BRITISH MECHANICAL GUNNERY COMPUTERS
OF
WORLD WAR II

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Abstract: Complex mechanical analog computing apparatus played an important role in World War II, particularly for the aiming of guns and other weapons from moving platforms or against moving targets. Such devices reached a very high degree of sophistication under the combined impetus of the mathematical complexity of the gunnery problems and the need for "real-time" solutions to these problems.

Mechanical analog computers had their origins in Naval Gunnery in World War I and were rapidly evolved in the 1920s in response to the substantial military threat by aircraft demonstrated in the final years of World War I. Development in World War II was rapid in response to the greatly improved capabilities of aircraft. Post World War II designs of mechanical computers remained in active military service into the 1970s and were, hybrided with electrical analog devices, the dominant form of military computing throughout the 1950s and 1960s yielding sway only slowly to electronic digital computing devices.

This paper describes the variety of mechanical analog computing devices in British military service in World War II. It concentrates on the more elaborate gunnery computers and describes their purpose, form, and functioning. The intention is to give an introductory picture of this era of computing technology. The historical development of the devices and their technology, and the generally similar equipment used by other countries, is not described in any detail.

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British Gunnery Computers

1. Mechanical Analog Computers

The origins of mechanical analog computing devices can be dated from the development of planimeters, devices for measuring the areas of irregularly shaped pieces on a map or plan, in the mid-nineteenth century. Although well disguised in some of the more successful designs, such as the Amsler planimeter, these intruments all involved a mechanical realisation of the mathematical principle of integration.

Significant advances were made in the 1870s by William Thompson, later Lord Kelvin, who applied an integrator invented by his brother James to the harmonic analysis of tide height charts and developed a complementary harmonic synthesiser for tide height prediction. Variants of Kelvin's designs, modified in detail only, remained in use by major maritime nations until at least the 1960s.

Kelvin also showed (in one of the most charming scientific papers I have ever read) that integrating devices could be applied to the solution of a wide range of differential equations in their integral form by the use of a "feedback" principle. His ideas were not, however, realised as the integrator mechanisms then available had too low a torque output to drive the interconnecting apparatus required by Kelvin's designs.

In the civilian field little further progress was made, aside from the development of harmonic synthesisers, until the work of Vanaveer Bush in the late 1920s. Bush rediscovered Kelvin's feedback principle and was able to embody it in a successful machine, the Differential Analyser, by using a capstan type of torque amplifier. Bush's designs were copied by other workers in the 1930s and their application to military problems, such as the calculation of artillery shell trajectories, was soon realised. With the outbreak of World War II the Differential Analysers were taken over for military uses.

Although a number of mechanical differential analysers and similar more specialised devices were developed after the war (frequently from cheap military disposals components) their usage died out in the 1950s with the increasing availability of electrical analog and electronic digital computers.

From the perspective of civilian scientific computing mechanical analog devices were of importance only over a short interval of about two decades and their use was never extensive. It is easy enough, from this perspective, to regard mechanical analog computers as of no great historical importance.

From the perspective of military calculating devices the picture appears very different. Mechanical analog devices were first used for naval gunnery in World War I, were greatly developed for naval and anti-aircraft gunnery betweeen the wars, were further developed and extended to aircraft systems during World War II, and continued in service in refined versions into the 1970s. The lifetime of mechanical analog computing technology was therefore much longer, about 60 years, in military than civilian usage, and their application as field service devices was very extensive.

This paper provides an introduction to the purpose, form, and functioning of military mechanical analog computing devices by describing some of the gunnery computers used by the British Navy and Army in World War II. It is essentially a descriptive paper. Only a brief history of the development of the designs is given, where it is known, together with a thumb-nail sketch of post-war developments. Similar equipment was developed and used by all combatants in World War II, but only items in British service are described here. Also omitted are the very many simpler pieces of military equipment which employed similar mechanical analog principles.

1.1. Gunnery Computers

Until the end of the nineteenth century naval engagements were fought predominantly by firing broadsides (all of the ships guns simultaneously) at, effectively, point blank range. Development in the late nineteenth century of breech loaded rifled naval guns with far superior ballistic characteristics, improved chemical propellant charges, and high explosive shells made feasible naval engagements at greatly increased ranges. At long ranges, and by World War II 20-30,000 yards were common, the time of flight of the shell is considerable, perhaps a minute. During this time the target ship could have moved up to a mile. It is therefore necessary to aim not at where the target is but at where it will be when the shell falls. The motion of the target, as well as that of the wind, the firing ship, and other ballistic factors, must be allowed for in determining the firing angles for the guns.

The first developments of fire control computers for gunnery purposes occurred before World War I with the development of the Vickers Range Clock and the Dreyer Table. These saw service, with somewhat limited success, during that war particularly at the Battle of Jutland. The Admiralty Fire Control Clock, which was based in part on the earlier work of Pollen, first saw service in HMS Nelson and Rodney in 1924. In its many variants it became the standard British Navy surface gunnery fire control computer throughout World War II and for many years afterwards.

Aircraft were first used by the military in the 1914-18 war, primarily for observation purposes but also for straffing and bombing. It rapidly became clear that an aircraft provided a most difficult gunnery target. In part this arises from geometrical considerations, the fact that the aircraft moves in three dimensions and at high speed, and partly from the fact that timed fuzes must be used in the shell, as the probability of a direct hit is small, and the fuze settings must be precomputed to a high degree of accuracy and set before the shell is loaded into the gun. There was no effective defence against even such slow moving targets as zepplins making bombing raids over London.

A great many simple aids to gun aiming and fuze setting were devised and tried during and after World War I but, except at close range, they proved generally unsatisfactory. It became evident that successful anti-aircraft gunnery would require a computing mechanism of considerable mathematical and mechanical complexity that was rapid in action and possibly automatic to a substantial degree. Several such instruments were developed in the 1920s and the first, the Vickers Predictor, saw service use in 1928. The American Sperry Predictor was developed in the early 1930s and, together with the Vickers, formed the basic Army anti-aircraft defence instruments for much of World War II.

Two important characteristics of military gunnery computers are evident from the foregoing. First, each of the computing instruments was highly special purpose in its function. The generality of function of the Differential Analysers was entirely absent. Second, the instruments were required to function in "Real-Time". The reduction of sighting observations of the target to produce gun aiming data had to be carried out continuously and, effectively, instantaneously after some inevitable initial delay in putting the instruments and guns on target.

Two further matters strongly influenced the designs. The instruments had to be ruggardised or "soldier-proofed" to withstand field service conditions. The basic components had to be much more solidly constructed than the rather delicate and sensitive components of the Differential Analyser (although much of the military equipment was in service before the Differential Analyser was invented). This robustness of the mechanism meant compromises for accuracy which led to further mathematical elaboration of the instruments. Finally, the gunnery computer had to be effectively interconnected with the rest of the gunnery system, particularly the optical or radar sighting systems and the guns themselves. Generally some form of automatic electrical transmission system was used, such as selsyns or magslips. These interfaces formed major parts of all practical designs.

World War II saw significant developments on two fronts, aside from the spread of mechanical analog computing technology to a wide range of military applications.

Developments in aircraft meant that target speeds increased considerably. One consequence was that the simplifying mathematical assumptions made in the earlier instruments had to be abandoned and more complex mathematical treatments, and hence mechanisms, adopted in their place. Another was the increased provision of mechanical aids to the observers tracking targets such as the gyro-stabilisation of naval observation platforms and the adoption of aided-laying and regenerative techniques whereby the operators are relieved of much of the difficulty in following fast moving targets.

A second development was the increased use of servo-mechanisms of all sorts. In part these relieved the need for the instrument operators required to carry out "follow up" functions, but it also meant that a more accurate and predictable response could be obtained from the instrument. Servo-mechanisms also gave more flexibility to the designer and made possible mathematical approaches that were previously infeasible. The ultimate ideal, of a fully automatic gunnery computer, was not, however, generally realised until the equipment was redesigned in the years after World War II.

1.2. The Torpedo Control B-Sight

The equipment described in this section is typical of the style of mathematical computing mechanisms used in gunnery computers, particularly with respect to the highly "special purpose" nature of the design. However the equipment is far simpler than any that will be described in the remainder of the paper. It is intended merely to show the style and character of the mechanisms employed.

The torpedo firing problem is illustrated in Figure 1. The course and speed of an enemy ship relative to the water is assumed known. A torpedo is effectively a small unmanned submarine whose speed is known and whose course, so that it will intercept the enemy ship, is the parameter that must be determined by the mechanism. From Figure 1 we see that the triangle is determined, save for a scale factor, by the given quantities and that the time of travel can be ignored. The problem is solved in the B-Sight by constructing a mechanical analogue of this triangle as shown in Figure 2. Since the scale of the triangle is unimportant the length of the "torpedo" bar is taken as constant and the length of the "enemy" bar is taken as v_e/v_t, the ratio of the velocities of the enemy ship and the torpedo. The torpedo bar is made fixed in length to ensure that the triangle is as large as possible so that the solution for the director angle will be as accurate as possible. The enemy bar is then set to the known inclination of the enemy's course to the line of sight. This in turn forces the slotted bar representing the line of sight to move right or left and carry with it the torpedo bar to generate the required torpedo director angle.

The length of the enemy bar is set by the scroll mechanism shown in Figure 3. The upper plate carries a slot representing the enemy bar of Figure 2 and is set for the inclination of the enemy ship's course to the line of sight. The lower plate carries a spiral groove which determines the length of the enemy bar. The logarithms of the speeds of the torpedo and the enemy ship are set into the mechanism by the simple expedient of setting the known speeds on logarithmically calibrated dials. These logarithms are subtracted and the difference, $\log(v_e/v_t)$, is used to rotate the lower plate. As the displacement of the groove in the lower plate from the centre is made proportional to the anti-logarithm of the rotation of the plate the length of the enemy arm is made v_e/v_t as required. The lower plate is also rotated, via a second differential, by the inclination so that as the inclination is changed both plates move together and the length of the enemy bar is not changed.

The torpedo has only a limited range of travel before its power source is exhausted. The torpedo cannot, therefore, be fired until the present firing range of the enemy ship is such that the point of impact is within the maximum torpedo range. However, the maximum firing range varies with the torpedo director angle as can be seen by reference to Figure 1. The mechanical realisation of this triangle can thus be used to indicate the maximum firing range.

The mechanism is shown in Figure 4. The pointer is displaced along the drum by an amount proportional to the side AB of the triangle by the slots engaged by the pins of the torpedo and enemy bars. The drum is rotated for the maximum torpedo range, a splined shaft being employed to allow the drum to move along its axis. Printed on the drum are curves from which the maximum firing range can be read against the pointer.

This calculating mechanism, with some refinements to prevent the possibility of its jamming if extreme values are set upon it, is mounted on a pedestal with a sight to allow the line-of-sight relative to own ship to be determined. There are electrical connections to the remainder of the ship's fire control system to allow the inclination of the enemy and its speed to be received and for the director angle to be sent to the torpedo firing tubes. The entire apparatus, after allowance for waterproofing the casework etc., weighs about 200 lb (90 kg).

2. Naval Surface Gunnery

The general geometry of the Naval surface gunnery problem is shown in Figure 5. The firing ship (own ship) observes the present range and bearing of the enemy ship and measures or estimates its speed and course (inclination angle to the line of sight). The computing mechanism determines the aiming point, effectively the future position of the target when the shell lands, as its range and bearing from the firing ship at the moment of firing. The range is transformed to the required elevation angle of the guns by the Range-to-Elevation gear.

The future range and bearing are determined from the present range and bearing by the application of Corrections in range and Deflections in bearing. The principal factors considered are the movement of the target ship (assumed to be in a straight line at its current course and speed), the "throw" given to the shell by the movement of the guns being carried with own ship at the moment of firing, and the shell being carried with the wind. The computing mechanism is greatly simplified by assuming that the corrections and deflections are small quantities so that they may be computed and applied independently of one another. Further, the corrections and deflections are all assumed to be linear functions of the speeds of the target, own ship, and wind. The computing mechanism is, therefore, mathematically relatively simple.

A characteristic of naval surface gunnery was the application of spotting corrections in both range and bearing. The fall of a salvo of shells (group of shells fired simultaneously by several guns) relative to the target was observed and corrections applied to the aiming of the guns to bring the fire onto the target. This practice relieved the computing mechanism of demands for extreme mathematical accuracy. The mechanism applied the more straightforward and simply calculated corrections and served effectively as an aid to the fire control officer who applied such further spotting corrections as his judgement might indicate. The simpler fire control computers, most commonly used in smaller ships with lighter guns of shorter range, differed in applying fewer corrections automatically and transferring a greater responsibility for the gun aiming to the gunnery officer although the final accuracy required is less.

In the following sections we shall consider the Fire Control Boxes used with smaller guns and as emergency turret controls in larger ships, The Admiralty Fire Control Clocks used as secondary controls in heavy ships and as primary control in medium ships, and the Admiralty Fire Control Tables used as primary control in heavy ships. There was also a number of simpler ancilliary calculating devices, akin to the torpedo sight described above, but these we will neglect.

2.1. Fire Control Box

The Fire Control Box (FCB) makes automatic allowance only for own and target ship velocity. Its mechanism is shown schematically in Figure 6.

Own ship speed is set into the calculating mechanism by hand and the present bearing of the target is received from the director control tower, high in the ship, which contains the optical sights and is therefore updated automatically as own ship changes course. The target speed and the inclination of its course to the line of sight are set by hand to values estimated in the director control tower.

Both own and target ships velocities are then resolved by the mechanism of the FCB into component speeds along and across the line of sight. This is done by the resolver mechanism shown in Figure 7 which is similar to the mechanisms described in connection with the Torpedo sight.

Own and target speeds along the line of sight are added to give the rate of change of range. The computed rate of change of range is used to position the balls of a variable speed drive unit, the Range Rate Clock, shown in Figure 8. The disc of the Range Clock is rotated at constant speed so that the output is turned at a rate proportional to the rate of change of range. This output is added to the initial range of the target, determined by optical range finders in the director control tower or by Radar, to give a continuously updated Clock Range - the present range of the target. No range corrections are computed in the Fire Control Box and any corrections desired are applied as spotting corrections to Clock Range to give Gun Range.

Gun elevation angle is derived from the gun range by the Range-to-Elevation gear shown in Figure 9. Pins are spaced at uniform intervals along a spiral curve on the disc rotated for range. The pinion is free to slide along its splined shaft to remain always in engagement with the pins but forces the shaft to rotate with itself. When the spiral is near the edge of the disc the elevation changes rapidly with range (as at long ranges) but when the spiral is near the center of the disc the elevation changes only slowly with range (as at short ranges). The pin wheel mechanism is, in effect, a special form of cam but it is compact, easy to manufacture, has positive drive of the output in both directions, and has high accuracy because of the high scale factor (the large number of revolutions made by the input and output shafts over its range of action).

Deflection due to own speed across the line of sight is taken to be directly proportional to the speed across and independent of range. The deflection due to target speed across depends on the speed across, the range and the time of flight of the shell. A drum is rotated by Gun Range and a pointer is moved over its surface, parallel to the axis, by the component of target speed across the line of sight. Printed on the drum are curves of deflection which are read by an operator and re-entered into the mechanism by a hand wheel. The curves on the drum include an allowance for drift - the amount that the path of the shell is deflected to one side in flight by the interaction of its gyroscopic spin from the rifling of the gun and the gravitational couple acting on it in flight due to its asymmetrical shape.

The gun bearing is formed from the present bearing of the target, given by the director control tower, by the addition of the target deflection and drift read from the drum, the own ship deflection taken from the own ship speed across resolver, and spotting deflections. In some marks of the FCB there is a convergence correction due to the separation of the director control tower and the turrets along the axis of the ship. This correction is obtained by a mechanism like a resolver that is rotated for bearing relative to the ship and with a pin displaced by a scroll cut for 1/Range.

No range corrections or bearing deflections for wind are computed by the FCB and these must be allowed for in the spotting. There is an auxiliary hand calculator for wind deflection and this is used to provide an initial spotting deflection.

The various marks of the Fire Control Box differ from one another principally in the arrangements for electrical and mechanical connections to the director control tower or other sighting apparatus and to the gun turret. The box was generally mounted in a secure position below decks or in the turret it controlled. With the mounting pedestal and interconnection arrangements the FCB weighed about 1/4 ton. I do not know how many FCBs were manufactured, but it must have been at least 500.

2.2. Admiralty Fire Control Clock & Table

The Admiralty Fire Control Clock (AFCC) and Admiralty Fire Control Table (AFCT) are more elaborate computing mechanisms than the Fire Control Box. They make provision for automatic application of range corrections and bearing deflections due to own ship and target velocity. All corrections are assumed to be linear in the speed. The dependence on range, when considered, is taken as a linear function either of the Time of Flight of the shell or of a function made up of half range and half time of flight. These functions, and in particular the function of range basis, are purely empirical and are obtained by fitting to data from the range tables describing the ballistic properties of the gun concerned. Linear functions are chosen to simplify the mechanism as far as possible. A correction is also made for deviation of the atmospheric conditions from normal temperature and pressure. This correction is taken as linear in the function of range.

The general form of the calculation made by the AFCC is shown in Figure 10. Aside from the multiplying linkage shown in Figure 11 it uses components generally similar to those of the FCB. Note that Figures 6 and 10 simply show the form that the calculation takes. The actual mechanisms are in many cases rearranged to allow for such mechanical constraints as the limited torque available from the variable speed drives, resolvers, and cams.

The drift deflection also includes a component due to latitude of the ship as the Coreolis force due to the rotation of the earth produces a similar effect to the drift and is represented by an alteration in the drift constant.

The target height correction is used when firing at coastal targets to allow for the height of the target above water level. In this case the target speed and direction are set to the reverse of the tidal flow of the water in which the ship lies, since own velocity is measured relative to the water.

The time of flight clock rings a bell shortly before and at the moment when a salvo of shells is due to land. This is an aid to the spotting officers in the director control tower who might otherwise be confused by splashes from shells fired from other ships.

The AFCT contains mechanisms additional to those of the AFCC. Most conspicuous amongst these are the range and speed across plots. The range plot plots the difference between True Range (Clock Range plus spotting corrections) and measured range on a continuously moving sheet. The slope of this plot is a measure of the error in the estimated speed of the target along the line of sight. The speed across plot similarly plots the difference between the speed across (obtained by integrating the sum of own and target speeds across in the same manner as the range rate clock) and the bearing rate or observed speed across (obtained by integrating true range by observed target bearing) on a continuously moving sheet. The slope of this plot is a measure of the error in the estimated speed of the target along the line of sight. The measured slopes of the two plots can be used to correct the target speed and inclination settings of the AFCT. The plots can also be used to aid blind firing when the target is temporarily obscured from sight.

The AFCT also contained Position In Line (PIL) gear to enable the fire of several ships to be concentrated on a single target. The master ship follows the target and radios information respecting its position to the other slave ships. The slave ships follow the master ship with their instruments and the AFCT infers from the relative position of the master ship and the radioed information the relative position of the target. The use of the PIL gear was obsolete before 1950, possibly due to the use of Radar ranging and changes in naval battle technique.

As with the FCB there were numerous marks of the AFCC and AFCT differing mainly in their connections to the director control tower instruments and to the gun turrets. I do not know the weight of these computing mechanisms but they must have been in excess of a ton. The ranges of serial numbers employed suggest that a total of about 300 AFCCs and AFCTs saw service in World War II. Instruments similar to the AFCT were used to control coast defence artillery.

3. Army Anti-Aircraft Gunnery

Some measure of the difficulty of the anti-aircraft gunnery problem may be gained by recognising that the standard British army 3.7" heavy anti-aircraft gun fired a shell with a lethal blast range for an aircraft of only about 30 feet. If fired at a bomber flying at 200-300 mph at an altitude of 15-25,000 feet the shell would take 10-20 seconds to reach the aircraft and the guns need to be aimed about a mile ahead of its present position. It is not, therefore, suprising that 3-5,000 shells were expended for each aircraft brought down, although the defence was also considered successful if it prevented the aircraft from accurately bombing its target. Figure 12 illustrates the geometric and timing constraints within which the computing equipment must operate.

Many technological innovations contributed to anti-aircraft defences in World War II. The most important of these was Radar which as early as 1940 was in use for providing range information for gunnery and superseded the earlier far less accurate optical height and range finders. Radar could not, however, be used to provide directional information of an accuracy suitable for gunnery purposes until late in the war with the advent of centimeter wavelength radar. Another important development was the proximity fuze, worked from a radio transmission by the shell, which obviated the calculation and setting of fuze before the shell was fired. With these and other improvements very high rates of success, in some cases over 90% destruction, were achieved against such "easy" targets as the German V-1 flying bomb.

Interesting and important as these developments were, I shall concentrate here on the evolution of the calculating mechanisms themselves. As aircraft speeds increased during the war it became necessary to eliminate many of the simplifying assumptions made in the earlier designs of anti-aircraft gunnery computer and achieve a more accurate mathematical solution. As speeds increased it also became more difficult to track the aircraft accurately to obtain the present position information necessary for the prediction of its future position and the calculation of gunnery data. Increased feedback from the computing mechanism to the sights evolved to alleviate this difficulty. This line of development continued and did not reach its full flowering until the 1950s.

An early difficulty in anti-aircraft gunnery was to determine the present position of the aircraft. It is easy enough to determine its azimuth angle (or Bearing) and elevation angle (or Angle of Sight) from a single telescopic instrument. To locate it in space requires a third linear coordinate - the slant range, ground range, or height. Height was commonly adopted as, on the assumption that the aircraft is flying straight and level at constant speed, it will remain unchanged throughout the engagement. This assumption was justified in view of the very limited rate of climb capability of aircraft in World War I and tactical considerations.

The earliest height finders employed two sighting instruments sited some distance apart and making purely angular observations - the so called "long base" approach. This method presents difficulties in transmitting data from one instrument to the other and in ensuring that both instruments are sighted on the same aircraft in a squadron. By the early 1920s this approach had been replaced by the use of a "short base" rangefinder of the Barr and Stroud type modified to give a direct indication of the target height. The use of this instrument was difficult and its accuracy poor at long ranges. A really satisfactory range/height finder was not available until the introduction of GL (Gun Laying) radar at the start of World War II.

By the early 1920s the attention of designers of anti-aircraft computing instruments had focused on the development of "Central Post" instruments - single instruments located at the gun battery that could perform the entire gunnery calculation and included part or all of the sighting and range/height finding apparatus. Early designs included that of Holden (British Patent 167191 of 24 Sept 1918), Vickers (BP 199411 of 22 Dec 1921) and Barr and Stroud (BP 194826 of 28 Dec 1921). Several others are described in the Text Book of Anti-Aircraft Gunnery, 1924.

3.1. The Vickers Predictor

The first design of anti-aircraft gunnery computer to see service use, in 1928, was the Vickers Predictor (BP 236250 of 3 March 1924) which in various revised and modified forms saw service throughout World War II. The designer, P.W. Gray, had also been responsible for the earlier 1921 Vickers design and, at an earlier date, for Naval range-keeping gunnery calculators.

The Vickers predictor is a tachymetric instrument that infers the course and speed of the target aircraft from the rate of change of its bearing and angle of sight from the predictor. The calculations within the Vickers predictor are carried out in polar coordinates and the main function is to determine the lateral and vertical deflections from the present line of sight to the aircraft to the future line of sight when the shell reaches it. (This approach is analogous to that used in Naval surface gunnery computers.) Although the mathematical functions which must be computed in the predictor are complex in the polar coordinate system the deflections calculated, being relatively small quantities, can be found to a relatively lower precision and the manufacture of the instrument is thus simplified. As aircraft speeds increased in World War II so did the necessary deflections and the advantage in using polar coordinates was to some extent lost.

The flow of the calculation in the Vickers predictor is shown in Figure 13. B_p and B_f are the present and future bearing of the aircraft and S_p, S_f the corresponding angles of sight or elevation. $\omega_L=\dot{B}_p$ and $\omega_V=\dot{S}_p$ are the rates at which the tracking telescopes must move to follow the aircraft. The lateral and vertical deflections, $D_L=B_f-B_p$ and $D_V=S_f-S_p$, and the time of flight, t, of the shell to the future position of the aircraft are the principal quantities determined by the predictor.

The time of flight is given as a function of S_f and the target height, H, by an operator following a height curve on a drum chart. The deflections are given by the equations

$$\frac{\sin D_L}{t} = \omega_L \frac{\tan S_f}{\tan S_p}$$

and

$$\frac{\sin D_V + \Psi}{t} = \omega_L \frac{\sin S_f}{\sin S_p}$$

where

$$\Psi = (1-\cos D_L)\,\sin S_p \cos S_f.$$

The deflections are not calculated directly by the predictor but each side of the above equations is computed separately and their difference exhibied on lateral and vertical balance dials. Operators adjust each of the deflection inputs until the differences are zero and the dials are stationary. In this way the operators provide the torque for the mechanisms that the deflections must drive. A technique similar to this is used in many of the computers described in this paper.

The wind deflects the trajectory of the shell and must be corrected by additional deflections given by the approximate equations

$$W_L = (H-c)\ W\ a\ \sin\theta$$

and

$$W_V = (H-c)\ W\ b\ \cos\theta$$

where a, b, and c are constants and θ is the angle between the wind direction and the future bearing of the target aircraft.

The gun elevation, or Quadrant Elevation (QE), is determined by adding to S_f the Tangent Elevation (TE) found by following a height curve on a drum chart. The fuze is found from the time of flight by adding the Fuze Time Difference given by a cam.

Following the introduction of Radar ranging it became possible to determine the aircraft height with sufficient precision to abandon the assumption that its flight was horizontal. The Vickers predictor was therefore modified to enable the engagement of "gliding" targets for which the rate of climb or descent is constant but the path is still a straight line. The future height is given by

$$H_f = H_p + \dot{H}t$$

and the deflections may be obtained by multiplying the time of flight t in the above equations by H_p/H_f. As well as the mechanisms required by these equations the predictor was modified by substituting cam mechanisms for the time and tangent elevation drums since it is not practicable for an operator to follow height curves when the height is changing.

The Vickers predictor weighed about 7 cwt (350 kg). Serial numbers of instruments I have seen show that about two thousand had been manufactured by Sperry in the USA by 1941 so I estimate that the total World War II production was around 3-5,000. Each predictor provided (identical) firing data for a battery of four anti-aircraft guns.

3.2. The Sperry Predictor

The Sperry predictor (BP 418670 of 25 March 1933) is another tachymetric instrument but employs cartaesian coordinates. By the assumption that the target aircraft is flying straight and level at constant speed both the northerly and easterly components of its velocity are constant. In the cartaesian coordinate system the prediction of the future position of the aircraft is therefore particularly simple.

The flow of the calculation in the Sperry predictor is shown in Figure 14. The observed height and angle of sight of the target are combined to yield the present ground range, r_p, which is then resolved into northerly and easterly components, N_p and E_p. Each of these is then differentiated by an auto-balance mechanism (a ball and disc integrator appropriately connected) to yield the velocity components of the target. These are multiplied by the time of flight and a wind correction to give the displacement of the target during the time of flight of the shell. A further correction for a possible displacement of the gun battery from the predictor can also be applied. The future position of the aircraft is then resolved back into polar coordinates and the gun data are computed by cams.

The flow of the calculation in the Sperry predictor is particularly straight forward and arises from the complete decoupling of the northerly and easterly components of the aircrafts motion. The main difficulties arise from the coordinate conversions which demand a mechanism of considerable accuracy, and hence size, and the second conversion which demands the assistance of an electrical servo-mechanism.

Later models of the Sperry predictor, when radar range data were available, were modified like the Vickers predictor to engage gliding targets whose height was changing. This involved a height prediction section identical to those for the northerly and easterly components of the aircraft motion, but no other changes. The simplicity of these changes highlight the advantages of the cartaesian coordinate approach adopted by the Sperry design.

A further variant of the Sperry predictor was adapted for dual role anti-aircraft and anti-ship coastal defence. Since the prediction process is the same in both cases the only changes required are for the different ballistic characteristics of armour piercing anti-ship shells. The ballistic cams of the predictor are so made that when the target height is zero they have the characteristics required of anti-ship rather than anti-aircraft shells, so that no change to the predictor is required in changing from one role to the other.

The Sperry predictor was a larger instrument than the Vickers and weighed about half a ton (500 kg). I do not know how many were manufactured but it must have been comparable with the Vickers - some thousands.

3.3. The Kerrison Predictor

Both the Vickers and the Sperry predictors were designed primarily for use against high flying bombers, from which much of their demand for mathematical accuracy arises. Low flying aircraft present a very different problem with very short engagement times and high angular rates but little demand for ballistic accuracy or elaboration. The Kerrison predictor was a very much simpler instrument designed to meet these requirements. It was designed by Major A.V. Kerrison at the Admiralty Research Laboratory, Teddington, in the late 1930s.

The key to the design of the Kerrison predictor was the use of Aided-Laying to assist the operators in following the target. This type of mechanism is of considerable importance and is sketched in Figure 15. With the clutch in position "B" and the ball cage at the center of the disc of the variable speed drive the output of the variable speed drive is stationary and the handwheel turns the training directly. This position is used initially to put the predictor on the target. When on target the clutch is moved to position "A" so that as the target is tracked the balls are displaced from the center of the disc and the variable speed drive provides an increasing proportion of the motion required to track the target. When the balls are displaced an amount proportional to the rate of change of bearing of the target no further motion of the handwheel is required unless the rate changes. Any motion of the handwheel then, to bring the director back onto the target via the direct drive, also adjusts the rate. Position "C" is used to automatically recenter the balls of the variable speed drive before commencing to track another target. As well as the training angle the training rate is also supplied to the calculating mechanism, so the aided-laying mechanism also serves as a differentiator.

The flow of the calculation in the Kerrison predictor is shown in Figure 16. It consists of little more than aided-laying mechanisms for bearing and elevation of the target and a linkage mechanism to multiply the rates by the time of flight of the shell to give the future position of the target. An approximate correction is applied to the elevation rate to give the tangent elevation - the angle through which the shell will drop during flight due to gravity.

The Kerrison predictor does not calculate fuze as the shell of the 40mm Bofors gun, with which it was designed to work, is contact fuzed. The range of the aircraft, or time of flight of the shell, is simply estimated by an operator. However, the ammunition included a tracer so the fire could be brought onto target visually, rather after the manner of hitting a moving object with a stream of water from a garden hose. The Bofors gun included oil powered servo-mechanisms to allow it to follow the predictor indications automatically without manual intervention.

Similar in some respects to the Kerrison predictor was the No.7 anti-aircraft composite predictor also designed by Kerrison. This was intended for use in close defence and also against targets at intermediate heights of 6-14,000 feet. The design was developed originally for the 6-pdr naval gun, but was later adapted to the 40mm Bofors.

The No.7 predictor used aided-laying in tracking the target aircraft and also in following slant range indications from radar. Letting the slant range to the present position be R_p, and working in polar coordinates, the future slant range is

$$R_f = \left[(R_p+\dot{R}t)^2 + (R_p^2\cos^2 S_p\dot{B}^2t^2 + R_p^2\dot{S}^2t^2)\right]^{½}.$$

If we can assume that the time of flight is a function of the slant range only then this equation can be solved for the time of flight without reference to the lateral and vertical deflections (which are given by equations similar to those used with the Vickers predictor). This assumption simplifies the basic feedback loop in the Vickers predictor in which the deflections affect the time of flight which in turn affects the deflections giving rise to a complex interaction between the operators and making the Vickers predictor slow to settle onto a target. The No.7 predictor made extensive use of cam and servo-mechanisms and was, aside from the tracking of the target, completely automatic in operation. It was therefore quite a complex device.

The No.7 predictor saw, so far as I am aware, only limited service use in World War II and I have little information relating to it.

4. Naval Anti-Aircraft Gunnery

Naval anti-aircraft gunnery computers differed considerably from those in Army service. In some part this might be attributable to differences in the nature of Naval aircraft targets - bombers will have to attack from a lower altitude than over land because of the possibility of a ship taking avoiding action during the fall of the bomb, and torpedo attacks will be launched from a low altitude. However the differences do not seem to be attributable to this cause alone. A more likely cause is that Naval and

Army designs evolved quite independently. Credence is lent to this view by the separate companies supplying the two services and who did much of the design work.

4.1. The Fuze Keeping Clock

The first Naval anti-aircraft gun computer that I shall describe, but certainly not the first to see service use, is the Fuze Keeping Clock (FKC) introduced in 1939. Although naval anti-aircraft gunnery is complicated by the forward movement and pitching and rolling of the ship, these do not significantly alter the basic gunnery problem or its solution.

The present position of the target aircraft is determined from a director control tower high on the ship not unlike that used to guide surface gunnery. In the smaller ships on which the Fuze Keeping Clock was used the same director usually served both gunnery purposes. The present position of the target aircraft was comprised of: the Director Training (or Bearing); the Director Setting (or Elevation) from which the present angle of elevation of the aircraft above the horizon, or Angle of Sight, was computed by applying a correction for the roll of the ship measured by the Gyro Level Corrector; and the present Range of the aircraft measured by an optical rangefinder.

To simplify the computation of the future position of the aircraft when the shell reaches it, it was again usual to assume that the aircraft would in the intervening time fly straight and level on its present course and at its present constant speed. The mathematical analysis is derived on this basis. For the Fuze Keeping Clock the aircraft speed is estimated by the Control Officer in the director control tower and the course is inferred from the Angle of Presentation, the angle that the aircraft's course, as indicated by the orientation of its fuselage, makes when viewed in the control offficer's binocular sights. The computer is thus a gonometric rather than a tachymetric instrument as the target course and speed are entered directly and not inferred from the observed angular rates.

In the Fuze Keeping Clock the gunnery data are determined in two largely independent mechanisms. The Fuze Clock portion determines the fuze setting to be made before the shell is fired. As the fuze is continuously changing and there is some delay, the Dead Time, between when the fuze is set and the shell is fired the mechanism must compute the fuze setting ahead of the present position of the aircraft. To aid the computation a rigid timing discipline in loading and firing the guns is used and is controlled by the FKC. The second part of the computing mechanism, the Deflection Calculator, determines the angular setoffs of the gun to be made from the present position of the aircraft to ensure that the paths of the shell and aircraft will intersect.

The general form of the computations made by the Fuze Clock portion of the mechanism is shown in Figure 17. The equations that the mechanism implements are shown in the following text. Many of these are derived from applying spherical trigonometry to the three dimensional geometry of the problem. However these equations are all solved by flat geometric mechanisms, somewhat similar in character to those we have already described for surface gunnery, and not by spatial mechanisms directly modeling the three dimensional situation. As before we shall ignore the rearrangements of the mechanism necessitated by such practical engineering constraints as the limited power or torque of the outputs from various of the mechanisms.

The straight line path of the aircraft and the ships director together define a plane, the Flyplane, in which the line of sight to the present position of the aircraft lies. Most of the calculations are carried out with respect to this plane. The angle between the present line of sight and the aircraft path is the inclination, ϕ, and can be found from the angle of presentation, AP, measured by the control officer in the director by the relation

$$\cot\phi = -\cos AP \cot S_p$$

where S_p is the present Angle of Sight or elevation of the line of sight to the aircraft above the horizontal plane. The estimated speed, u, of the aircraft may then be resolved into components $u\cos\phi$ along and $u\sin\phi$ across the line of sight. The present range, R_p, observed in the director is continually updated by the rate along by a variable speed drive, in the same manner as for surface fire control. This clock range is sent to the range finder in the director as an aid to the rangefinder operator who then has only to make range adjustments and not follow the target in range which would be a very demanding task.

The fuze prediction is carried out continuously and allows for the aircrafts movement from its present position over a time interval, T, made up of the dead time, D_t, to set the fuze and load the gun plus the time of flight of the shell, t_f, to the future position of the aircraft. The range to the future position of the aircraft is given by the approximate formula

$$R_f = R_p - T\left[u\cos\phi - \frac{t_f+D_t}{2R_f}(u\sin\phi)^2\right]$$

where the quantity in square brackets is the Mean Range Rate of the aircraft and is composed of the present speed along and the Secondary rate which depends on the speed across. When implementing this formula for Secondary Rate it is assumed that t_f is a linear function of R_f to sufficient accuracy for the present purpose. This approximate future range is further corrected for the dependence of the time of flight on the height of the target aircraft (for a given range) via a graphical representation of this effect, and for any deviation of the atmospheric conditions or the gun muzzle velocity from the standard conditions assumed. The height of the aircraft, which is assumed constant throughout, is just

$$H = R_p \sin S_p.$$

Finally, the fuze setting for the shell, the Fuze Number, is read from a graphical chart that is moved for the future range, R_f, and the height, H. This is transferred verbally to the gun mount and is also used in the deflection calculations.

The Deflection Calculator computes the deflections to be applied to the Director Training and Director Setting to give the Gun Training and Gun Elevation. It does this by constructing a three dimensional model of some aspects of the physical situation.

Since the target aircraft is, by assumption, flying straight and level at constant velocity its position after a given time interval will be at some point on a horizontal circle about its present position. Conversely, if its future position after the time of flight, t_f, of the shell is known, its present position must lie at some point on a circle about that future position. When viewed obliquely from the gun position, that circle becomes an ellipse whose eccentricity depends on the Angle of Sight to the future position, S_f, and whose size depends on the speed of the aircraft and the time of flight of the shell. The ellipse is represented in the mechanism by a solid circular aperture that is tilted relative to a pin hole sighting position by S_f, to give the eccentricity, and moved towards or away from the sight, to alter the apparent size, as shown in Figure 18.

The present position of the aircraft on the horizontal circle is determined by its course angle. This is defined approximately in the mechanism by a pointer centered in the direction of the center of the ellipse and oriented by the Angle of Presentation, AP, determined by the control officer in the director tower. Cross wires may be set to the apparent intersection of the angle of presentation pointer and the ellipse to give the vertical and lateral deflections to be applied to the present line of sight to give the future line of sight.

The lateral deflection must be corrected to give the deflection in azimuth required by the gun mounting according to the formula

$$\tan D_A = \tan D_L \sec S_f.$$

This is done by a flat link mechanism.

To the vertical deflection must be added the Tangent Elevation to allow for the fall of the shell under the influence of gravity during its flight. This is read from a graphical tabulation of Tangent Elevation as a function of the angle of sight, S_f, and the fuze number which represents the future range, R_f. (The fuze number used is that last sent to the guns since the fuze setting must be determined the dead time, D_t, ahead of the gun deflections.)

The scale of the ellipse, determined by moving the circular aperture towards or away from the pin hole sight, is expressed in terms of the ratio of the target speed, u, and the Average Projectile Velocity during the shell's flight. This latter is read from a graphical tabulation against S_f and the fuze number in a similar way to the Tangent Elevation. The Average Projectile Velocity is also used as the basis of a drift correction in azimuth.

In some models of the Fuze Keeping Clock a further correction in the gun aiming is made to allow for the speed of own ship by the approximate formulae

$$D_V^S = \frac{S}{V} \cos GT \sin S_f$$

$$D_A^S = \frac{S}{V} \sin GT \sec S_f$$

where S/V is the ratio of the ship speed to the muzzle velocity of the gun and GT is the gun training, when fired, relative to the course of the ship.

The addition of the total deflections to the Director Training and Director Setting to give the Gun Training and Gun Elevation was generally performed in a Fire Control Box or Fire Control Table which was used with the same director for surface gunnery.

The Fuze Keeping Clock weighed about 1100 lb (500 kg). I do not know how many were manufactured, but I believe it certainly to have been hundreads.

4.2. The High Angle Control System

The precursor to the Fuze Keeping Clock was the High Angle Control System (HACS) introduced in the early 1930s. This was generally similar to the Fuze Keeping Clock save in two respects:

(1) A projector system was used for the ellipse instead of a pin hole sight. Whilst this means that more than one operator can study the display, it has the disadvantage that, because of the limitations of the projector system, the geometric fidelity is not so great.

(2) The future range for fuze prediction is not based on a mechanical linkage for mean range rate but on the extrapolation of a range plot. Since a plot of range against time has a high curvature near the point of closest approach of the target aircraft, the plot used is actually of logR against time. This has a lesser curvature and points of inflexion at the quarters so that extrapolation is easier. LogR also proves to be a convenient function for use in the calculating mechanism.

The High Angle Control System was generally a larger and more elaborate unit than the Fuze Keeping Clock and was employed in larger ships. I have been able to account for about 135 HACS allocated to service by early 1941.

The High Angle Control System had a fairly elaborate evolutionary history in response to the changing needs for aircraft defence during the war, particularly increased target speeds.

The ellipse projection system used in the HACS did not accurately reflect the geometry of the anti-aircraft problem. To do so it would have needed to project an ellipse of variable size (cone angle) and eccentricity from a fixed distance. A mechanism to do this adequately could not be devised. Instead the system used an ellipse of variable eccentricity but fixed size (cone angle) whose apparent variation in size was achieved by moving the projector nearer to or further from the screen. The geometric distortion which resulted (and from which the Fuze Keeping Clock did not suffer) was partially relieved about 1935 by the ARL (Admiralty Research Laboratory) mechanism which displaced the image of the ellipse on the screen.

Both the HACS and the FKC suffered a residual fault from assuming that the lines of constant vertical and lateral deflection are orthogonal sets of straight lines on the screen. However lines of constant angle of sight and lines of constant bearing are curves when viewed along the line of sight. This difficulty is partially alleviated in both devices by using the present angle of presentation to determine the deflections in place of the average angle of presentation over the prediction interval. Not only does this reduce the distortion, but it also simplifies the mechanism considerably. However, the residual errors became significant as aircraft speeds increased.

In later models of the HACS these errors were reduced by feeding to the calculating table both a false angle of presentation and a false target ground speed, both so chosen that the deflections found by the table would be more nearly correct. The false values were prepared by the Gyro Rate Unit Box (GRUB) which interrupted the flow of data from the director to the HACS calculating table. This approach still left residual, though smaller, errors.

A fast aircraft is a difficult object to track with optical apparatus, especially from an unstable, moving ship as a base. The most difficult task is rangefinding which requires two images of the target to be accurately aligned in a split image field by the operator. In all designs, therefore, the clock range was fed back to the rangefinder so that the operator had only to make corrections to the clock range, i.e. the operator became responsible for changes in range rate rather than for changes in range.

Tracking in elevation was made difficult by the pitching and rolling of the ship. Initially a Gyro Level Corrector was provided, comprising a vertical axis gyro oriented to measure roll in the direction of the director training, i.e. the roll of the line of sight. This angle was added to the director elevation to give the present Angle of Sight for the calculating table. Later, with the development of oil powered servos of substantial power output, the level correction was used to alter the director elevation so that the director was effectively gyro stabilised, tracking was made far easier, and the present angle of sight could be measured directly.

The director bearing is also altered, though to a less significant extent, by the cross roll or component of roll at right angles to the line of sight. The Gyro Cross Level Corrector determined this correction and was later used to stabilise the director in training. Similar corrections were also made for gun bearing and gun elevation.

Near the point of closest approach of the target aircraft its bearing changes rapidly. Tracking in this circumstance was made easier by the provision of aided-laying gear in which the operator following the target adjusts the rate of change of bearing. Aided-laying was not provided for director elevation as the elevation rate is small near the point of closest approach and only moderate in the quarters.

Critical to the entire prediction process are the data on the present motion of the target aircraft which, by assumption, are supposed to continue unchanged throughout the prediction interval. The aircraft speed was simply estimated by the director control officer, presumeably from knowledge of the characteristics of target aircraft types, and the angle of presentation was determined from the orientation of the aircraft fuselage. Both are liable to be in error if there is any substantial wind at the altitude the aircraft is flying.

Much better estimates were obtained with the introduction of the Gyro Rate Unit (GRU). This contains a gyro that is kept caged as the director is first put on target. When uncaged the gyro will tend to remain stationary whilst the director moves in following the target. A joystick is used to apply torques to the gyro to maintain a sight, carried with the gyro, on the target. The torques then represent the lateral and vertical rates of the aircraft and the ratio between them gives the angle of presentation. The lateral and vertical rates are combined with the range and angle of sight in the Gyro Rate Unit Box to give the ground speed and angle of presentation required by the HACS calculating table. These quantities are further adjusted by the GRUB, as previously described, to correct for the deficiencies of the projection system of the HACS.

This entire complex of apparatus, which evolved throughout World War II, gives very much the impression of a cludge on top of a cludge. No doubt the development took the direction it did as a response to finding rapid solutions to the problems raised by battle experience and a need to use, as far as possible, the considerable amount of complex equipment already in service and the existing experience of trained personnel.

5. Other Military Developments

This paper has adopted a narrowly British perspective of World War II mechanical analog gunnery computers. It makes no pretence to completeness in an historical sense. Similar developments were made by other nations, and the American Ford Naval Rangekeeper (BP 128569 of 19 June 1918), for example, anticipated many of the features of the British AFCC and AFCT. Neither has any attention been paid to aircraft developments, such as bombsight and gunsight computers, which used similar mechanical analog calculating technology but were subject to severe weight constraints.

A particularly important development during World War II was the Bell Telephone Laboratories electrical predictor which introduced electrical analog computing to military use with great success. The idea of electrical computation was not new, many World War I predictor designs were based on similar principles, but the adoption of electronic summing and servo amplifiers made possible a degree of accuracy and automatic operation that could not previously be obtained. This predictor greatly influenced post World War II developments.

The nature of many military systems changed dramatically in the years after World War II, particularly under the influence of the Cold War. Whilst digital computers were introduced for strategic and tactical control in the 1950s they had little importance for direct weapons control until the 1970s. Naval surface gunnery, and the mechanical analog computers, changed little through the 1960s until the guns themselves were replaced by surface missile systems. Heavy anti-aircraft guns for defence against high flying bombers were rapidly replaced after World War II by high performance fighter aircraft and then missile systems. Light anti-aircraft guns for close defence remained, however, of considerable importance throughout the 1960s. Although their control systems were completely redesigned after World War II two at least, the Naval MRS8 and the Army FCE7, retained elaborate and newly designed mechanical analog computing systems until the 1970s when the guns themselves were abandoned. Both systems incorporated accurate mathematical representations of the anti-aircraft problem and, by the extensive use of servo-mechanisms, were completely automatic in operation. Aircraft weapon systems appear to have evolved as a hybrid of electrical analog and mechanical analog components through the 1960s.

The picture that emerges is that mechanical analog computers remained of considerable military importance certainly until well into the 1960s and have only been superseded by digital computing systems in the 1970s. This picture is greatly at variance with the civilian scientific experience in which mechanical analog technology was obsoleted early in the 1950s. As interesting is the observation that military developments of mechanical analog computing technology during and after World War I preceeded by at least a decade any comparable civilian developments.

It is also interesting to realise that the mechanical analog technology was expensive for the military. I understand that during World War II a Vickers predictor cost about £4,000, much more than the then cost of a fighter aircraft and equivalent to about $1/2 million at todays values. The fire control systems, including mechanical computers, of the battleship King George V cost £213,000 in 1939 or about $20 million at todays values. Total expenditure on military mechanical analog computing equipment in World War II must have amounted to the equivalent of tens of billions. It is likely that this experience led the military to accept computation as a complex and expensive art. Perhaps their readiness to support expensive and complex developments of digital computers in the post-war years is, in part, directly attributable to their wartime experience of mechanical analog computing systems.

Acknowledgements

The material presented in this paper has been derived, in the main, from World War II technical documents describing the principles involved and details of particular instruments. I am indebted for access to these materials to the personnel of various military establishments and other individuals in Australia and England. Without their generosity and support this work could not have been carried out. In particular I wish to thank: Mr Abe Deitch; Mr P.G. Ford; Dr A. Nutbourne; Mr N. Evans, Mr R. Evans, Mr Keith Anderson, Equipment Development Establishment, Maribyrnong; Grace Klemer, Artillery School, North Head; Commander Hickie, RAN, Sydney; Commander J.I. Redrobe, HMS Belfast Museum, London; Major-General B.P. Hughes, Brigadier R.J. Lewendon, Royal Artillery Institution, Woolwich; Mr D. Brown, Miss White, Naval Historical Branch, Fulham; Commander B. Witts, HMS Excellent, Portsmouth; Professor J.W. Skinner, Royal Military College of Science, Shrivenham; Captain B.G. Gibbs, HMAS Cerberus, Westernport; Imperial War Museum, London; Ordnance Factory, Maribyrnong; and the many individuals with whom I have talked in mess and ward rooms.

Bibliography

The following is a guide to the technical literature pertaining to each of the instruments and issues discussed. In general material has been assimilated from many diverse sources, only the more important and basic of which are listed here. For the Naval instruments, in particular, there was generally a separate Book of Reference (BR) for each mark number of which only one is cited.

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Figure Captions

Figure 1. The geometry of the torpedo firing problem. The course of the torpedo, the torpedo director angle, is determined by the B-Sight.

Figure 2. The geometry of the torpedo firing problem as represented in the mechanism of the B-Sight.

Figure 3. The scroll plate mechanism for setting the direction and length of the enemy bar.

Figure 4. The mechanism for determining the maximum torpedo firing range.

Figure 5. The geometry of the Naval surface gunnery problem.

Figure 6. The flow of calculation in the Fire Control Box (FCB).

Figure 7. The scroll plate mechanism for resolving ships motion from polar coordinates (course and speed) to cartaesian coordinates (speed along and speed across).

Figure 8. The Range Rate Clock for maintaining a continuously updated range to the target. The annotations show how the ball and disc variable speed drive can serve as a general purpose integrating device.

Figure 9. The Range-to-Elevation pin wheel cam mechanism.

Figure 10. The flow of calculation in the Admiralty Fire Control Clock (AFCC) and Admiralty Fire Control Table (AFCT). The AFCT also provided range and bearing plots to enable correction of enemy speed and inclination and Position-in-Line (PIL) gear to coordinate the gun fire of several ships.

Figure 11. The multiplying linkages used in the AFCC and AFCT are based on a mechanical representation of similar triangles.

Figure 12. The approximate envelope for a 3" 20-cwt anti-aircraft gun in relation to the effective range of searchlights and realistic siteings of equipment in defence of a target. Improvements in gun and aircraft performance in World War II did not relieve the tight timing and aiming constraints under which the anti-aircraft guns must operate. [Adapted from Hayes, T.J., "Elements of Ordnance", Wiley (NY), 1938.]

Figure 13. The flow of calculation in the Vickers Predictor.

Figure 14. The flow of the calculation in the Sperry Predictor.

Figure 15. The principle of the Aided-Laying mechanism.

Figure 16. The flow of calculation in the Kerrison Predictor.

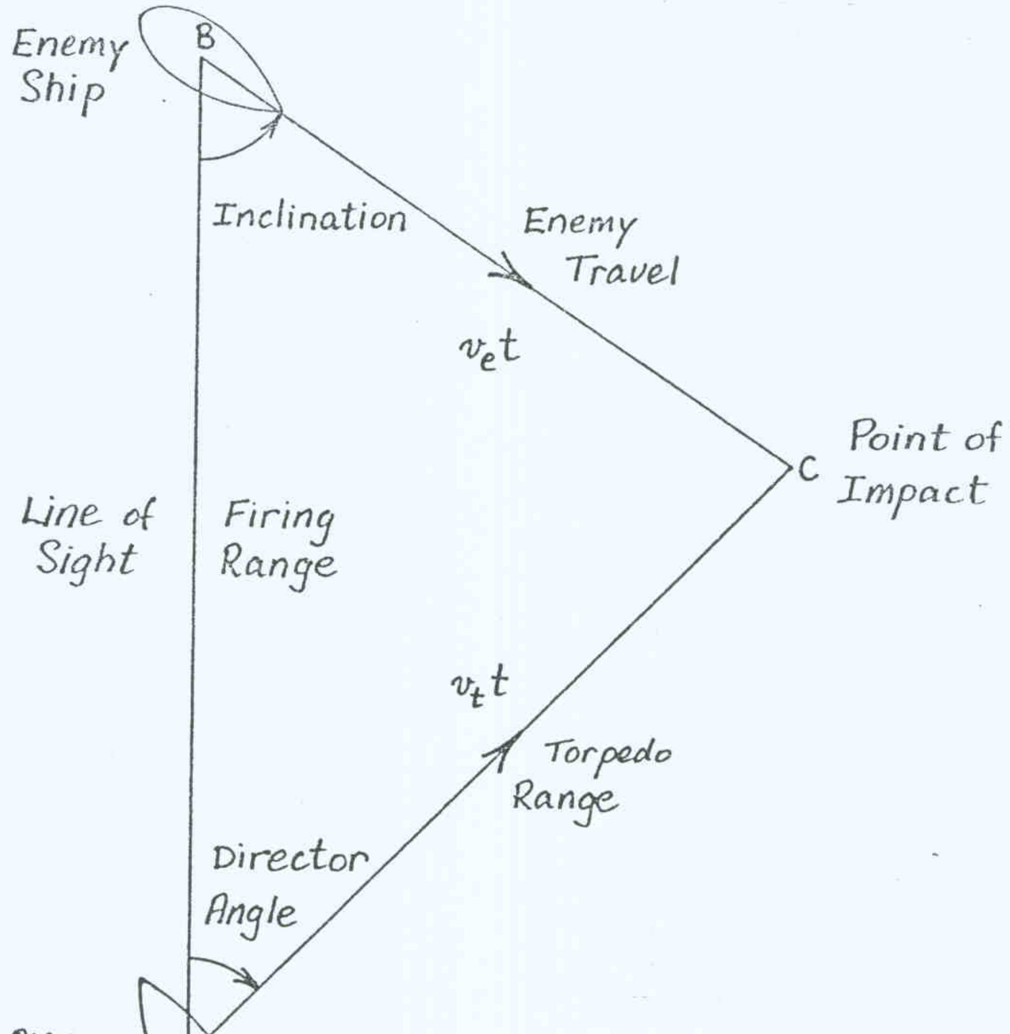
Figure 17. The flow of calculation in the Fuze Clock portion of the Fuze Keeping Clock (FKC).

Figure 18. The flow of calculation in the Deflection Calculator portion of the Fuze Keeping Clock.

Photo Captions

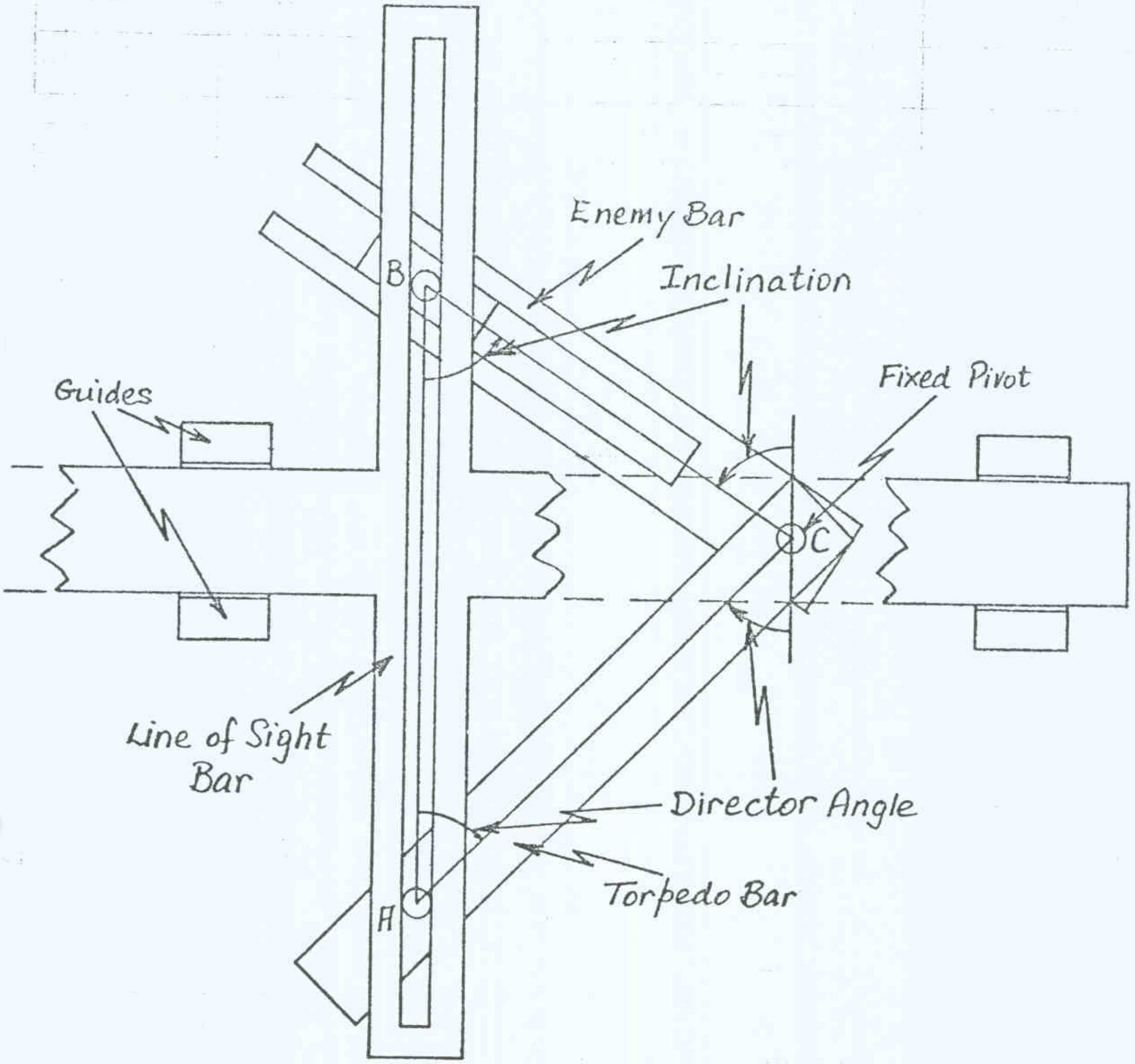
(To come)

Figure 1



Enemy Ship
B
Inclination
Enemy Travel
$v_e t$
C
Point of Impact
Line of Sight
Firing Range
$v_t t$
Torpedo Range
Director Angle
Own Ship
A

Figure 2



Enemy Bar
Inclination
Fixed Pivot
Guides
B
C
Line of Sight Bar
Director Angle
Torpedo Bar
A

Figure 3

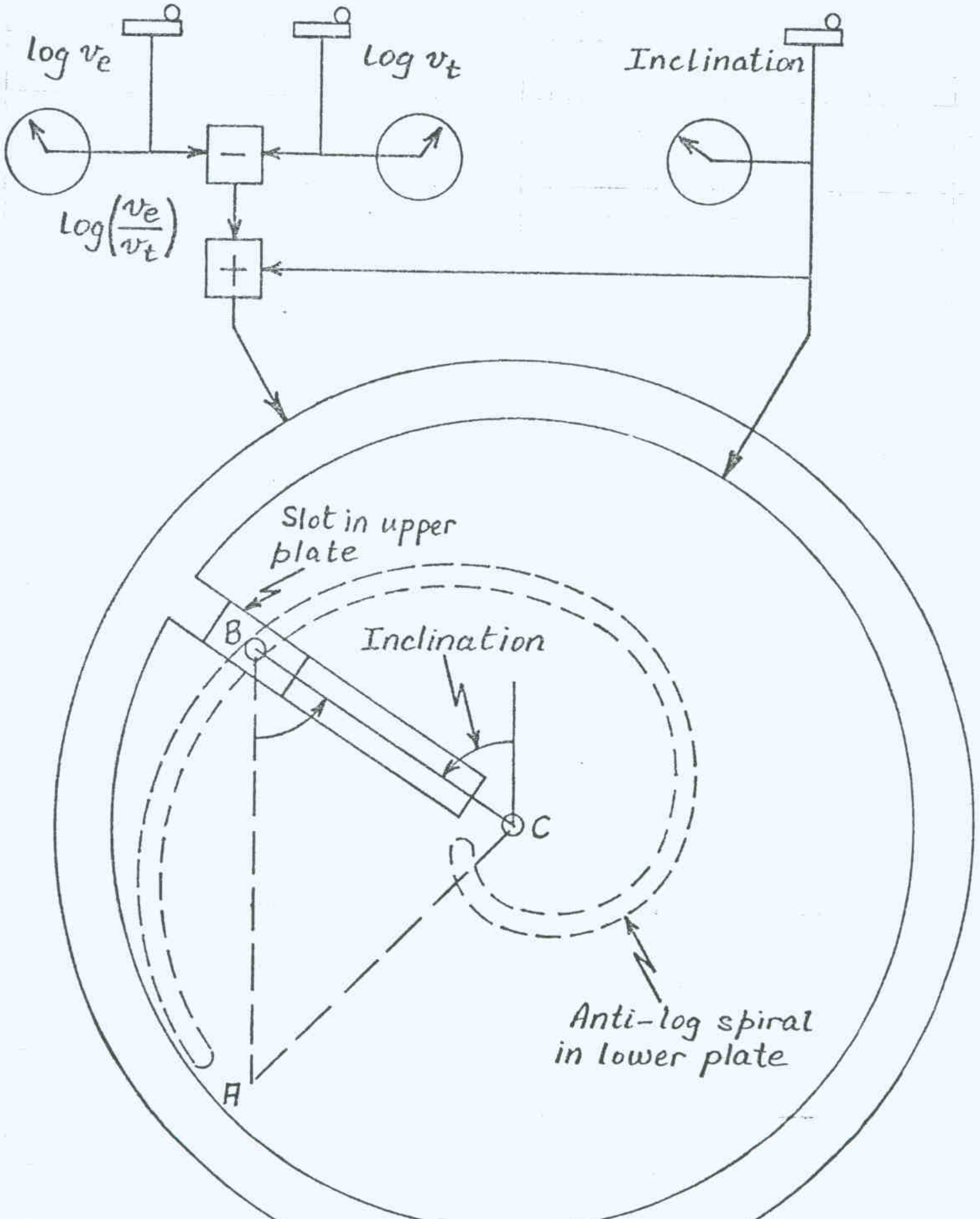

$\log v_e$
$\log v_t$
Inclination
$\log\left(\frac{v_e}{v_t}\right)$
−
+
Slot in upper plate
B
Inclination
C
Anti-log spiral in lower plate
A

Figure 4

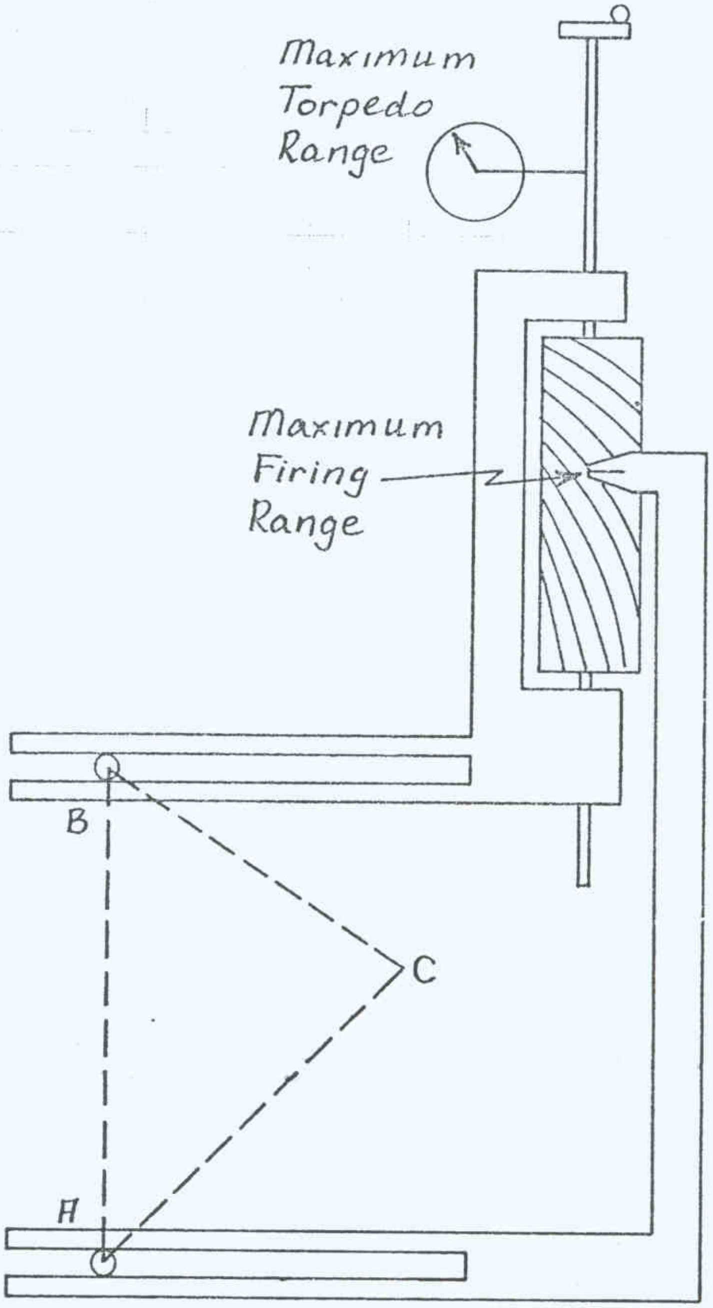


Figure 5

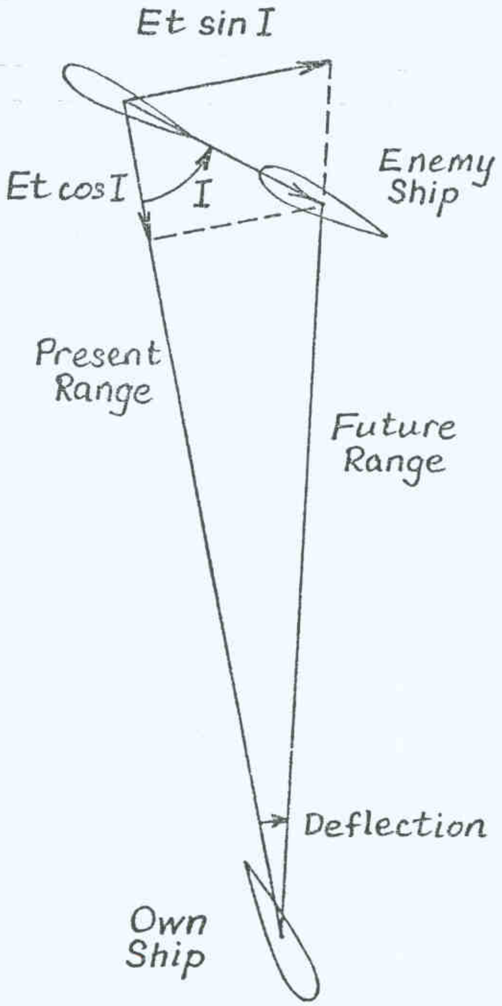
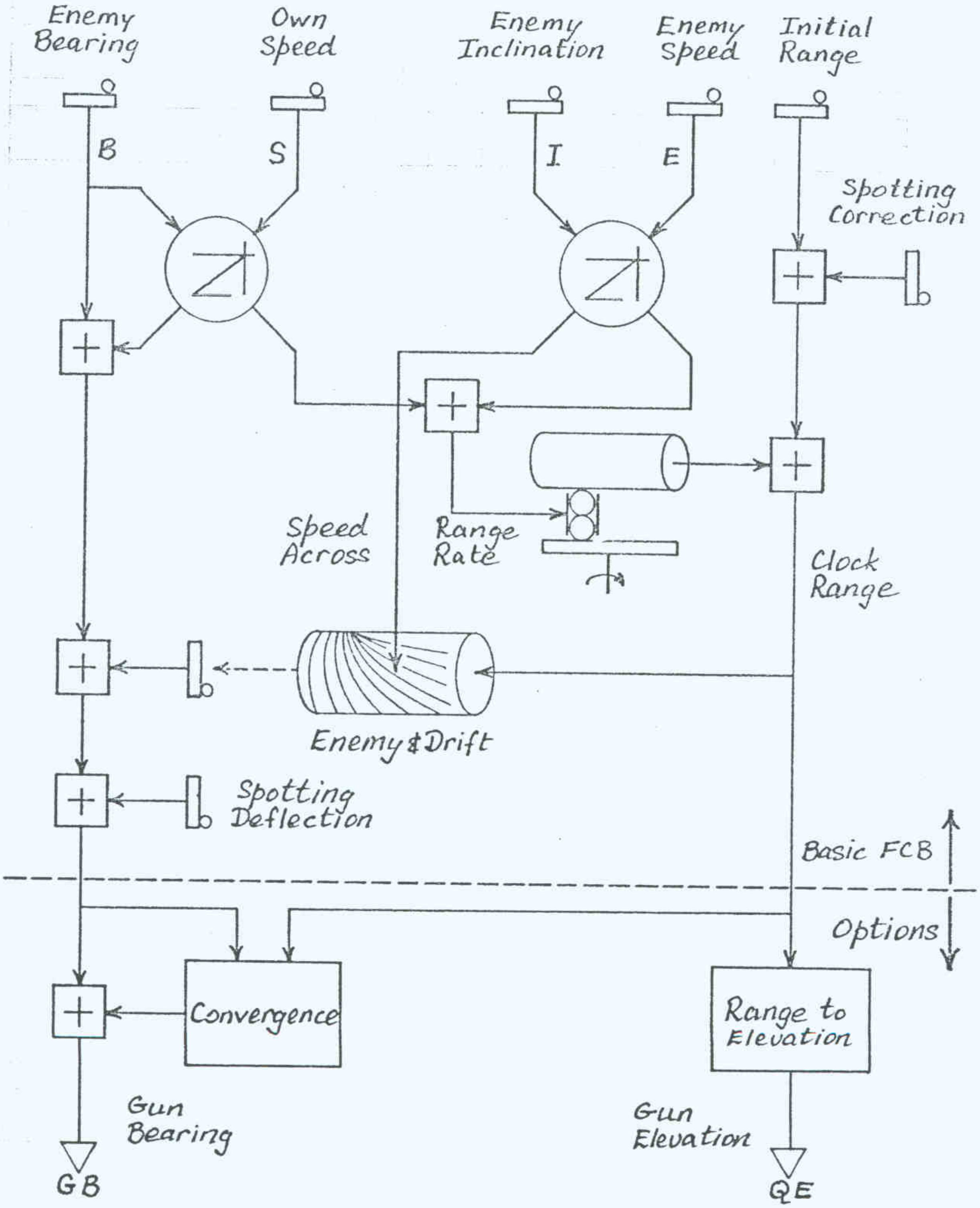

Et sin I
Enemy Ship
Et cos I
I
Present Range
Future Range
Deflection
Own Ship

Figure 6



Enemy Bearing
Own Speed
Enemy Inclination
Enemy Speed
Initial Range
B
S
I
E
Spotting Correction
Speed Across
Range Rate
Clock Range
Enemy & Drift
Spotting Deflection
Basic FCB
Options
Convergence
Range to Elevation
Gun Bearing
Gun Elevation
GB
QE

Figure 7

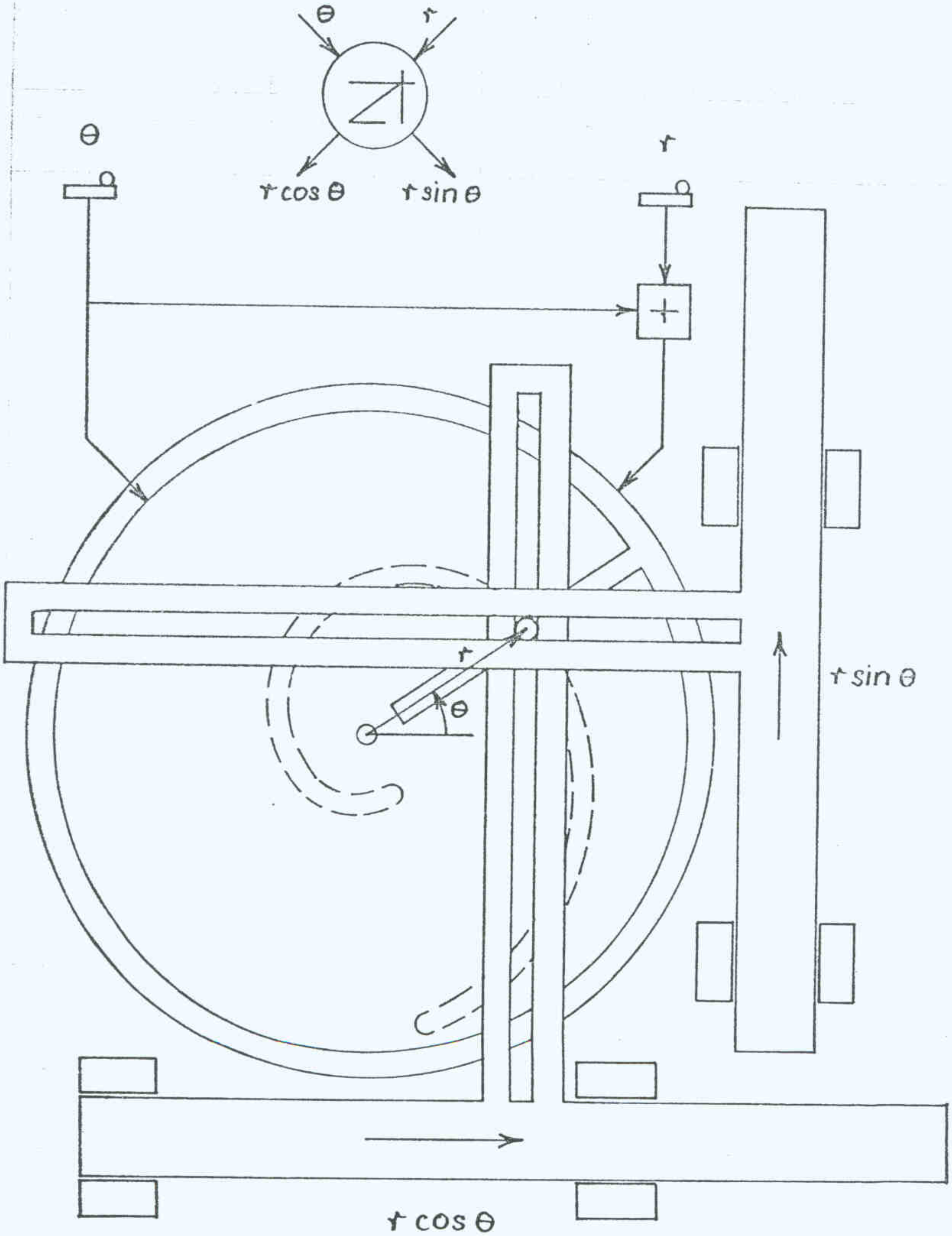
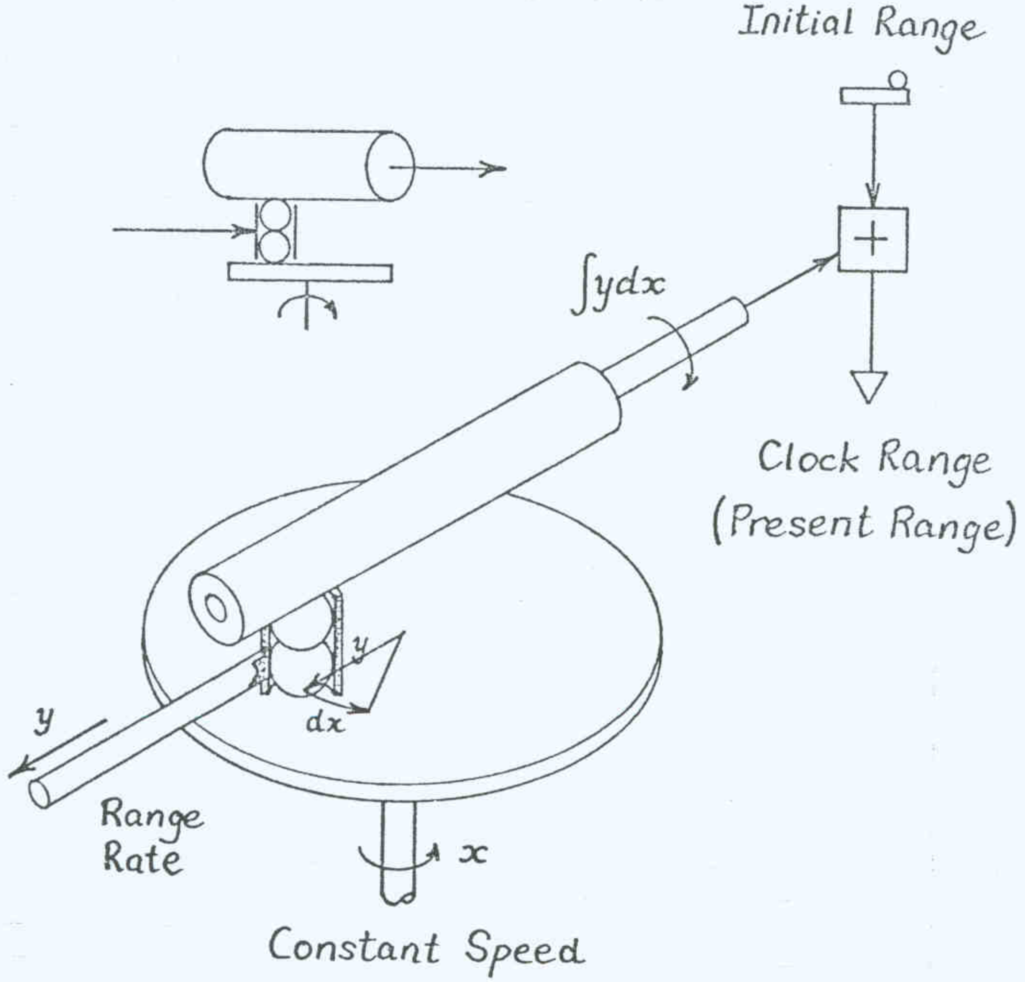


Figure 8



Initial Range
+
$\int y\,dx$
Clock Range
(Present Range)
y
dx
y
Range
Rate
x
Constant Speed

Figure 9

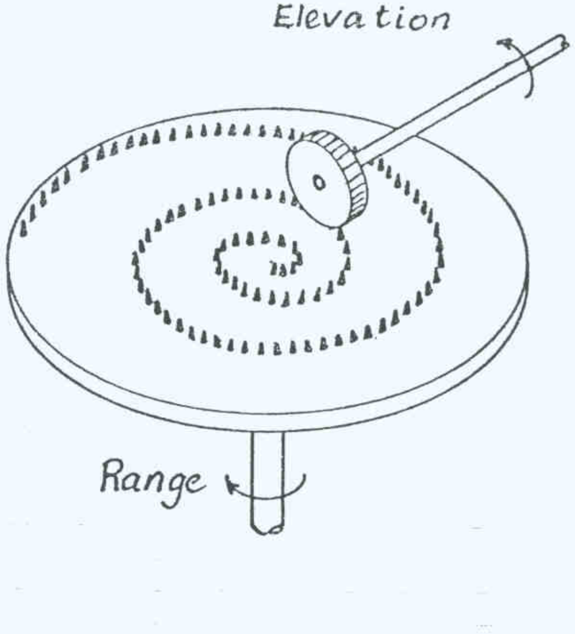


Figure 10

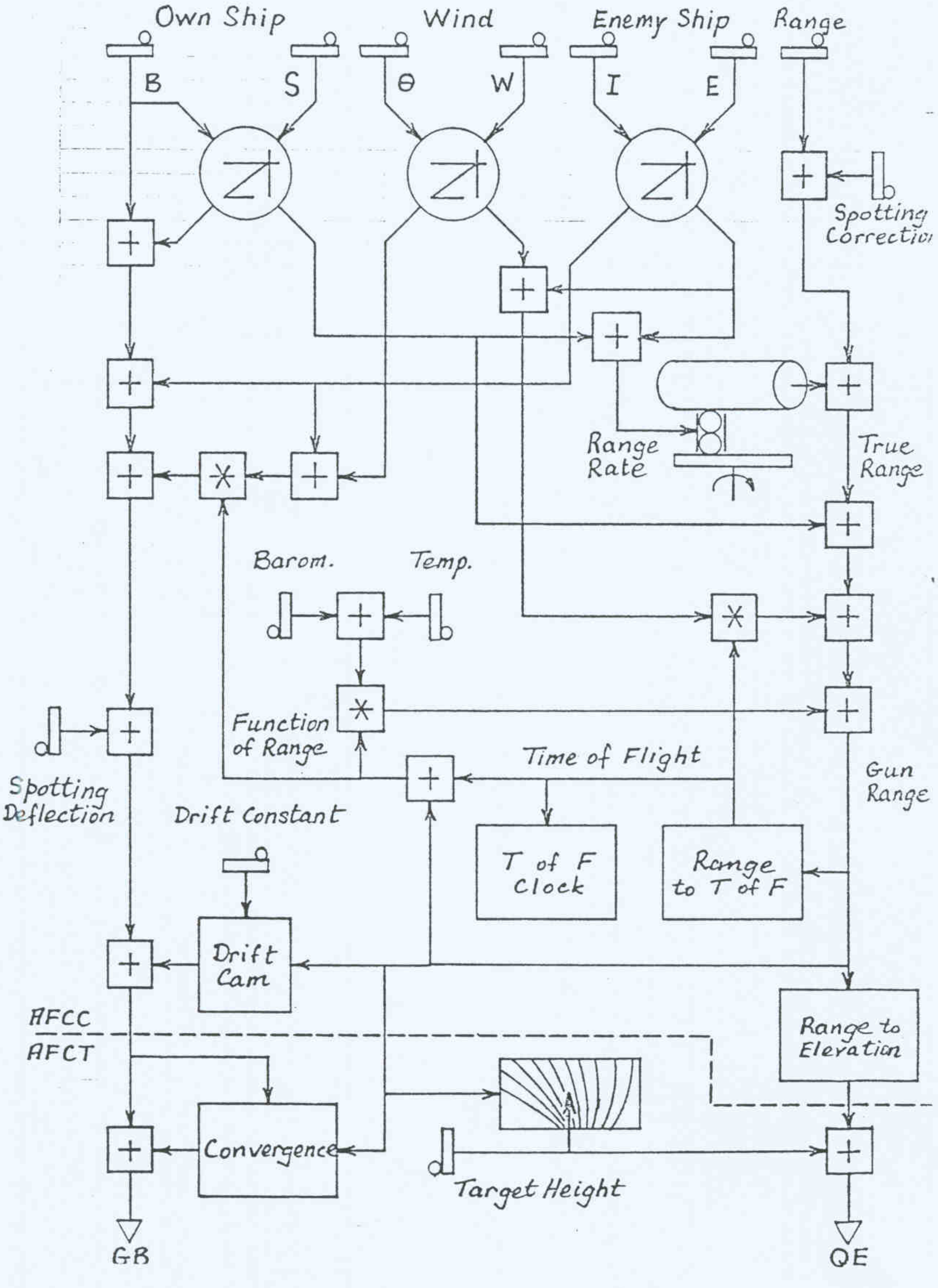

Own Ship
Wind
Enemy Ship
Range
B
S
θ
W
I
E
Spotting
Correcti
Range
Rate
True
Range
Barom.
Temp.
Function
of Range
Time of Flight
Gun
Range
Spotting
Deflection
Drift Constant
T of F
Clock
Range
to T of F
Drift
Cam
AFCC
AFCT
Range to
Elevation
Convergence
Target Height
GB
QE

Figure 11

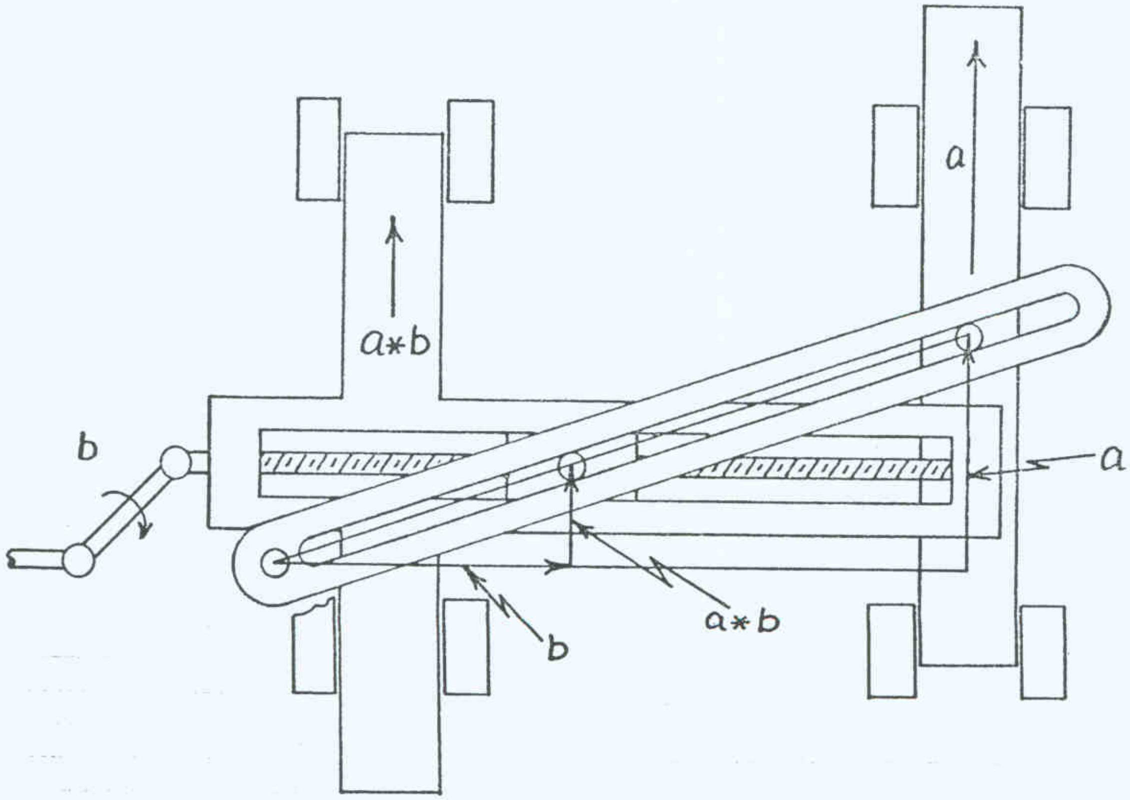


Figure 12

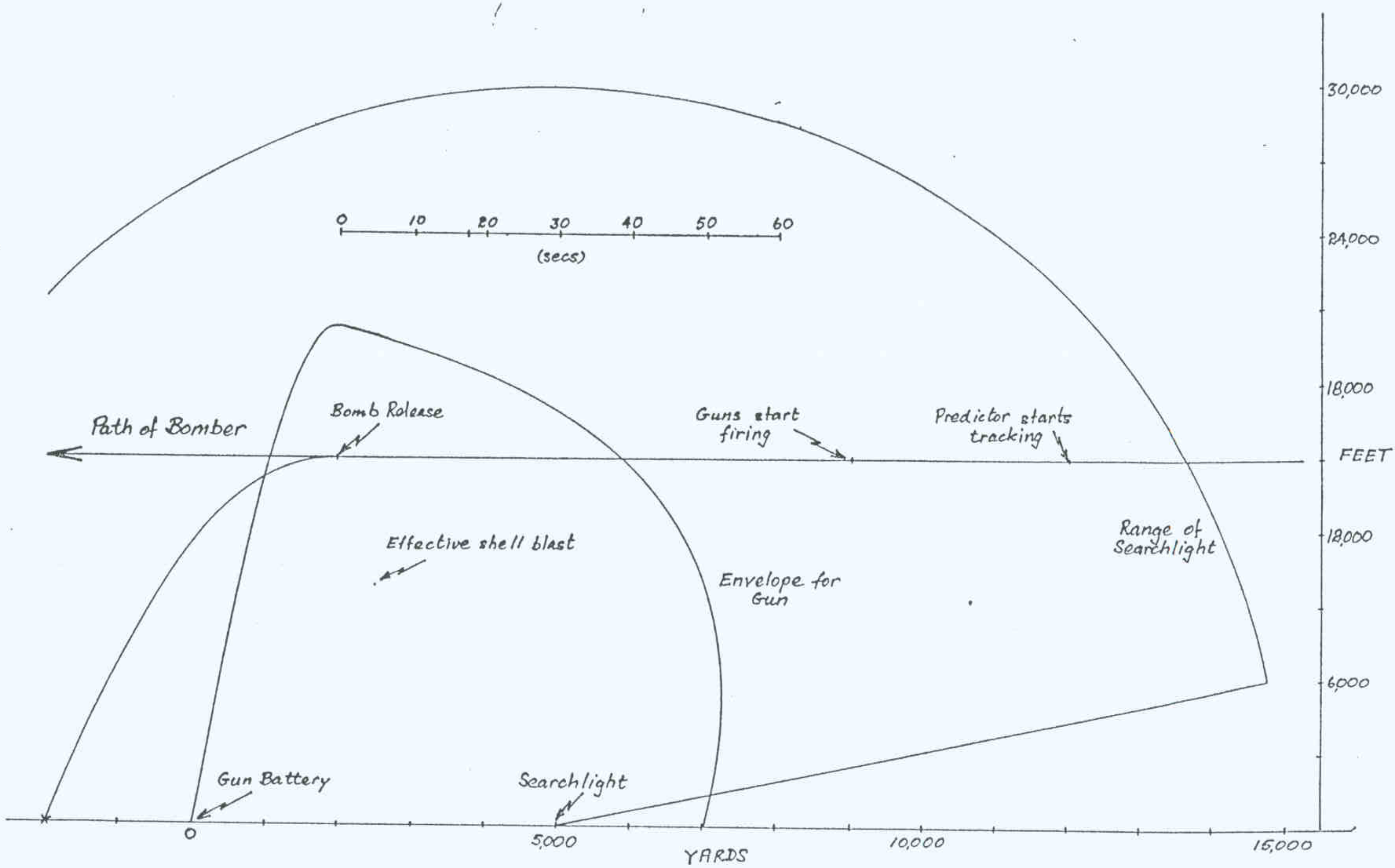

0
10
20
30
40
50
60
(secs)
Path of Bomber
Bomb Release
Guns start firing
Predictor starts tracking
Effective shell blast
Envelope for Gun
Range of Searchlight
Gun Battery
Searchlight
0
5,000
YARDS
10,000
15,000
30,000
24,000
18,000
FEET
12,000
6,000

Figure 13

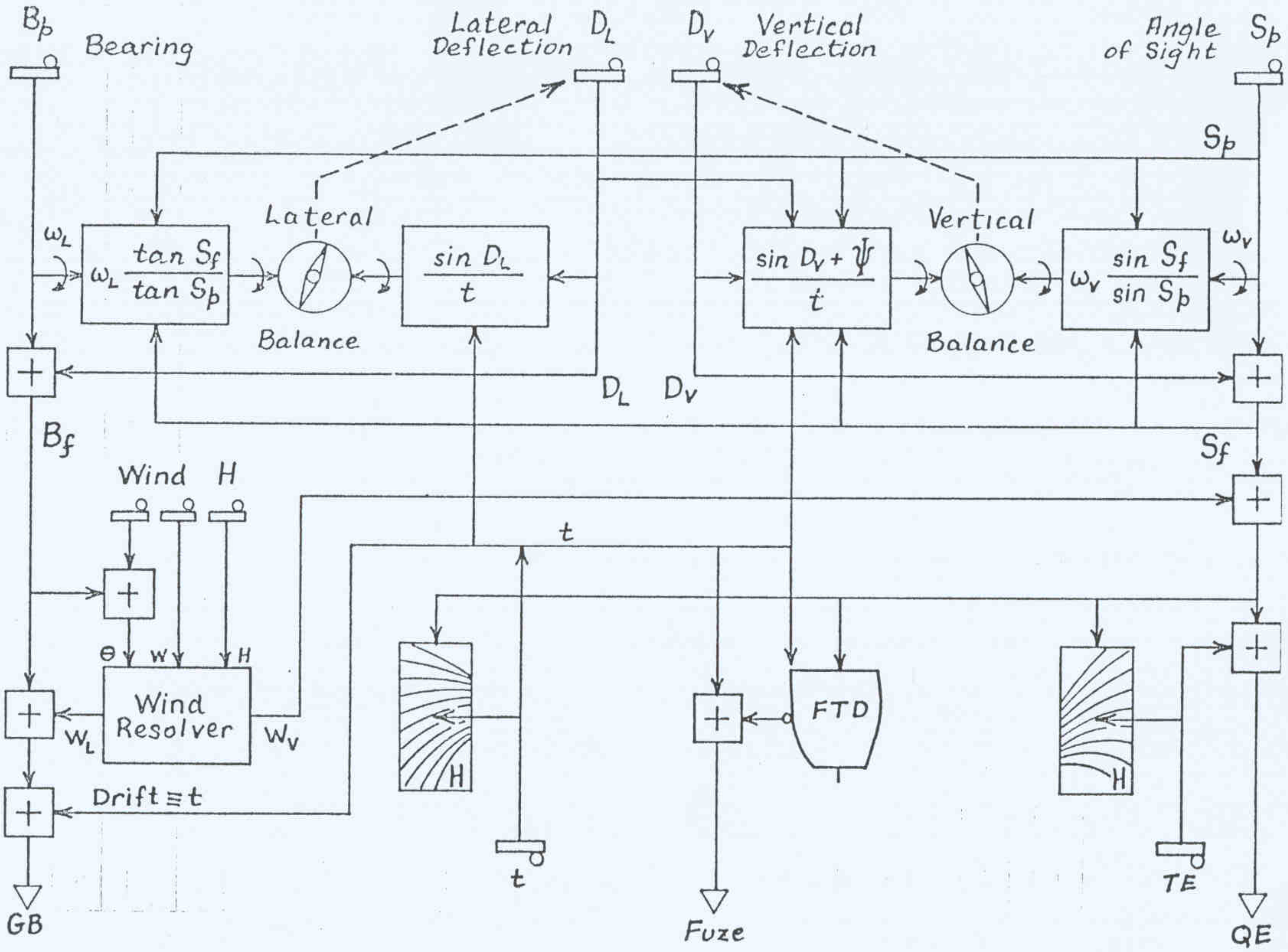
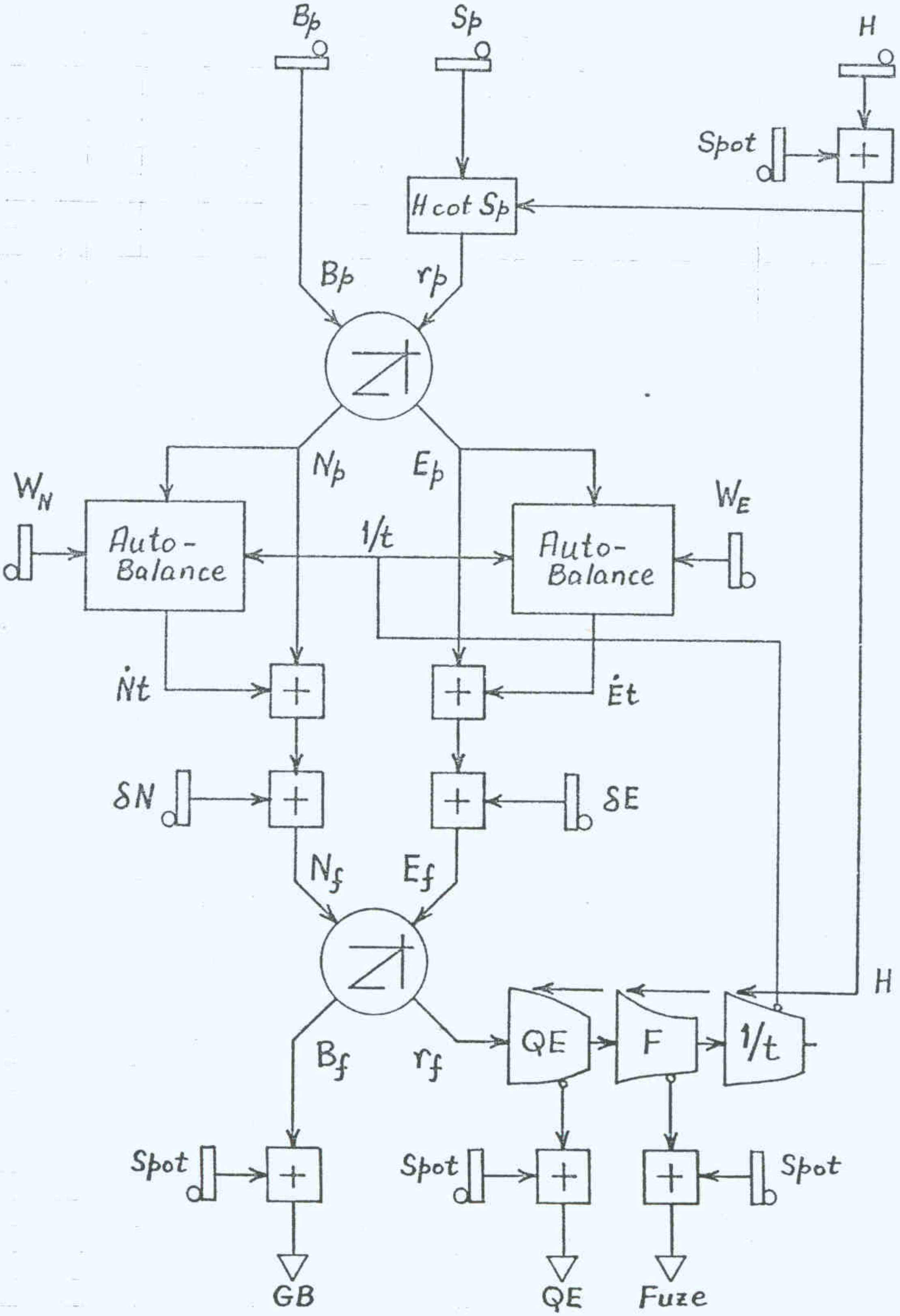

B_p
Bearing
Lateral Deflection
D_L
D_V
Vertical Deflection
Angle of Sight
S_p
S_p
ω_L
$\omega_L \frac{\tan S_f}{\tan S_p}$
Lateral
Balance
$\frac{\sin D_L}{t}$
$\frac{\sin D_V + \Psi}{t}$
Vertical
Balance
$\omega_V \frac{\sin S_f}{\sin S_p}$
ω_V
D_L
D_V
B_f
S_f
Wind
H
Θ
W
H
Wind Resolver
W_L
W_V
t
Drift ≡ t
H
FTD
H
t
TE
GB
Fuze
QE

Figure 14



Bp
Sp
H
Spot
H cot Sp
Bp
rp
Np
Ep
W_N
W_E
Auto-Balance
1/t
Auto-Balance
Ṅt
Ėt
δN
δE
Nf
Ef
H
QE
F
1/t
Bf
rf
Spot
Spot
Spot
GB
QE
Fuze

Figure 15

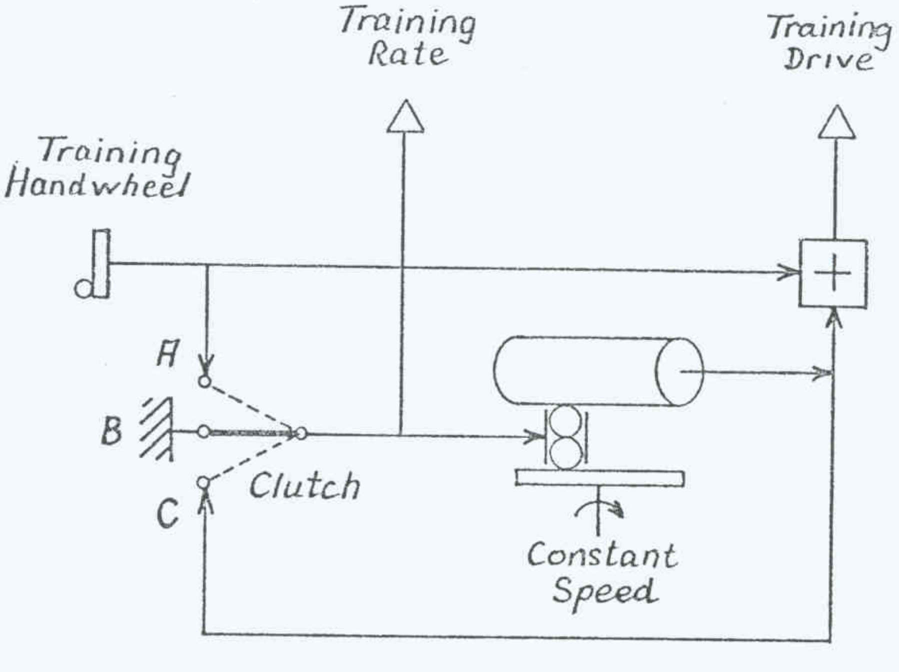

Training Rate
Training Drive
Training Handwheel
A
B
C
Clutch
Constant Speed

Figure 16

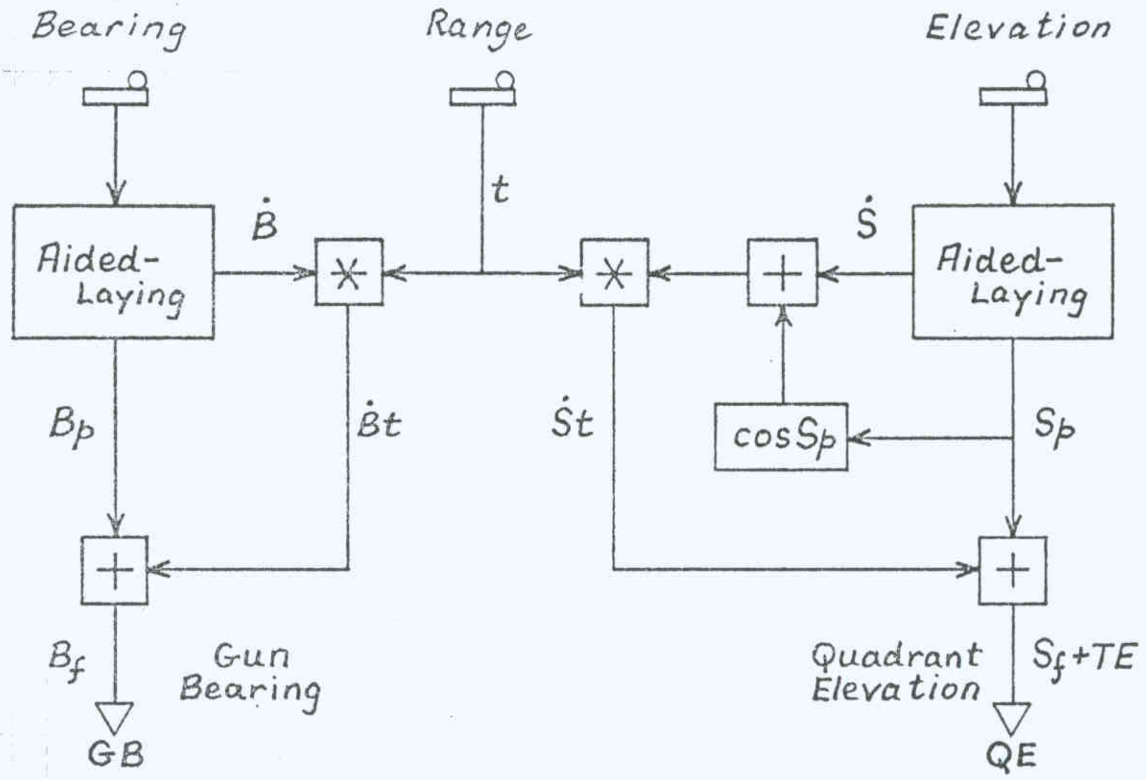
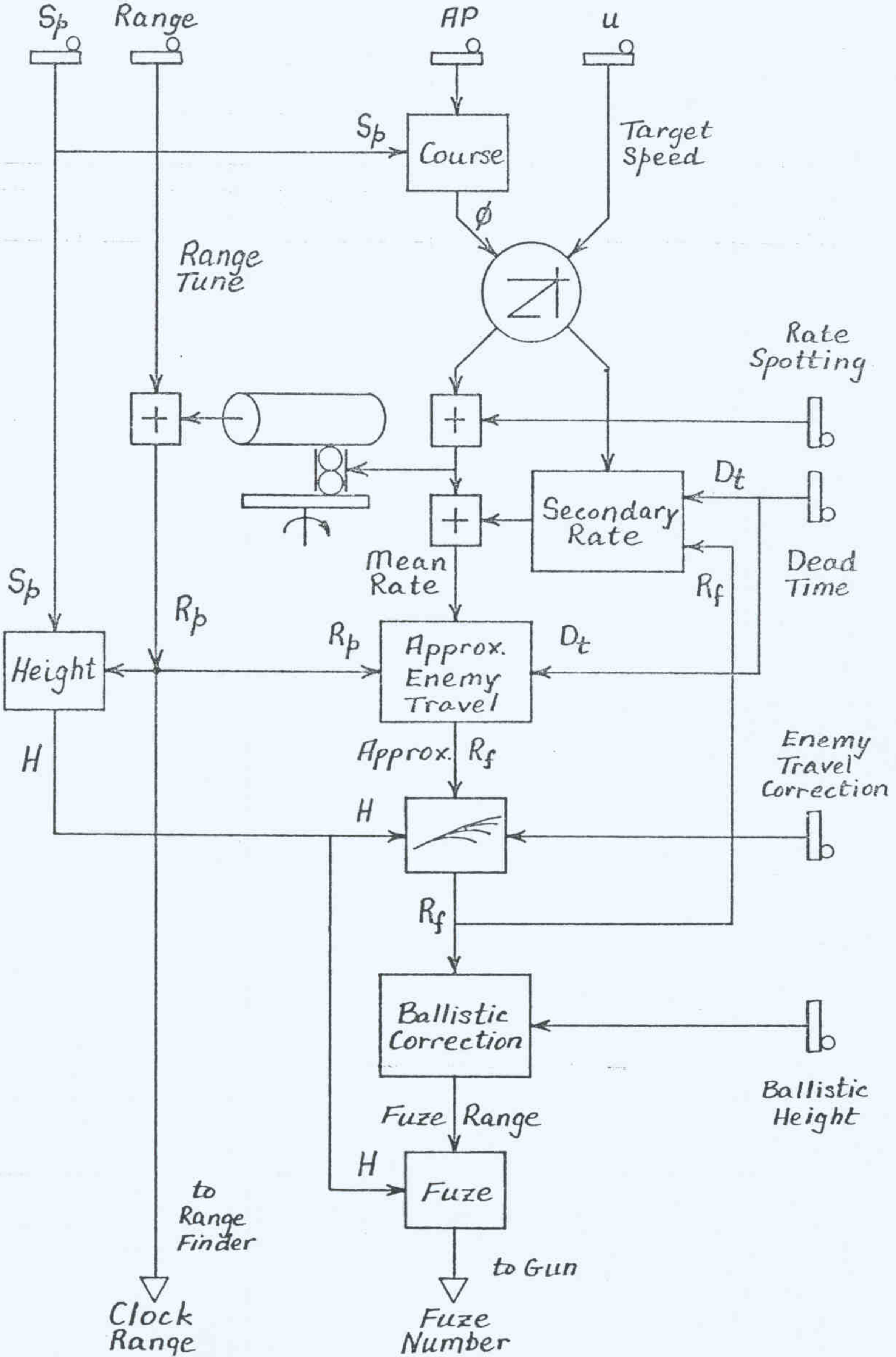
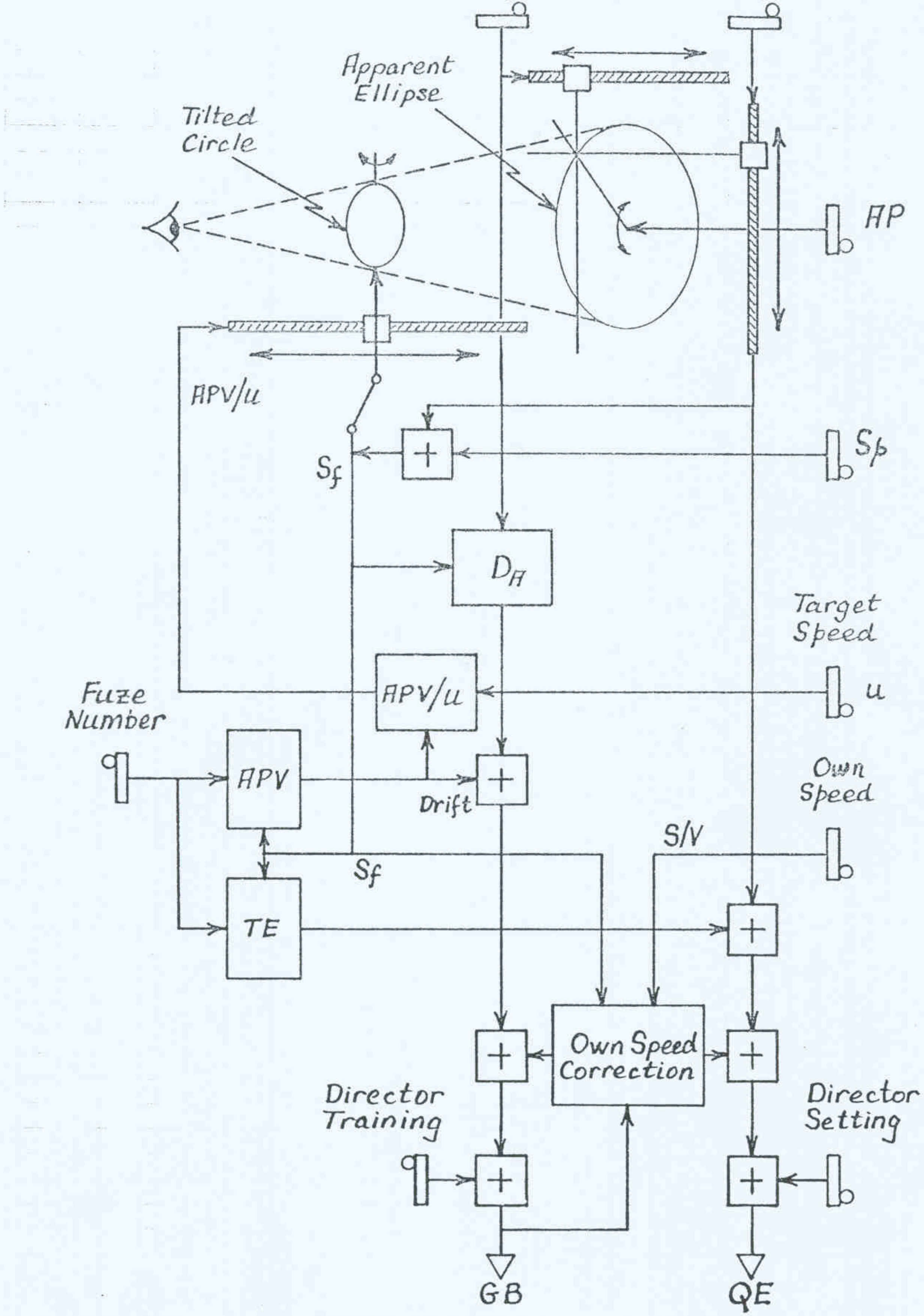

Bearing
Range
Elevation
Aided-Laying
$\dot{B}$
t
$\dot{S}$
Aided-Laying
B_p
$\dot{B}t$
$\dot{S}t$
$\cos S_p$
S_p
B_f
Gun Bearing
Quadrant Elevation
S_f+TE
GB
QE

Figure 17



Sp
Range
AP
u
Sp
Course
Target Speed
ϕ
Range Tune
Rate Spotting
+
+
+
Dt
Secondary Rate
Mean Rate
Dead Time
Rf
Sp
Rp
Rp
Dt
Height
Approx. Enemy Travel
H
Approx. Rf
Enemy Travel Correction
H
Rf
Ballistic Correction
Ballistic Height
Fuze Range
H
Fuze
to Range Finder
to Gun
Clock Range
Fuze Number

Figure 18



D_L
D_V
Apparent Ellipse
Tilted Circle
AP
APV/u
S_p
S_f
D_A
Target Speed
u
APV/u
Fuze Number
APV
Drift
Own Speed
S/V
S_f
TE
Own Speed Correction
Director Training
Director Setting
GB
QE