THE FLYPLANE PREDICTOR SYSTEM

BY

LIEUTENANT-COMMANDER A. R. WARD, R.N., M.A., A.M.I.MECH.E.

This article has been written with the object of providing an introduction to anti-aircraft fire control for those who form the large majority in the engineering specialization and who not only have no knowledge of flyplane predictor systems but, indeed, have never had to consider the problems to be faced in orthodox anti-aircraft fire control.

The A.A. Problem

The basic anti-aircraft problem is to fire a shell in a direction and at a time so that the shell and the target meet at a point called the ' future ' position of the target, the target position at the instant of firing being its ' present ' position.

Since the time of flight of the shell to the target, at a range of 3,000–5,000 yards, is of the order of five to eight seconds, it is necessary to have complete knowledge of the movement of both the target and the shell during that time. This information is not all available in orthodox gunnery and certain assumptions have to be made about the movement of target and shell during the time of flight.

THE GENERAL SOLUTION

The predicted motion of the target is based on an accurate knowledge of its movements immediately before firing the shell, and it is the function of the ' tracker ' to obtain this information and present it to the ' predictor ' in a suitable form.

The assumption which can be made about target movement during the time of flight is threefold. Firstly, the target can be assumed to fly at a constant speed in a straight line and at constant height. Secondly, it can be assumed to fly at a constant speed in a straight line but not necessarily at a constant height. Thirdly, it can be assumed to fly on a predetermined curved course.

The predicted motion of the shell during the time of flight is based on a mixture of experiment and theory. The reliability of this method is dependent upon the reproduction of the experimental and theoretical conditions in practice. Such variables as atmospheric conditions, wind at the different heights throughout the trajectory of the shell, wear of the gun, charge temperatures, and variations between shells all add up to make prediction complex. However, many of these can be allowed for, but their infinite variation makes absolute solution impracticable.

The general principle is to solve the target prediction problem, assuming target movement during the time of flight to be one of the three above and to be under selected standard ballistic conditions. Corrections are then made to allow for variations from standard. Corrections also have to be made to allow for the fact that the gunmounting and tracking head, i.e. the director, are not in coincident positions in a ship but are separated both vertically and longitudinally.

Finally, a form of stabilization has to be provided to make allowance for ship movement while tracking.

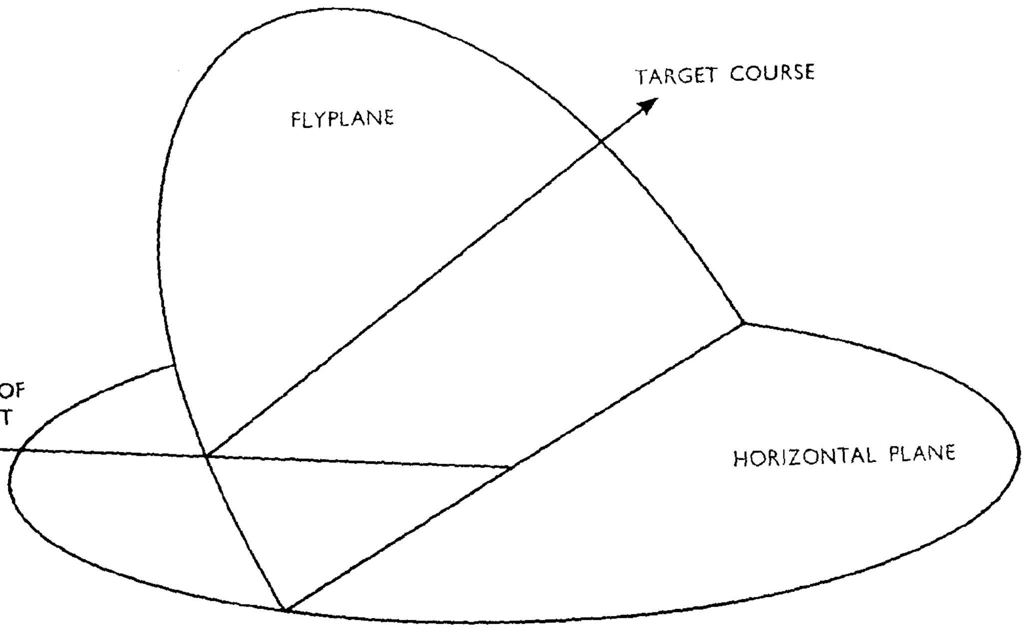

FLYPLANE
TARGET COURSE
LINE OF SIGHT
HORIZONTAL PLANE

Fig. 1

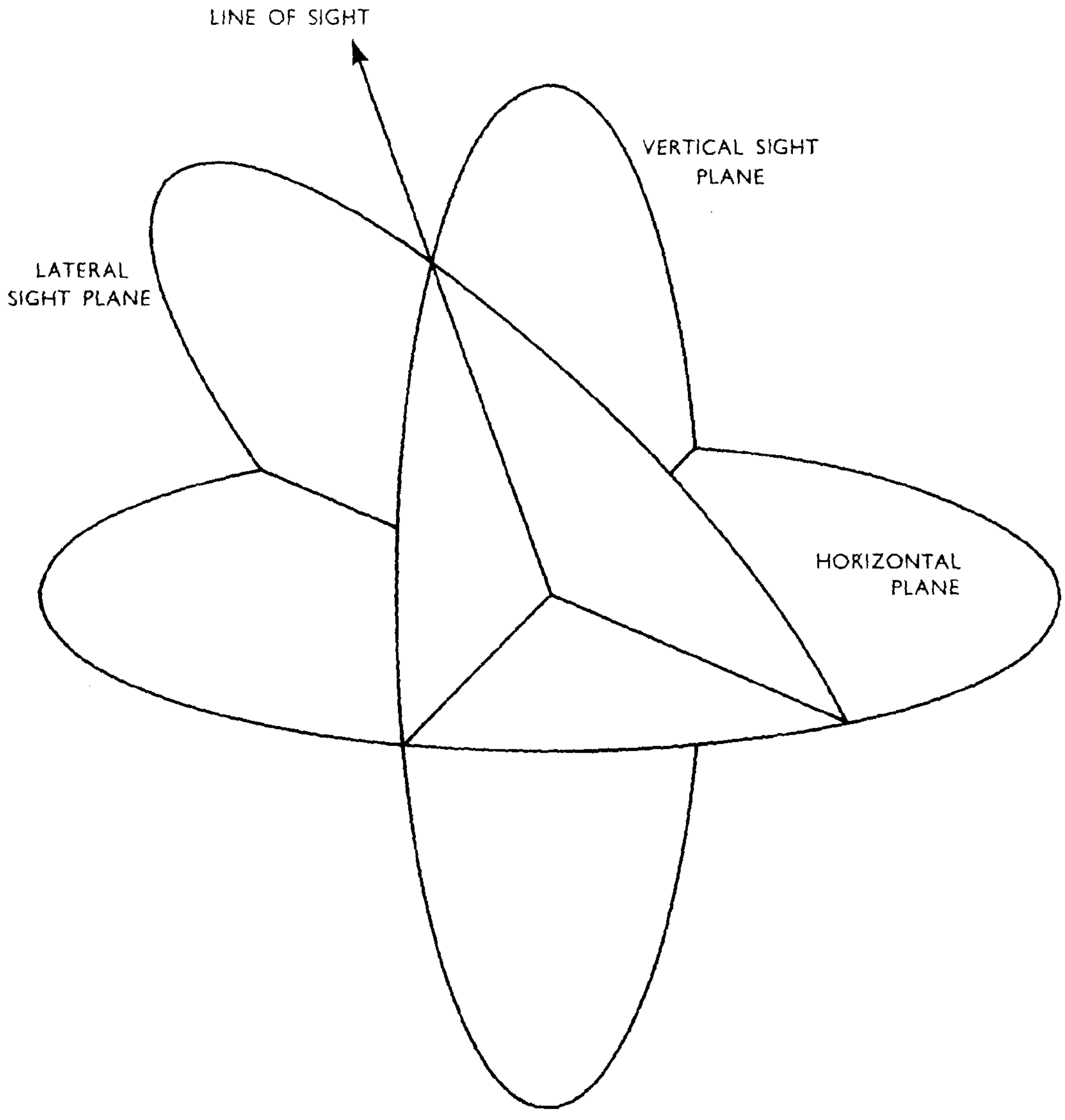

LINE OF SIGHT
VERTICAL SIGHT PLANE
LATERAL SIGHT PLANE
HORIZONTAL PLANE

Fig. 2

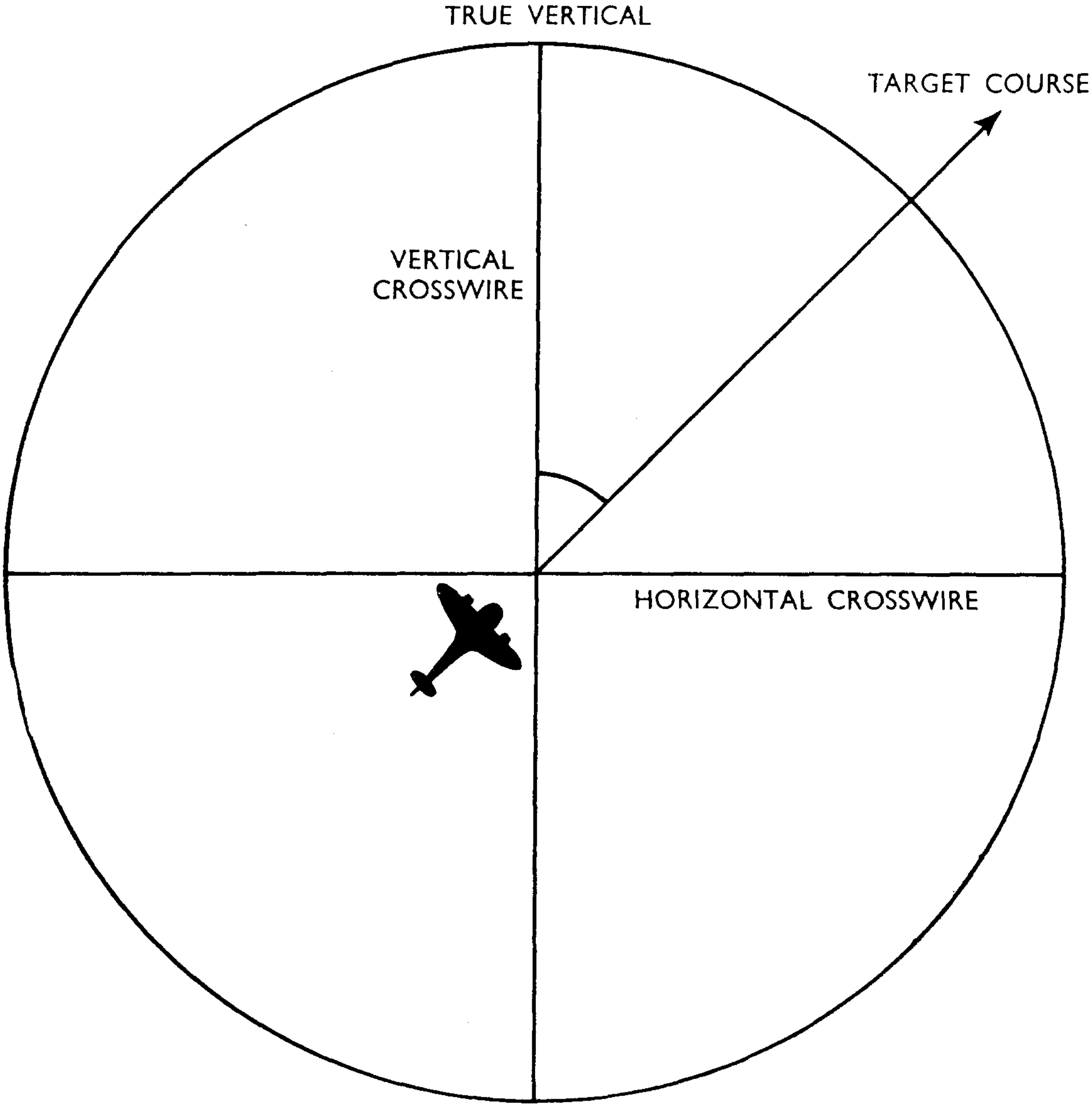


FIG. 3

THE FLYPLANE SOLUTION

Setting up the Flyplane

The basic assumption made in the flyplane system is that, during the time of flight, the target flies at a constant speed in a straight line but not necessarily at constant height.

FIG. 1 illustrates the flyplane, which can be defined as that plane swept by the line of sight in tracking the target along its line of flight during the time of flight. It will be seen, therefore, that if we can once ‘ set up ’ the flyplane, the problem of predicting the future position of the target (in the flyplane) is simplified to a two, instead of a three, dimensional problem. The flyplane tracking system sets out to do just this.

In the latest flyplane system—Flyplane Predictor System, Mark 5 (F.P.S.5)—the tracking system comprises essentially the Mark 6M Director, the Gyro Rate Unit Stabilizer, Mark 3 (G.R.U.3), the Below Control Unit, Mark 5 (B.C.U.5) and a number of electronic units and electro-mechanical servos housed together in racks and collectively designated the ‘ Tracker ’.

A layer and trainer either in the director or at the B.C.U.5, using an optical sight or a radar display respectively, track the target in the vertical and lateral sight planes (FIG. 2) and in so doing measure the components of target speed

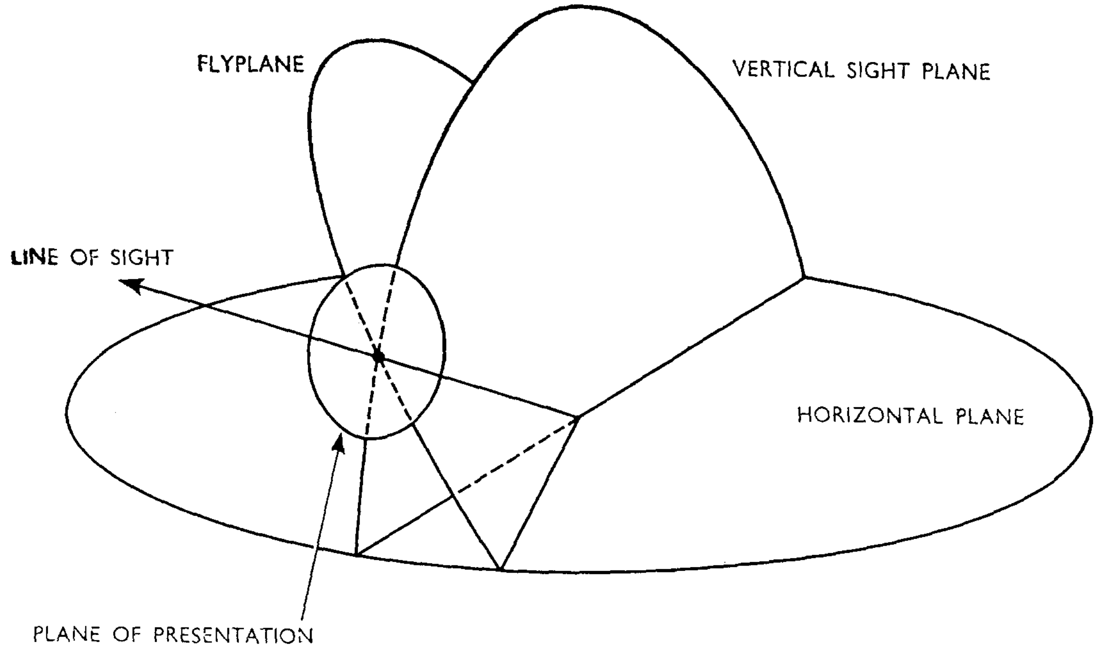


FIG. 4

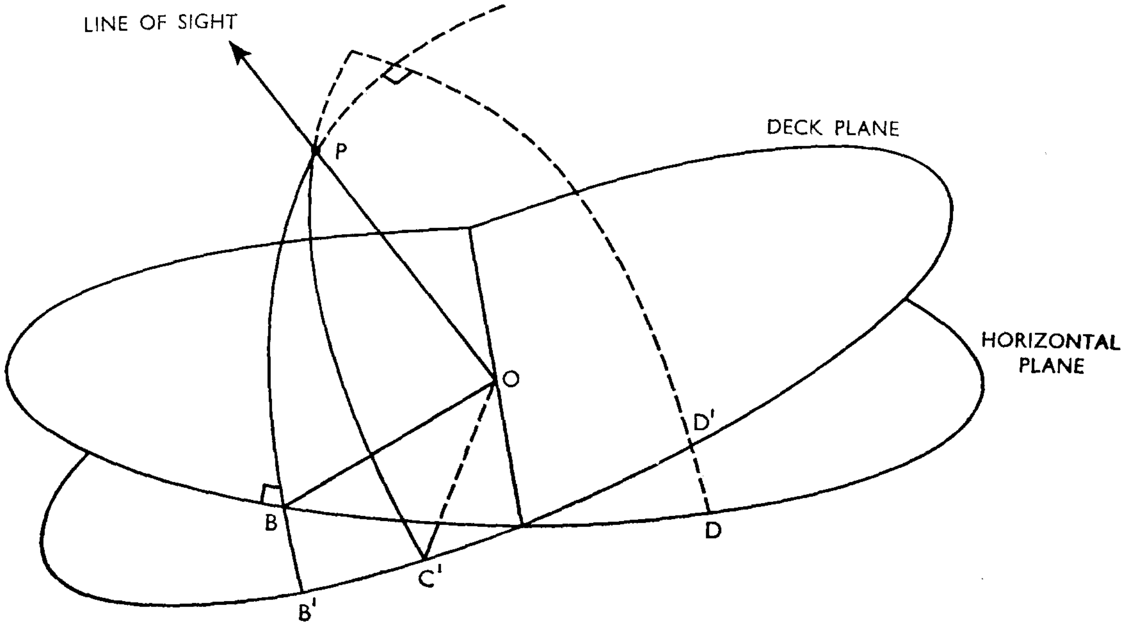


FIG. 5

in those planes. A range-taker at the B.C.U.5 measures slant range to the target and the component of target speed along the line of sight by the use of a radar display in that co-ordinate.

FIG. 3 represents the field of view through an optical sight with the target at the intersection of the cross-wires. The target will appear to be flying along some course at a given speed in the plane containing the field of view. That speed and the angle between the vertical cross-wire (which is in the vertical sight plane if the deck is horizontal) and that apparent target course define the position of the aircraft relative to the line of sight at any instant.

The plane represented by FIG. 3 is called the plane of presentation and the angle between the vertical sight plane and the apparent target course, the angle of presentation. This arrangement is more clearly illustrated in FIG. 4. In the flyplane tracker, this angle and function of target speed are derived from the vertical and lateral components of target speed measured by the layer and trainer.

Director Control

The G.R.U.3 comprises two gyro units. The upper unit contains a gyro whose spin axis is maintained vertical. The lower unit (the rate unit) contains a gyro whose spin axis is maintained in the direction of the line of sight by signals of the vertical and lateral components of target speed, causing it to precess in that direction. Movement of the rate unit and its associated gimbal system causes the body of the G.R.U.3 to train, and a bow in the upper unit to elevate to follow the rate gyro, and in turn cause the director to follow the G.R.U.3.

Direction Stabilization

All the foregoing has assumed that the deck plane and horizontal plane are coincident. In practice this is rarely so and allowance has to be made for ship motion. The Mark 6M director, which carries the optical sights and radar nacelles, is a two-axis director, i.e. it can train in the deck plane and elevate normally to it.

The stabilization problem is shown in FIG. 5. With the deck horizontal and the target at P, the director has to be trained to the line OB and elevate through the angle BOP to make the line of sight pass through P. Now, with ship movement, this movement can be considered as composed of a pitch BB^1 in the vertical sight plane, and a roll DD^1 at right angles to this. In order to return the line of sight to P, the director must be trained through B^1 C^1 and elevated through an angle equal to the difference between PB and PC^1. These corrections are measured by the rate unit gimbal system of the G.R.U.3 and are applied to the director to stabilize it.

If, after these corrections have been applied, the target was observed through the optical sight, the cross-wires would appear as shown in FIG. 6 since the director could not move in a direction to take out the resultant angular movement of the ship about the line of sight. This angular movement is called ‘ rotation about the sight line ’ and is measured in the upper unit of the G.R.U.3.

The components of target speed measured by the layer and trainer are in terms of the true vertical and horizontal. Since the G.R.U.3 and 6M director move in deck terms, it is necessary for the signals representing these components of target speed to be modulated for rotation about the sight-line to convert them to deck terms. This is again achieved in the tracker.

We now have sufficient information to define target position in space and can pass this to the predictor to enable it to compute data to control the gun-mounting, so that the latter can be positioned to fire a shell to pass through the predicted future position of the target.

Regeneration

One final feature of the tracker is that it is regenerative, i.e. once the components of target speed and course have been applied to the tracker, the supply of this information to the predictor is self-sustaining. This is achieved by computing the rate of change of the components of target speed, i.e. the vertical, lateral and range accelerations of the target. The value of this facility is that, provided a target maintains its course and speed, the rate of change of components of target speed as the target approaches and passes the ship, are automatically computed and applied, and thus preclude the necessity for the layer,

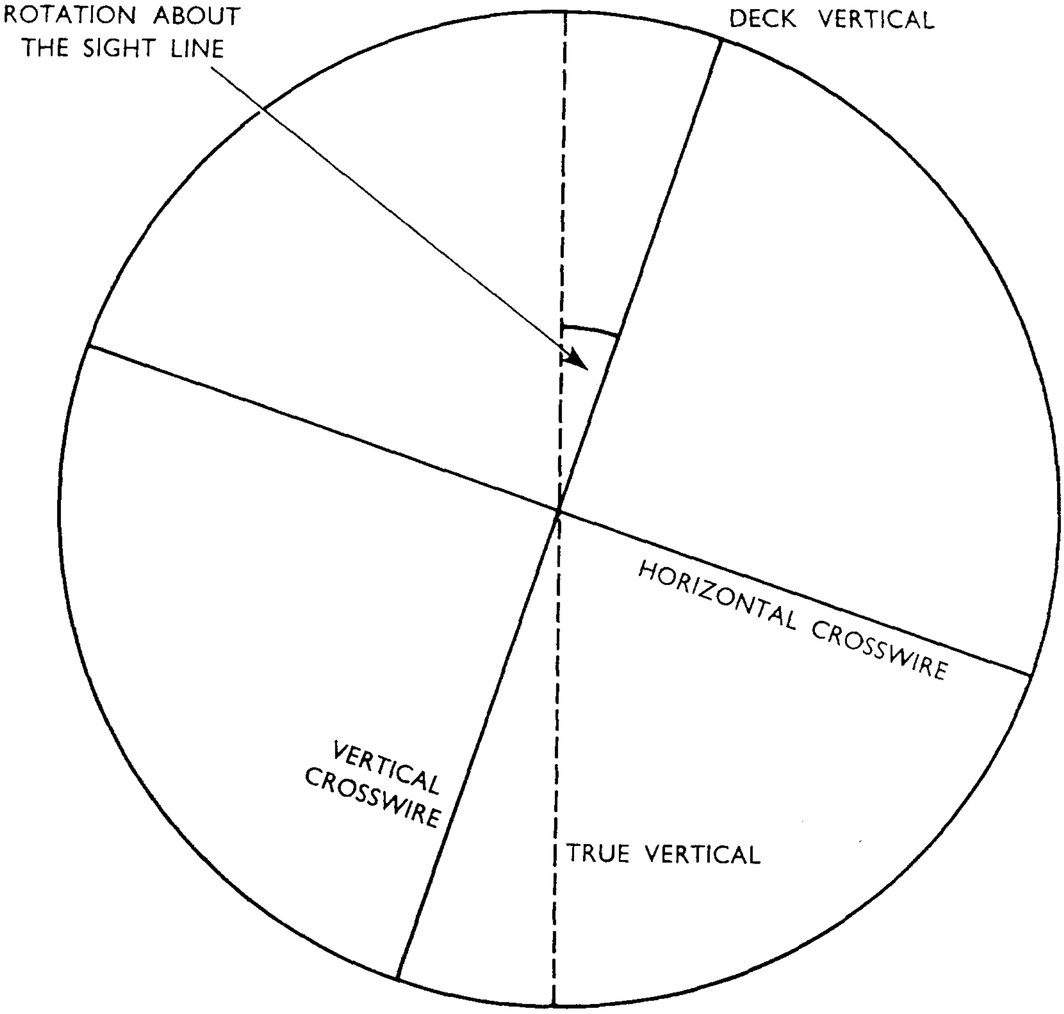


FIG. 6

trainer and range-taker constantly adjusting their controls. An advantage of this is that the quantities measured by these three operators do not get ‘ stale ’ since they are not being constantly altered.

The Predictor

The functions of the predictor, which comprises a number of electronic units and electro-mechanical servos mounted in racks, are fourfold. Firstly, the predictor must predict a future position of the target from data on present position given to it by the tracker. Secondly, it must apply corrections to the predicted future position of the target to allow for variations of ballistics from standard and for the separation of director and gunmounting. Thirdly, this corrected future position must be converted into terms of gun elevation and gun training for positioning the gunmounting. Finally, it must provide information for setting a shell fuze so that the shell bursts at the target future position. This is required only where time-mechanical fuzes, as distinct from proximity fuzes, are used.

The prediction of target future position is achieved by solving the triangle POF shown in FIGS. 7 and 8, where P is the target present position and F its future position, relative to a ship at O. The information we have available from the tracker to solve this triangle is the target speed and course in the plane of presentation, the range of the target at its present position, and the component of target speed in the line of sight.

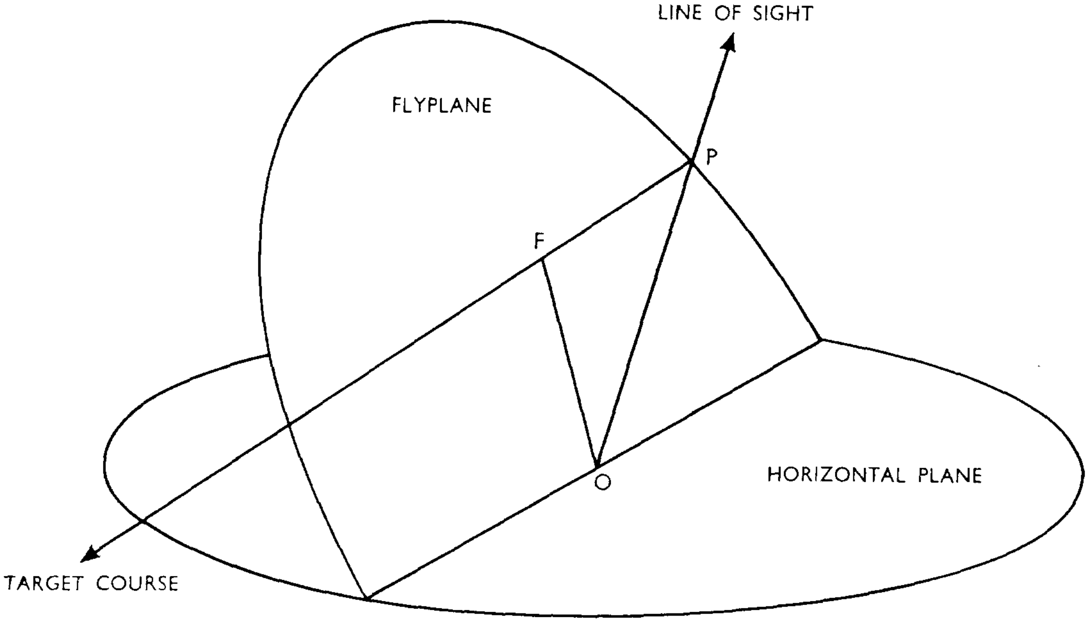

LINE OF SIGHT
FLYPLANE
P
F
O
HORIZONTAL PLANE
TARGET COURSE

FIG. 7

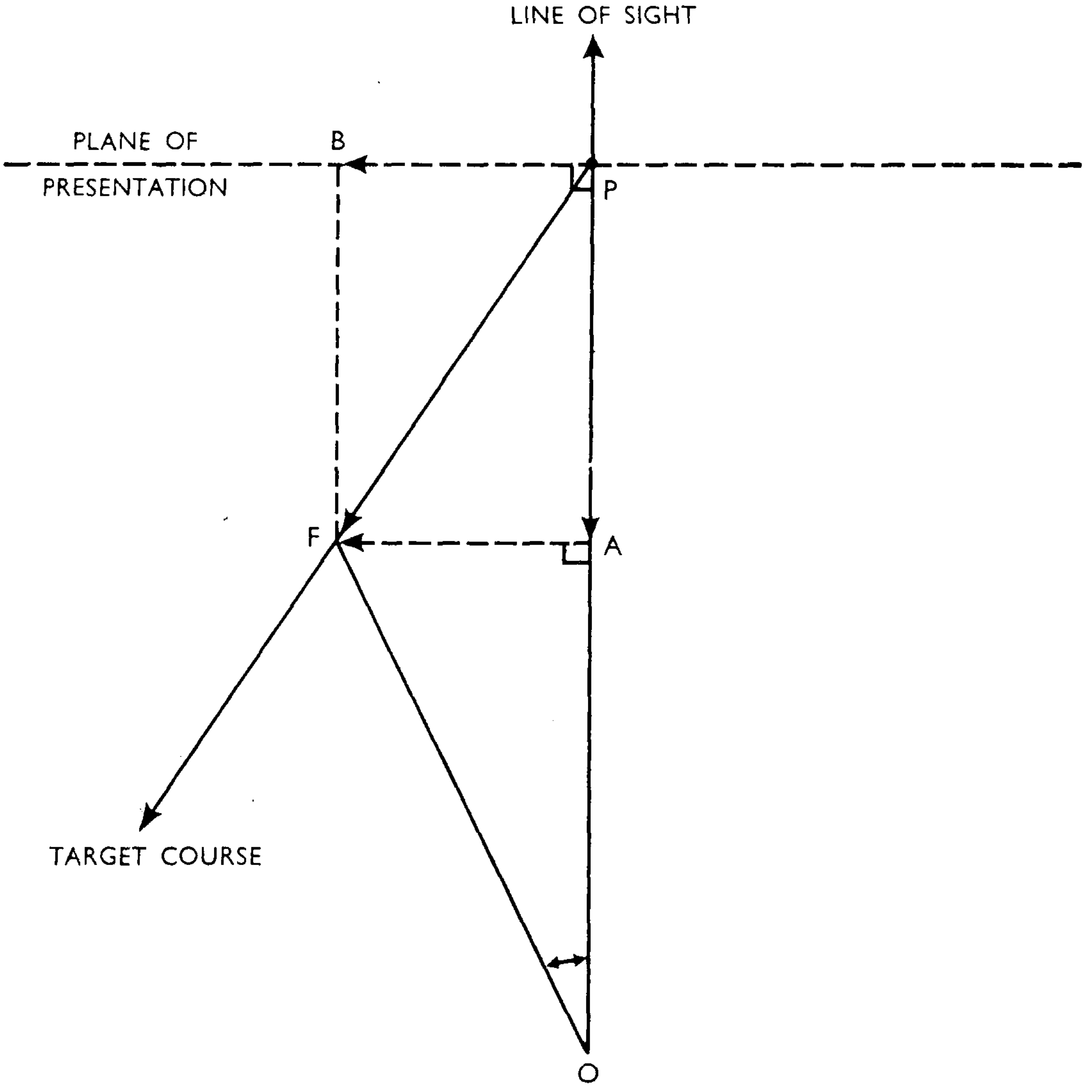

LINE OF SIGHT
PLANE OF PRESENTATION
B
P
F
A
TARGET COURSE
O

FIG. 8

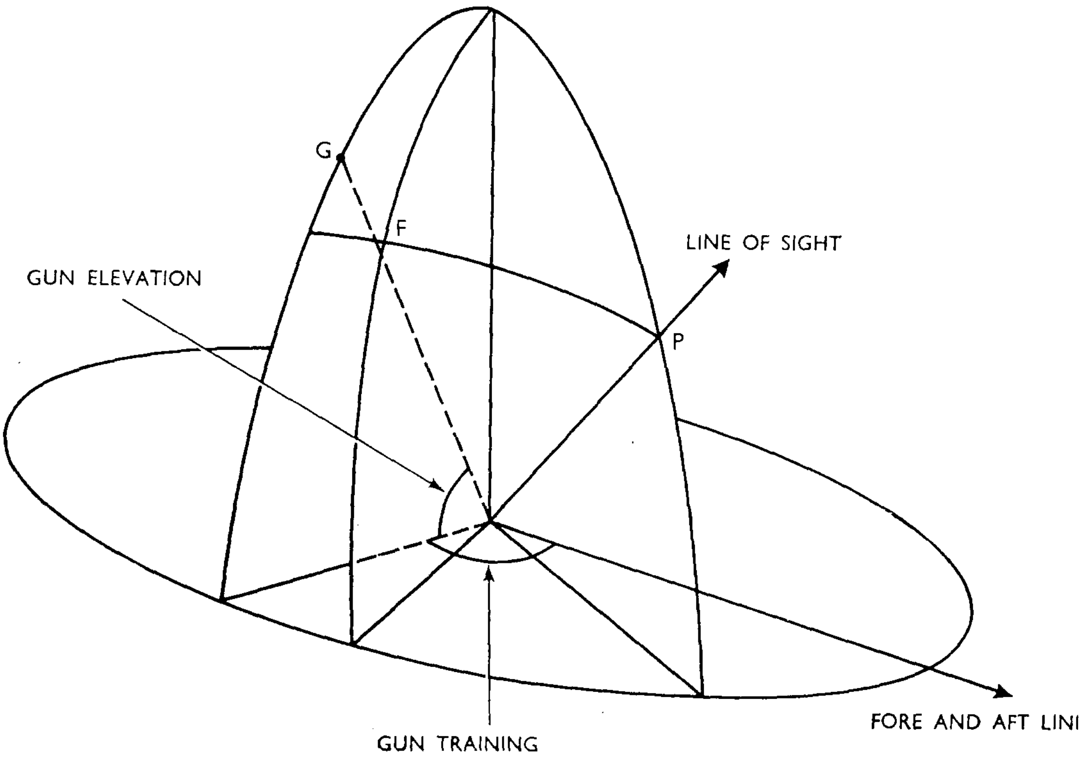


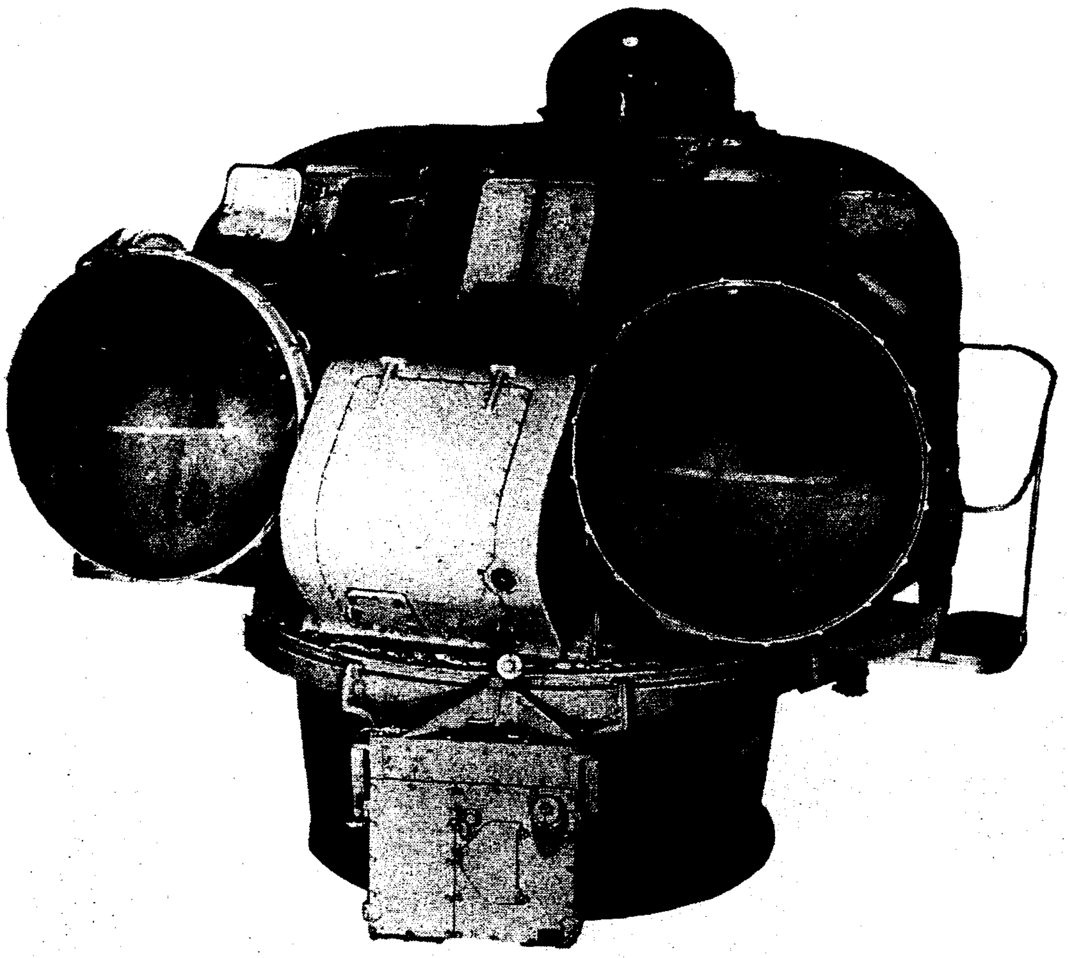
FIG. 9

Referring to FIG. 8, PF represents the distance travelled by the target during the time of flight, and can be resolved into the distances AF and PA. The components of target speed in these two directions have been measured in the tracker and the distances AF and PA are, therefore, the product of time of flight and these components of target speed. Since OP, the range to target present position is known, the distance OA is available in terms of time of flight. We are now in the position, therefore, of knowing AF and OA in terms of time of flight. The distance OF is range to the future target position and time of flight is a function of this range. These two quantities can, therefore, be considered as one unknown. In triangle FAO, therefore, there are now two unknowns, the distance OF and the angle FOA—which is called the flyplane deflection. It is now possible to produce a pair of simultaneous equations for triangle FOA in terms of the sine and cosine of flyplane deflection. These equations are solved by the predictor and produce flyplane deflection and future range from which is derived time of flight.

Referring to FIG. 8, we have now computed information to determine the future position under standard conditions. If we now add components of correction for ballistics and separation in, and normal to, the deck plane, we determine position G from which gun elevation and gun training are available and these are passed to the gunmounting.

The computation which produces information to set the fuze at the shell is similar to that above, which predicted target future position.

It is necessary to predict the fuze for a shell some seconds before it is fired because time is required to transfer the shell from the fuze-setting machine to the gun, ram it, withdraw the loading tray from the line of gun recoil and complete the firing circuits. This time is known as ‘ dead time ’. The time from fuze-setting to shell burst is called the ‘ prediction interval ’, and is equal to the sum of dead time and time of flight for fuzing. This time of flight for fuzing is predicted at the instant of fuze-setting. Time of flight for predicting target future position is being computed simultaneously, but the time of flight required



MARK 6M DIRECTOR

for fuzing is the time of flight of a shell to be fired at the end of dead time, i.e. a few seconds hence, and is therefore smaller for a closing target.

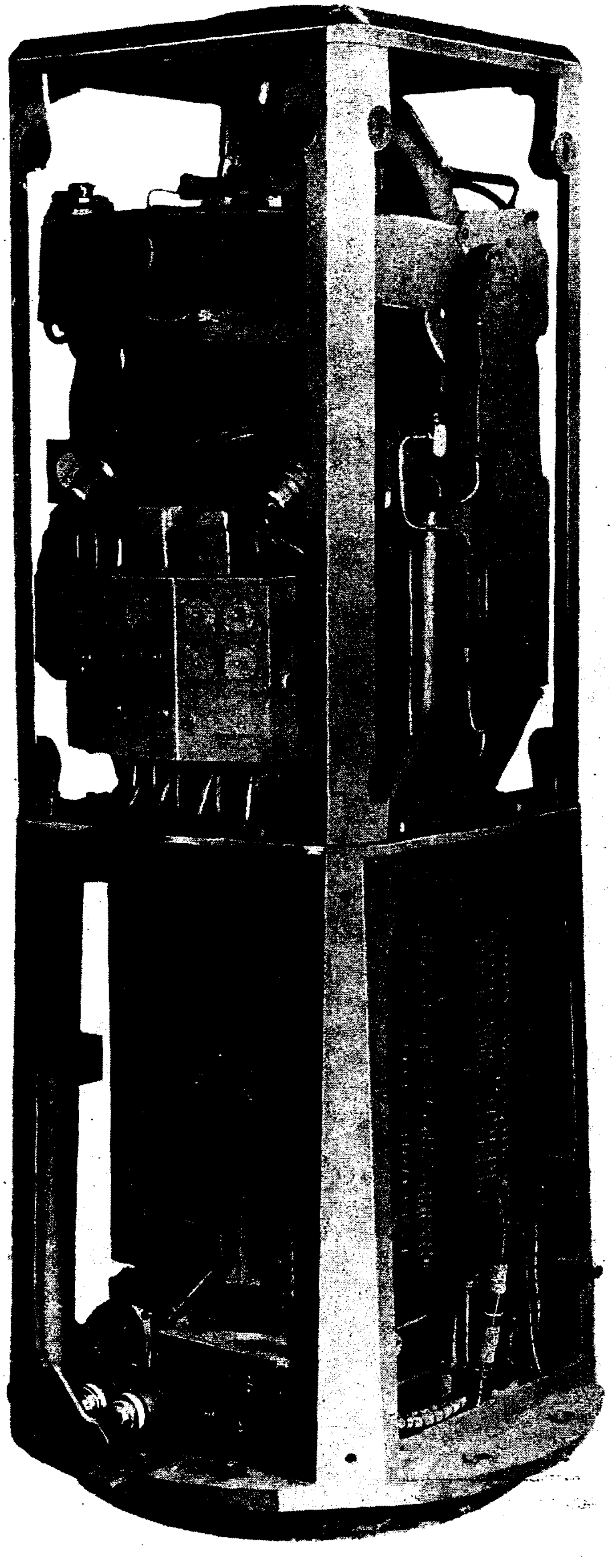
The solution of the fuze prediction problem produces range to target future position, time of flight and flyplane deflection for fuzing, and from the time of flight is produced an arbitrary quantity 'Fuze No. ', which is transmitted to the fuze-setting machine at the gunmounting and set on the shell.

NEW FEATURES INCORPORATED IN F.P.S.5

F.P.S.5 is the first A.A. fire control system to be completely designed in post-war years, and it is of interest, therefore, to examine some of the facilities and engineering techniques used which are novel to gunnery equipment.

Mark 6M Director

The primary consideration in designing this director was to make it operable under all action conditions for long periods. To achieve this, the three members of the director crew are given comfortable adjustable seats and the layer and trainer, who track the target, have optical sights known as Director Aimers' Binocular Sights, Mark 2 (D.A.B.S.2) which have fixed eye pieces, elevation of the line of sight being achieved by driving an elevating prism within the D.A.B.S.2. This arrangement enables the operator to view the target continually without moving his head, thus reducing fatigue. The whole of the director is lagged with cork to reduce the effect, inside the director, of changes in ambient



G.R.U. Stabilizer, Mark 3, with Covers removed temperature. When operating under tropical conditions, the director has its own air conditioning plant and blower to provide cool air to the crew. Under arctic conditions the crew wear heated suits. Under atomic, bacteriological and chemical warfare conditions, the director can be closed down and the air inside re-circulated, using a supply from the gas citadel as make-up when necessary. The design of this latter feature is still being developed. The radar nacelles have their own built-in air conditioning arrangements.

To provide more space for the crew, the elevating and training motors are situated outside the crew compartment. The elevating motor is situated in a compartment between the transmitting and receiving nacelles at the front of the director and the twin training motors are on the fixed structure driving the director through an external rack.

The strength of the director is derived from a box structure forming its centre section and accommodates the crew of three and all the instruments. Two side covers complete the director and these have no instruments or wires on them, so that damage to them in no way reduces the effectiveness of the director or crew. The centre pivot bearing is pre-stressed to 5g to reduce hammering of the roller path under conditions of shock and brinelling effects from ship's vibrations.

Gyro Rate Unit Stabilizer Mark 3

The principal new feature of the G.R.U.3 is the introduction of airborne gimbal bearings. These take the form of highly polished duralumin male and female hemispheres with an air film under pressure between them. The clearance between the hemispheres is 0·001 in. to 0·0015 in. and the air pressure 12½ lb/sq in on the upper bearings and 25 lb/sq in on the lower unit. The object of using this type of bearing instead of precision ball bearings is to reduce bearing friction to a minimum and thus reduce the spurious precessional torques on the gyros which cause them to wander. In addition, it is possible to use a gyro of smaller angular momentum and so reduce overall dimensions.

The G.R.U.3 has its own air supply unit which incorporates driers and filters to provide air of a suitable quality for supply to the air bearings and also to the airborne levellers. The function of the two levellers, which are mounted at right angles to each other on the upper (vertical) gyro unit gimbals, is to detect any movement of the gyro spin axis from the vertical and initiate signals which can operate servos to null this movement. The leveller consists, in essence, of an aluminium sleeve floating on an air film round a rod and carrying the soft iron armature of an electro-magnetic pick-up. Movement from the horizontal of the gimbal carrying the leveller misaligns the armature and coils of the pick-up and causes a signal to operate a servo to null the misalignment.

Another technique of interest in the G.R.U.3 is the method of applying the precession torques to the lower (rate) gyro. The method used is comparable with the principle of the steelyard, in which a constant force is applied to a beam at varying distances from its fulcrum. The force in this instance is applied by a spring loaded counter-balanced roller supported by a carriage whose movement is controlled by its associated precession servo motor. The roller is thus traversed along the precession beam which is centrally pivoted, the pivot being mounted on knife-edges and connected to a link gear which transfers the precession torque to the gyro.

This technique is used to provide accurate application of torque to the rate gyro. Accuracy is vital, since analysis shows that the source of largest errors in flyplane systems is the measurement of target rates.

Tracker and Predictor

These sections of the F.P.S.5 have little novel about them but they do use improved servo techniques and electronic units,designed to give a more reliable and stable performance and to be free of the less desirable features of earlier systems which so greatly increase the maintenance load.

CONCLUSION

It will, no doubt, already be apparent that the problem of hitting a high speed, highly manœuvrable aircraft is great and complex, and that, to increase the possibility of success, it is essential to be able to keep the projectiles up to date with target information right up to the ‘ collision ’ point, instead of predicting it during the time of flight. This can be achieved by the guided missile, which brings with it its own entourage of thorny problems. However, if we examine the performance that may be expected from F.P.S.5, it will be seen that the system goes a long way towards achieving a satisfactory result against A.A. targets. The system will track accurately from a slant range of 18,000 yards, an aircraft with a closing speed of 700 knots and vertical and lateral components up to 10 degrees per second. The ‘ miss ’ distance at the target for future ranges up to 5,000 yards is of the order of 25 yards or less. Limited experience to date has shown that, against towed, winged targets (180 knots airspeed) at ranges of 3,000 to 4,000 yards, over 30 per cent target triggered bursts, i.e. shells with proximity fuzes being triggered off by the target, will be obtained and, inside 3,000 yards, over 50 per cent of the shells fired will be triggered. These figures show up well compared with earlier systems, and it is expected that they will be obtained much more regularly. Further, with modern high rate of fire gunmountings, the number of shells actually bursting at the target will be quite high and one shell in the right place can do the necessary lethal damage. It is far more important to guarantee triggering half the shells fired every shoot than triggering every shell fired only once a commission.