearing, elevation, and range. The addition of the transmission (magslip) units to "Elsie" (the nick-name for S.L.C.) changed the name to "Maggie". A higher power transmitter, from the L.W. (A.A, No. 4 Mk. III) set, replaced the normal S.L.C. transmitter.

53. Two types of Maggie were produced in small numbers. The first, used only in A.A. Command consisted of converted Radar A.A. No. 2 Mk. III, i.e. Sound Locators Mk. IX with S.L.C. equipment in place of the sound location equipment; these were known as "Locator Maggie". The second consisted of a special two-wheeled trailer designed and constructed by A.D.R.D.E. on which the S.L.C. equipment was mounted; this was intended primarily for use in sea-borne landings, and was known as "Baby Maggie".

54. Trials carried out by A.O.R.G. on Locator Maggie (Report No. 123) and by S.A.A.A. on Baby Maggie (S.A.A.A. Trials R. No. 104) showed that on the whole, the accuracy to be expected was approximately the same as that with G. L. Mk. II. The chief limitations were the relatively low power, resulting in a short detection range, and the inaccuracy of the elevation measurements below about 24°. The elevations were about correct, however, in the neighbourhood of 14°, so that it was possible to determine a height at this point and then use F.H.C. drill. At high elevations, however, since the accuracy of elevation determination did not diminish as in G.L. Mk. II. F.A.P. drill was found to be more effective than F.H.C. and a change was recommended when the angle of elevation to the target reached 35°. Neither type of Maggie was used in action to any extent. One of the early experimental models was used at Dover with 3" guns to engage medium level dive-bombers by night, using a special diving target procedure with the Vickers predictor. Some firing was done with Locator Maggie in A. A. Command, and Baby Maggies were used in the Allied landings in Sicily and Southern Italy, but on the whole they were not successful.

VI. Centimetric Radar

56. With the advent of centimetric radar, early in 1943, it become possible, for the first time, for the accuracy of unseen A.A. fire to approach that of seen fire - Trials of the Canadian G.L. Mk. III (GL3C-Radar A.A. No. 3 Mk. I) by A.O.R.G., in conjunction with personnel of N.R.C. Canada, in the early months of 1942, and trials of the British G.L. Mk. III (GL3B-Radar A. A. No. 3 Mk. II) by A.D.R.D.E. and C.A.E.E. a few months later, both indicated that the accuracy of fire to be expected was of the order of that achieved by ordinary service personnel under seen conditions; under trials conditions, seen fire was still appreciably more accurate.

57. On coming into the service, however, a number of difficulties arose which prevented the expected great increase in effectiveness of fire from being realised. These were:-

(a) "Putting-on." The narrow beam of the centimetric radars meant that, like searchlights, they had to be directed into the close vicinity of the target before it could be "seen"; an auxiliary radar equipment was therefore needed for this "putting-on".

(b) Unfamiliarity and Difficulty of Operation. These were not serious in the case of GL3B, although there were certain changes in the method of operation, and the echoes had a high-speed "jitter" which was confusing at first. GL3C, however, had a totally different type of display from that of GL2, and what was more important, it had aided laying in both bearing and elevation, and velocity laying in range. Both these changes undoubtedly should have led to greater ease and accuracy of operation, but they were unfamiliar to the radar operators; in particular, the aided laying system was difficult to set up properly and required skill and experience on the part of the operators.

(c) A minor difficulty, encountered in GL3C only, was the impossibility of tracking aircraft at sufficiently long ranges. The power of the equipment was sufficient for the targets to be seen, and a relatively simple modification introduced by A.A. Command allowed tracking to begin at the necessary longer ranges, at the expense of the ability to track at very short range.

Putting-on

58. The radar equipments intended for putting-on were the Z.P.I. (A.A. No. 4 Mk. 1) for GL3C and the L.W. (A.A. No. 4 Mk. 3) for GL3B. Early trials with the Z.P.I. showed that it has considerable gaps in its coverage and modifications were made to effect an improvement. In Memorandum No. 239, A.O.R.G. considered the times taken by the average well-trained detachment to perform the various steps in the procedure; the range at which accurate tracking of the target must begin was thus deduced, and the range at which the putting-on equipment must detect the target, so that fire could be opened at the maximum fuze range of the predictor. These desirable ranges were compared with those of which the equipment

was capable the targets considered being a bomber aircraft at 200 m.p.h. and a fighter aircraft at 400 m.p.h. The conclusions reached were:-

(a) That the Z.P.I. coverage was still inadequate, except against bomber aircraft at relatively low heights;

(b) That the L.W. was satisfactory, but failed against high level fighter aircraft - the L.W. specially modified for putting-on did not show any substantial advantages over the standard L.W.

59. The detection range performance of GL2 (A.O.R.G. Report No. 94) was superior to that of the Z.P.I. at nearly all heights and to that of the L.W. at great heights; at very small heights, both Z.P.I. and L.W. were superior to the normal GL2, although special aerial systems were developed experimentally for the latter, which substantially improved its performance.

60. The inadequacy of the Z.P.I. was fully established in further trials (A.O.R.G. Report No. 171) and A.A. Command decided to use GL2 as putter-on in its place. In both Italy and N.W. Europe the L.W. sets gave satisfaction in putting-on GL3B; 21 Army Group, however, also used GL2, which, among other advantages, was much less susceptible to interference from the type of "window" the enemy used.

Automatic Following

61. The Possibility of arranging for centimetric radars to follow the target automatically, without the interposition of any operators, was realised almost as soon as it was found possible to build the radars themselves. Development work was already in hand both in this country and in America, but the first equipment to go into action (in late 1943) was one which was little more than a "mock-up" produced by A.A. Command for attachment to GL3C (A.A. No. 3 Mk. I).

62. The urgent requirement for this attachment arose from the great difficulty experienced by ordinary operators in handling the laying system of the normal GL3C (para. 57(b)). It cannot be said that this equipment was an unqualified success; it was largely constructed out of old sound locator parts and was difficult to keep properly set up. An improved model was produced later (in 1944), but this did not go into action, except to a very small extent against flying bombs.

SCR 584 (A.A. No. 3 Mk. V)

63. The advent of this American equipment into the British Service arose from the threat of attack by flying bombs. In the appreciation of the chances of success by A.A. guns against these missiles, made in January 1944 by A.A. Command, with the advice of A.O.R.G., the enormous improvement to be expected by the use of centimetric radar was stressed. It was pointed out, also, that it was unlikely that the detection range of GL3C against these very small very fast targets would be sufficient, and all available GL3Bs were ear-marked for the approaching invasion of Europe. A special plea was thus made to U.S. for a supply of SCR 584s.

64. In the actions against flying bombs, it can be said that for the first time, unseen A.A. fire was very nearly if not completely as accurate end effective as seen A.A. fire; this was due almost entirely to the excellent performance of the SCR 584 after a few “teething troubles” had been got over.

Operational Limitations of Unseen A.A. Fire with Centimetric Radars.

65. Nearly all the limitations imposed by the earlier radar equipments, disappeared when centimetric radars were introduced, although a few more only mitigated.

(a) The overall accuracy, as already mentioned, was, in action, normally less than that of seen fire. Under good conditions, automatic following radars could be as accurate as visual tracking, and with first-class operators, manual following radars were only slightly less accurate. In the actions concerned, however, the conditions, on the whole, were not good (see (d) below) nor were the operators first-class.

(b) The high angle limitation was removed except at very high elevations when the rate of change of bearing might be greater than the equipment could provide. This limitation is, of course, present when visual tracking is used, and indeed, the automatic radars can provide at least as great rates of change of bearing as the visual trackers.

(c) No arbitrary calibration of the elevation finding system was necessary, but alignment in both elevation and bearing was required. In addition, electrical setting-up of both transmitter and receiver, in order to get the maximum detection range, was more critical than with the early radars.

(d) Against normal, high level targets "clutter" was reduced almost to unimportance. Ground objects, balloon cables and a high density of targets were normally likely to give less trouble, owing to the narrow beam, but rain-clouds and shell bursts were now visible and the more accurate and more intense was the fire, the more clutter did the latter produce. When engaging very low targets such as the flying bombs, ground clutter still gave trouble, since the engagements took place at such small angles of elevation that even the narrow beam of the, centimetric radar "illuminated" ground objects. It is fairly certain that between them, shell clutter, rain clutter and ground clutter were mainly responsible for the fact that the centimetric radars did not perform as well against flying bombs as they had against co-operation aircraft (compare A.O.R.G. Report No. 259 and Memorandum No. 400). While it might be expected that manually operated radars (e.g. GL3B) might work through clutter more effectively than automatic following radar (e.g. SCR 584), there is no good evidence that, in fact, they did so.

(c) It was no longer possible to follow a target "out of sense".

(f) The constant height assumption was no longer necessary owing to the accuracy of the radar and the latest predictors (Nos. 9 and 10) did not require this assumption to be made. As will be seen in a later section, however, it was normally advisable to assume that the target would not change height during the time of flight of the shell.

(g) No mats were normally necessary and centimetric radar could be, and was, successfully used in seaborne landing operations. On the other hand, when engaging very low targets, it was found advisable to erect vertical wire-netting screens in order to remove, or reduce in magnitude, the effects of ground clutter. These were found to be of very great value in the flying bomb operations, both in Great Britain and in Belgium (compare A.O.R.G. Memoranda Nos. 371 and 468). A full discussion of the performance of centimetric radars, and the newly developed predictors against flying bombs, will be found in A.O.R.G. Report No. 259.

VII. The Development of New Predictors

66. It became clear, when radar first began to be used with the existing predictors, that in many ways the combination did not fit. In some respects, this lack of fit was due to the peculiarities of the visual tracking and range finding. The development was therefore put in hand of new predictors which would be more suitable for use with unseen targets.

67. Experience showed that there were three main features which were desirable in all predictors for unseen use:

(a) Provision should be made for making continuous use of radar slant range — i.e. height should not be, of necessity, preset, but should, be continuously evaluated by the predictor.

(b) Provision should be made for smoothing the rates of change of the target’s position co-ordinates; this was primarily of importance owing to the relative imperfection of the radar data, but such smoothing has been found to be of value even with visual tracking.

(c) Provision should be made for an easily visible display of the target's position and course, so that the Tactical Control Officer may have some information as to its relation to the gun position and to neighbouring places of importance, and also as to its general behaviour.

68. The predictors considered are the Bedford-Cossor (No. 9) and the BTL (No. 10 - developed in America), both of which are electro-mechanical in operation, and the U.T.P. and Plessey, both of which are purely mechanical. All those instruments work on the Cartesian principle, i.e. the target's position and rate of change of position are expressed in Cartesian co-ordinates (height, northings and eastings). The disadvantages of the rather complex series of co-ordinate conversions involved are offset by the capability of providing a high degree of smoothing (para. 63(b)) owing to the evaluation of quantities that can be regarded as invariant over the smoothing period.

Use of Radar Range

69. The changes introduced by the availability of accurate and continuous measurements of slant range can be demonstrated by comparing the resolving system of the pre-radar cartesian predictor (Sperry - No. 2) with those used in the newly developed predictors. In both cases, the final state - that of deriving northings and eastings from ground range and bearing (as r cos B and r sin B respectively) - is essentially the same; the difference lies in the derivation of ground range.

(a) Height Control in the Sperry; height (H) is set in by hand at infrequent intervals, and angle of elevation (S) is fed in continually by the layer for elevation; ground range (r)is then derived, by means of a cam, as r = H cot S.

Consideration of the geometry of the system shows that when the angle of elevation is small, owing to the very oblique intersection of the line of sight with the line of constant height, small errors in either height or angle of elevation lead to large errors in ground range. The system is therefore bound to be unsatisfactory for use against low altitude targets; against medium and high altitude targets the system was not too bad when visual range finding had to be used, since the range was inevitably fairly small, and the elevation large, and height could be found; but with the advent of radar, engagements could be begun at much longer ranges. With radar tracking indeed the vast majority of rounds are fired at angles of elevation less than 45°, even against moderately high targets.

(b) Range Control in the newly developed predictors; radar slant range (R) is accepted continually and ground range and height evaluated as r = R cos S
H = R sin S respectively.

At low elevations, therefore, when ground range is nearly equal to slant range, considerable errors in S cause only errors in r, and errors in H have no effect on the value of r. The value of H is, of course very susceptible to errors in S, and the Bedford-Cossor, the U.T.P. and the Plessey (all originally intended to be used with GL2) have means whereby the value of R sin S is continuously presented, so that a mean value of H, as estimated by an operator, can be set in and used by the predictor in subsequent computations.

70. Both electrical predictors were provided with means by which, if an optical range finder had to be used, height could be set; a slant range derived from height and angle of elevation, and then combined again with elevation gave ground range. This is clearly a rather clumsy method of using the original Sperry resolution and was only intended for use in emergency if the radar were out of action.

71. Neither the U.T.P. nor the Plessey were intended for use without radar, and Height Control was not possible as an alternative to Range Control. The U.T.P. however, provided for the use of F.H.C. drill (para. 31). Normally, one operator matched radar slant range at a follow-the-pointer dial by setting in ground range which was converted to slant range at a resolving mechanism; another operator similarly matched radar elevation and set in angle of elevation to the same resolving mechanism. (This procedure was used in order to avoid inserting a servo mechanism between the height-ground range and the northings-eastings resolvers - one resolver cannot properly work direct into another. It resulted, however, in some inter-action between the operators at crossing-point.) Alternatively, the elevation operator could set elevation into the resolver in such a way as to maintain a constant height, the ground range operator matching slant range as before.

Smoothing

72. In the electrical predictors (Nos. 9 and 10) Northings, Eastings and Height appear as electrical potentials; the rates of change of these quantities are derived by the use of suitable capacitative circuits. By the use of rather more complex circuits, these rates of change can be smoothed to any desired extent, and the weighting given to the instantaneous rates in different parts of the smoothing period, can be adjusted within limits. In both predictors, two alternative smoothing times are provided, the shorter for use at the beginning of an engagement, so that at least an approximate solution shall be available at the earliest moment. The shorter time could also be used during alterations of course by the target. The longer one was for use so long as the target is in unaccclerated flight and at all times when the tracking is erratic, as when GL2 is used. In No. 9 predictor, also, the rates are set in manually in such a way as to null meters which indicate the differences between the rates set and the rates derived by the differentiating mechanism; the operator can thus perform an additional smoothing operation. In No. 10 predictor rate setting can be performed manually if desired, but automatic setting is also available; trials have indicated that nothing appears to be gained, as far as smoothing is concerned, by the use of manual rate setting. (A.O.R.G. Memorandum No. 398.)

73. In the U.T.P. and Plessey, graphical methods of smoothing were used, in principle identical with those used to measure the co-ordinate rates on the S.A. Plotter for use with the amputated Sperry predictor (para. 19).

(a) In the Plessey, values of northings, eastings and height were each drawn by a pencil moving across sheets of paper which moved along uniformly with time. Three pointers wore advanced in the direction of motion of the paper by an amount representing the time of flight of the shell about to be fired, as computed automatically from the future ground range and height; they could also be moved across the paper by operators, who thereby set in future values of northings, eastings or height, as the case may be, and who positioned the pointers so that they lay on prolongations of the lines drawn by the present northings, eastings and height pencils. The effective smoothing times and the weights to different values of the rates at different instants in the past, were thus determined entirely by the judgment of the operators.

(b) In the U.T.P. no such complete freedom of Judgment was given to the operators. Future height could be set according to the judgment of an operator, but normally was either a mean value of present height, or was such that the assumed change in height during the time of flight of the shell was equal to the observed change in height during the same period before the shell was fired. Northings and eastings rates were measured as the observed change in northings and eastings in a fixed interval of time (normally 30 secs.); the smoothing time was thus fixed, and so also was the weighting, which was uniform throughout the smoothing period. In addition, however, complete freedom of judgment was given to the Plotting Officer to select the point of engagement; this will be considered in a later section. (para. 76.)

Display of Position and Course of Target

74. The Bedford-Cossor predictor was from the first, provided with a cathode ray tube which displayed either the present plan position of the target with respect to the gun position as observed by the radar, or the future position to which the predictor was directing the gun. This was undoubtedly of great value, although on too small a scale. A switch was provided for expanding the scale, so that the behaviour of the target could be examined, but the relatively small size of the screen resulted in the frequent disappearance of the target off one side or the other, and shift switches had to be operated to bring it back. The BTL was not initially provided with any plan position display, but an electronic (cathode ray tube) indicator was developed in late 1944 by A.A. Command. This was identical in principle with that provided in the Bedford-Cossor, but a considerably larger screen was used. Either present or future position, or co-ordinate rates could be displayed.

75. The Plessey had no display of present or future plan position, but the U.T.P. was provided with a large vertical glass screen on which the present position track was drawn by an ink pen, and on which the future position appeared as a spot of light. The scale was 111 to 1 mile, and topographical features, places of importance etc. could be drawn on the screen.

Curved Course Prediction

76. The U.T.P. was the first predictor to come into use which provided means for predicting the course of targets which were not in straight flight. The principle used was as follows. Suitable resolving and multiplying linkages combined the northings and eastings rates, measured as described in para. 73 into the speed along the course and multiplied it by the time of flight. This "distance travelled in time of flight" was taken to the plotting screen and maintained the future position spot the correct distance in front of the present position pen. No constraint, however, was put on the direction of the line joining present and future positions, and this could be set by the Plotting Officer according to his estimate of the direction in which the target would fly.

77. A considerable amount of investigation was made as to the extent to which T.C.Os. could thus anticipate the future course of the target (A.O.R.G. Reports Nos. 186 and 280; C.A.E.E. Reports summarised in 30/E/36). It is generally agreed that no effective anticipation can be performed. If instructed to predict in a continuation of the previous (curved) course the most usual result is a prediction in a direction tangential to the course at the present position pen, or somewhat earlier; if instructed to project tangentially to the most recent course, the usual result is a prediction based on the previous 5-10 secs. of track. There thus appears to be an inherent weighting of the information some 5 secs. stale, at the expense of the information only just made available.

78. A similar resolving mechanism has been made up experimentally for use with No. 10 predictor with plan position display attachment. Curved course prediction is made by setting in an estimated curvature. Trials carried out by C.A.E.E. (Report 101/A/3) showed that this system gave no better results than the unmodified predictor.

79. The possibility exists of predicting on curved courses with the Plessey predictor, since the operators setting in future northings, eastings and height could be instructed to extrapolate along the curved tracks of, say, northings and eastings, instead of along rectilinear tracks. No trials have been carried out, and it is probable that the inherent operators lag described in para. 77 would again be observed.

Reflected Memory Point Prediction

80. It seems clear that, whatever is the course of the target, prediction must be based on some assumptions as to its future behaviour; effective shooting will not be obtained by allowing the T.C.O. to pit his wits against those of the pilot. In Reports Nos. 227 and 262 A.O.R.G. studied the results to be expected, when various assumptions were made, against targets following courses similar to those adopted by German aircraft over London in late 1943 and early 1944. The general principle was propounded that when engaging a target on a curved and "unpredictable" course, the prediction assumptions should be such that the future position track crossed the present position track as frequently as possible. In other words, since accurate prediction is impossible the endeavour should be to put the largest possible fraction of the rounds fired in the vicinity of the target; the inevitable tracking errors (perturbations) will lead to some of these being lethal. Empirical analysis of the recorded tracks of German aircraft showed that the most effective assumptions for this purpose are:

(a) Uniform velocity along the target course.

(b) Change of heading (direction of flight) in the time of flight of the shell will be equal to change of heading in 10 secs. (approximately) before the moment of firing. The assumptions are equivalent to assuming that the future course of the target can be found by reflecting the past course about the normal to the course at the present position - hence the term "reflected memory point".

81. This type of curved course prediction is, of course, ineffective against a target which is weaving. In this case, however, unless the aircraft is controlled by an automatic pilot whose properties are known to the ground defences, the most effective direction of prediction is along the mean course; prediction in a direction tangential to the most recent course is nearly as good, unless the period of the weave is very small. Reflected Memory Point prediction is of value when aircraft are attacking a large gun defended area, such as London. Sooner or later all the aircraft will make a considerable turn in one direction in order to return to base, and many will make this turn over the defended area.

The Value of Predicting in Height

82. This problem is discussed in A.O.R.G. Memoranda Nos. 255 and 321.

The provision of radar for range estimation, together with elevation tracking by centimetric radar or visually, removes the necessity, as far as accuracy is concerned, for treating height in any way differently from the other co-ordinates defining the target's position and rate and direction of movement. Accordingly, all the newly developed predictors were provided with mechanisms for predicting in height, as well as in ground plan.

83. It is not by any means certain, however, that height prediction is always desirable. Owing to the unavoidable tracking perturbations and fuze prediction and running errors, the rounds will not all burst at the same height, even if there is no height prediction, but will be distributed over a certain zone. This zone will be increased when height prediction is used owing to the magnification of the tracking perturbations. For height prediction to be of value therefore, the following criteria must be satisfied.

(a) The target must continue on a steady rate of change of height for a period at least equal to the time taken by the predictor to measurem *[sic]* and smooth this rate, and for the shells to reach the target - in all, about 20 — 30 secs. on an average;

(b) The total change in height during the time of flight of the shell must be such that the target is so far removed from the unavoidable zone of scatter of the shell-bursts, that the chance of obtaining a lethal hit is substantially reduced;

(c) The fraction of all targets engaged that satisfy criteria (a) and (b), must be sufficiently large that the gain in total chance of hitting one of these more than offsets the loss of chance of hitting the remainder owing to the increased dispersion of the shell bursts in height.

In the case of the attacks on London in early 1944, the first in which centimetric radar and the new predictors were used to any extent, study of the general behaviour of the attacking aircraft indicated that criterion (c) was not satisfied. Height prediction was ordered to cease and a modification introduced into No. 10 Predictor in order to allow this to be done.

84. This policy was amply justified when the flying-bomb engagements began. Not only did the bombs maintain a very constant height, but the determination of height particularly at long ranges, was apt to be erratic and the zone of dispersion in height rather large. This resulted from the very low elevation of the targets in the initial stages of the engagement, owing to their small height; height errors resulted almost entirely from elevation errors (para. 69 (b)) and these were large owing to the effects of clutter (paras. 65(d)).

The Operational Performance of the New Predictors

85. Of the four new predictors under consideration, there is no doubt that the only really successful one was the BTL (No. 10). Under action conditions, the Bedford-Cossor, when properly set up and adjusted gave results which were as accurate as those given by the BTL; but under trials conditions with very good input and skilled operators, the difference was appreciable (compare A.0.R.G. Report No. 211 and Memorandum No. 395 and C.A.E.E. Reports summarised in 30/E/36). This difference was primarily the result of the Bedford-Cossor being originally designed in 1941; the need for more predictors was urgent, the production capacity to make them almost non-existent, and the radar data on which they would probably have to work erratic. Ease of manufacture was of the greatest importance and tolerances were accepted which left no margin for attaining the necessary overall precision. The general principles of the design were excellent for the purpose for which it was intended, but great care and attention was needed in setting it up, and the adjustments were not very stable.

86. The above remarks apply with even greater force to the performance of the U.T.P. (A.O.R.G. Report No. 280). This instrument was designed for the Specific purpose of providing fire control information to enable the 5.25" guns to engage anticipated raiders at heights of up to 36,000 ft., for which no alternative fire control instruments existed, except the semi-automatic plotter. Being an entirely mechanical instrument moreover, production, capacity was even more difficult to discover, and existing parts, designed for other instruments, had to be used wherever possible. This resulted in many inperfections *[sic]* in the detailed design, and inadequate precision in manufacture. Again, however, the fundamental, principles were excellent; the addition of over-riding control of direction of prediction by the Plotting Officer was, as it turned out, of no practical advantage, but this fact could not have been demonstrated had the U.T.P. not provided the opportunity of performing the necessary trials.

87. The Plessey again largely owing to manufacturing difficulties has not completed trials, and no operational experience is available.

VIII. The Engagement of Long Range (German A4) Rockets

88. The conditions of engagement of the long range rockets were so different from those of the engagement of aircraft or flying-bombs, that the fire control methods were of necessity improvisations. Indeed the wheel came round full, circle and the method employed was that of the predicted barrage, in principle, very much similar to the Fixed Azimuth system developed for the defence of London in 1939 and 1940, except that observations by radar were used instead of by sound locator.

89. In the absence of radars and predictors capable of controlling direct fire against the rockets, the method of defence consisted in directing a large number of shells so that they would burst within a reasonably small volume of sky which was in the expected path of the rocket. The rocket descended with such speed (approximately 3000 m.p.h.) that impact with a shell fragment of reasonable size would very probably result in detonation of the war-head, even though the fragment itself was "spent" and on its way to the ground. No very exact timing of the shell-bursts was needed therefore, provided that they occurred in front of the rocket.

90. The prediction methods used were described in A.O.R.G. Memorandum No. 572, and the radar problems were reviewed in Memorandum No. 518. Briefly prediction was based on the following considerations.

(a) The rockets followed regular trajectories of known form. Basically the trajectories were parabolic, but relatively small, and reasonably well-known corrections had to be applied for:

- (i) the rotation of the earth;
- (ii) the curvature of the earth;
- (iii) the retardation due to the earth's atmosphere in the last few miles of descent;
- (iv) the form of the trajectory during the first few miles of ascent, while the propulsion unit was burning;

(b) With these corrections, therefore, the point of impact with the ground could be predicted if the position of the rocket could be determined at three points along its trajectory.

(c) The first of these points was the point of launch. It was known that this must lie within a relatively small area, in the neighbourhood of the Hague, Holland, both from information from agents and from information given by the long range, early warning, CH radar stations; greater precision, however was obtained by siting a radar SCR 584 with certain special modifications, so as to be able to track the rockets during the early part of their ascent. This, of course, could only be done after the occupation of South Holland by Allied forces.

(d) The second two points were obtained by .means of specially modified GL2 stations situated at Wrentham and Adleburgh *[sic]* in Suffolk; and at Walmer, in Kent. The siting of these stations was conditioned by the following requirements.

- (i) In order to allow time for the necessary computations, and for the shells to reach the necessary height, the last point observed on the trajectory had to be about 60 miles from London.
- (ii) Good radar signals could only be obtained when the line of sight from radar to rocket was approximately at right angles to the long axis of the rocket. Even then, no measurements of elevation were possible, and measurements of bearing could only be made with difficulty.

(e) The station at Aldeburgh, therefore, observed the bearing of the rocket only, and signalled to the stations at Wrentham and Walmer at the moment the rocket crossed two vertical planes in space, defined by bearings 180° and 200° respectively. At the signal both Wrentham and Walmer measured the slant range to the rocket, thereby defining; (i) the height of the rocket at that moment; and (ii) in conjunction with the known launching-point, the line of fire, on which the point of impact must lie. At the second height. (Walmer was, unavoidably, so situated that it could not be relied upon to receive good radar signals at the second point of observation.) From the two heights so determined, the ground range from launch to impact could be deduced, and hence the point of impact.

91. The chain of radar stations was in operation for approximately 6 weeks before the rocket firing ceased, although modifications and improvements continued to be made; the complete prediction system, however, was fully operational for only 5 days and permission to open fire was not obtained. Analysis of the results achieved during the final 15 days showed that the point of impact was, or could have been, predicted for 44% of the rockets falling in London; of the rockets on which predictions were made, one quarter fell within 1½ Kilometres of the point predicted, and three quarters with 5 Kilometres.

IX. The Influence of A.A. Radar on Problems of Air Defence.

92. The introduction of really effective methods of unseen A.A. gun fire had a profound effect on the whole problem of ground defence against air attack. The value of being able to use the A.A. guns effectively in all weather conditions, and against aircraft at greater heights and at greater distances than with seen procedures, is obvious. But, in addition, continuous radar tracking, and the use of electrical transmission throughout the chain from radar to guns, enabled records to be made, for the first time, of the tactics and general behaviour of the attacking forces. Moreover, the accuracy of the fire of the A.A. guns could now be recorded and assessed without the use of special equipment, and in all weather conditions. The results achieved in action could thus be compared with those to be expected from the results of trials, and of semi-theoretical analyses, such as those of the Ordnance Board (E.B.D. Reports Nos. 3 and 23) and of the Air Warfare Analysis Section (A.W.A.S. Reports Nos. 35 and 42).

93. Knowledge of the accuracy of the fire control methods and likely tactics of the attacking aircraft, which was now available, allowed quantitative assessments to be made of the probable value of new and existing weapons and defence methods, including, in addition to unseen heavy A.A. gun fire; - the use of searchlights in gun defended areas to provide illumination for heavy and light A.A. guns using "seen" procedures, and for deterrent effect; the use of A.A. Rockets; the siting of L.A.A. guns for use against very low flying attacks; the use of A.A. Smoke Screens; and the use and value of A.A. Operations Rooms for centralised control of the gun defences. In all these studies, allowance had to be made for the possible types of evasive action on the part of the attacking aircraft, and their influence on the effectiveness of the A.A. defences. Further, investigations could be made, and were made, as to the best methods of using existing equipment in the event of serious attempts by the attacking aircraft to adopt tactics designed to defeat the A.A. defences, such as very high concentration in time and space, and the use of "window" or of radar jamming. No such attempts were, however, ever made, and no practical confirmation of these appreciations could be obtained.

Prepared by L.E. Bayliss
formerly O. i/c. O.R.S.1.

H. A. Sargeaunt [?]
Lieut. Colonel
Superintendent O.R.G. (W. and E.)