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AN ELECTRONIC METHOD OF SMOOTHING TARGET DATA (C)

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AN ELECTRONIC METHOD OF SMOOTHING TARGET DATA [C]

INTRODUCTION

The problems involved in the development of the Automatic Aircraft Intercept Control System[1] (AAICS) are of such magnitude and complexity that several years may be required to make the system available to the Fleet. The present rapid development in high-speed military aircraft and high-devastation weapons necessitates an immediate improvement in the methods of intercept aircraft control. An interim system of the semiautomatic, manually aided type has, therefore, been proposed,[2] and considerable effort has been expended upon the development of such a system at NRL.[3]

The purpose of the proposed system is to bring about an improvement of fleet facilities for handling aircraft interceptions at the earliest possible time while causing as little disruption as possible of existing facilities and procedures. In order that the system fulfill its purpose, a primary requirement exists that the design be such as to permit the smooth evolutionary introduction of components now being developed as part of the long-range AAICS program. The gradual introduction of such components will result in improvements in the capacity and accuracy of the system. During this process of evolution the interim system must be fully compatible with AAICS.

PROPOSED INTERIM SYSTEM

The proposed interim system is shown in block diagram form in Figure 1. In brief, the system functions as follows: a stylus mounted above a radar PPI is manually and successively positioned over the targets to be tracked. This stylus is a part of the pick-off unit. Potentiometers, actuated by the movement of the stylus, give voltages proportional to the positions of the targets in rectangular coordinates. The pick-off operator repeats the cycle of target position determinations as often as possible, keeping the target position information in an up-to-date condition. The selector switch, also operated by the pick-off-operator, sends position data of all targets to a servo-operated summary plotting board which automatically displays the successive positions of all targets being tracked. Simultaneously, the selector switch routes the position data of individual targets to manually aided, target-data smoothers known as tracking integrators.

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[1] Riccobono, S., "Automatic Aircraft Intercept Control System Study," NRL Report R3342 (Secret), 30 August 1948

[2] Paine, H. G., "An Electronic Aid for Aircraft Tracking and Interception," NRL Report 3665 (Secret), 27 April 1950

[3] Wedding, P. L., "A Method of Data Pick-Off and Display," NRL Report 3959 (Secret), April 1952

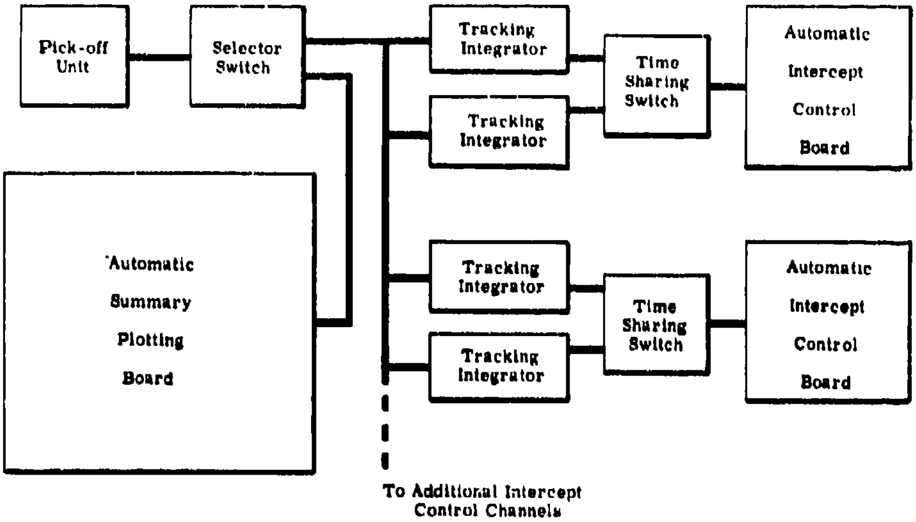

Figure 1 - Block diagram of interim intercept control system

An automatic intercept control board is time-shared between the outputs of two tracking integrators so that smoothed tracks of two aircraft are displayed on a single board. The rate of switching of the board is sufficient to produce two essentially continuous tracks. The selector switch is manipulated in such a manner that the track of a hostile aircraft and that of its assigned interceptor are displayed on the same board. Height data is obtained by separate means and is displayed at the intercept control board. From the data thus displayed, the intercept control officer directs the interceptor. Sufficient numbers of tracking integrators and intercept control boards are provided for the maximum number of interceptions that the pick-off operator can handle. The speed and course of each aircraft is available at the tracking integrators. Data is electrical in form for easy transmission to other parts of the ship or to other ships of a task force. Offset voltages are easily inserted to permit plotting on a common grid, the data originating at other ships.

It is believed that a system of the type described can be made compatible with AAICS in such a manner that units of AAICS may be incorporated into the interim system as they become available. Such a program of gradual conversion will keep fleet facilities in the most advanced state of development possible at every instant of time, and will simultaneously prepare personnel through a gradual process of training for the full utilization of AAICS when it is available. The interim system, or an intermediate form of it, should be of considerable value in smaller fleet units after the advent of full AAICS, since present indications are that AAICS will be restricted to large ships by the amount of equipment required.

DATA SMOOTHING

The meaning of the term "data smoothing" as used in this report is somewhat different from that which is frequently used. Normally, data smoothing means the taking of several target position points and, by least squares or some other mathematical operation, determining the probable track; here, data smoothing means the adjustment of the tracking integrator controls in such a manner that the predicted target track will conform as nearly as possible to the position points determined by the radar. Exactly how this is done will be reserved for a later section.

Smoothing of the position points to produce a smooth track may be referred to as position smoothing. Smoothing as it appears in the interim system more nearly corresponds to velocity and course smoothing in which the position points are used as they come from the radar. Values of speed and course are determined from successive pairs of points and these values are then smoothed to determine the probable speed and course.

Any intercept control system which derives its initial data by means of a conventional radar must employ some method of data smoothing. This is true because of the inherent errors which exist in the data presented by the radar.

As a practical example of the necessity of smoothing target data, consider the problem of determining the azimuth angle of a target at every instant of time. The errors which arise in this problem may be classified as being of three types:

1. Errors which exist in the instantaneous target position as presented by the radar.

2. Errors in the predicted target position between radar scans produced by maneuvering of the target.

3. Errors which appear in the interpretation of the radar presentation.

Errors of the first type[4,5] result from:

a. Radar fading caused by change of aspect of the complex reflective surface presented by an airplane.

b. Modulation of the return signal by propeller rotation in the case of propeller-driven aircraft.

c. The finite time lapse between successive pulses.

d. Destructive interference of waves return from different parts of the complex reflective surface.

e. Atmospheric refraction.

f. Erratic operation of the radar.

For an analysis of the errors, a through f inclusive, the reader is referred to the references given. It is therein shown that although these errors are in general, small in magnitude, they are of sufficient importance to warrant correction when high-speed interceptions at long ranges are made.

[4] Siepian, P., "Searching-While-Tracking Channel," Vol. II, Servo Corporation of America Report 400-R12 (Secret), 15 September 1948

[5] Close, R. N., and Wheeler, R. C., "Theoretical and Experimental Investigation of the Inherent Angular Accuracy Obtainable with Search Type Radar," Airborne Instruments Laboratory Report 363-1 (Confidential), October 1950

The second type of error (due to target maneuverability) may be introduced by intentional maneuvering by the hostile aircraft. A factor producing a similar effect in the predicted track of the interceptor is the inability of the plane-pilot combination to maintain exactly a prescribed course and speed.

Errors of the first and second types are random in nature and their origins are beyond the scope of the control system, since they are produced by factors which cannot be governed or predicted by the control system. Many of these errors may be reduced directly by electronic means, but the final attack must be through some method of data smoothing. The method of data smoothing used in the interim intercept control system to combat these errors is described in this report.

Errors of the third type are the result of imperfections in the control system. It is here that the greatest improvement may be obtained by simple and direct electronic means.

Among the errors of this type which exist in the intercept control system now in use by the Fleet are those which result from: misalignment of the PPI cursor over the target, estimation of the exact center of the pip, reading the compass rose or bearing dial, and plotting the data supplied by the PPI operator. Similar errors exist when a reflection plotter is used with the PPI, and target tracks are plotted directly thereon.

In the proposed interim system, errors in reading dials and in manual plotting are eliminated by the automatic method of plotting. Errors which may occur in placing the stylus over the target return are added in a random manner to the other random errors and are suppressed by the smoothing operation.

A comparison of the smoothing operation in the interim intercept control system with the corresponding operation in the intercept control system now used by the Fleet and with the smoothing operation which may be used in a completely automatic system may be helpful to the reader.

In the interceptor control system now used by the Fleet the intercept control officer must estimate the probable course of the target by visual observation of the unsmoothed track. This is data smoothing as it appears in the present system. He must also estimate the position of the target at times between radar sweeps and during fades, in order to give instructions to the interceptor pilot at the proper times. Simultaneously, with the performance of the two tasks just described, the intercept control officer must determine the proper intercept course and transmit his instructions to the interceptor pilot. These three jobs require that he divert part of his attention from his primary mission of guiding the interceptor pilot to the correct point in space for tally-ho. With the increasing speed of military aircraft, this division of attention becomes a serious weakness of the intercept control system now used by the Fleet. In the interim intercept control system the intercept control officer is assisted in performing the data smoothing and is presented a smoothed, continuous, easily interpreted target track from which to make his intercept course determination.

In a fully automatic system, data from successive radar scans may be stored in electronic storage elements until a sufficient number[6] of data points (6 to 10) have been acquired. These data may then be manipulated automatically to obtain the probable track. Such a system displays an error during and immediately after a maneuver, which increases with the

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[6] Alderson, W. S., Guarino, P. A., and Varela, A. A., "A Study of Computers and Radar for Aircraft Interception Control," NRL Report R-3368 (Secret), 13 October 1948

abruptness of the maneuver. While this error may be small in the case of a slight maneuver, it may be great during a radical turn, and the system cannot again predict an accurate course until six or more data points occurring after completion of the maneuver have been gathered. To make such a system suitably responsive, radar scanning rates much in excess of those at present available to the Fleet must be used. In keeping with the requirement, that the introduction of the interim system cause as little disruption to present facilities as possible, it is necessary that the interim system work with radars available at the present time. It will be seen later in this report that the smoothing process used in the interim intercept control system consists of adjusting speed and course dials to settings where the random errors which appear from point to point seem to balance one another. The successive errors are stored visually as discontinuities in the plotted track and the approximation of the balance condition is done by eye. This method of smoothing and plotting minimizes the errors associated with a maneuver by removing the time lag inherent in the automatic system described.

PURPOSE OF THE TRACKING INTEGRATORS

The tracking integrators serve two major purposes in the interim system. First, they facilitate the performance of the intercept control officer's duties, and second, they open the way for the incorporation of the automatic intercept course computers of AAICS.

The primary contribution which the tracking integrators make to the first of these purposes is the generation of a continuous target track. The low scanning rates of present radars and the frequent occurrence of radar fades make it highly improbable that the radar will present target position data at the moment at which the intercept control officer should issue instructions for the final turn which will bring the interceptor into position for tally-ho. Without continuous track generation, it is necessary for the intercept control officer to estimate this time - a process which may involve considerable error. The accuracy and speed of this determination may be greatly improved by the use of tracking integrators.

In addition, the tracking integrators should assist the intercept control officer in the smoothing operation, particularly in the problem of distinguishing between those deviations from the course which result from the beginning of a maneuver and those which result from random errors in the data.

It is believed that these features will materially assist the intercept control officer; increasing both his speed and accuracy.

Another important reason for the tracking integrators is the possibility which they present of using the intercept course computers of AAICS with the interim system. The course computers require, and the tracking integrators provide, continuous data on target position, speed, and course. These data may be obtained from the tracking integrators in the form needed by the course computers. This combination of equipments would provide an accurate, rapid system of considerably greater capacity than the present system and at a date far in advance of that now anticipated for the completion of AAICS.

The method of data smoothing used in the interim system will be described after a brief introduction to the theory of the tracking integrators and their associated circuits.

BRIEF THEORY OF THE TRACKING INTEGRATORS

The interim system employs target position data in rectangular coordinate form. The target's position is thus represented by a north-south or 'Y' coordinate and an east-west

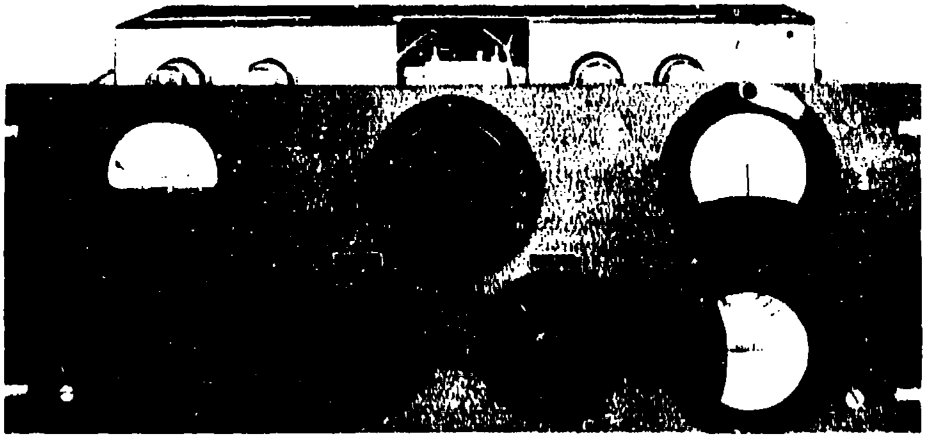

Figure 2 - Early tracking integrator showing control panel

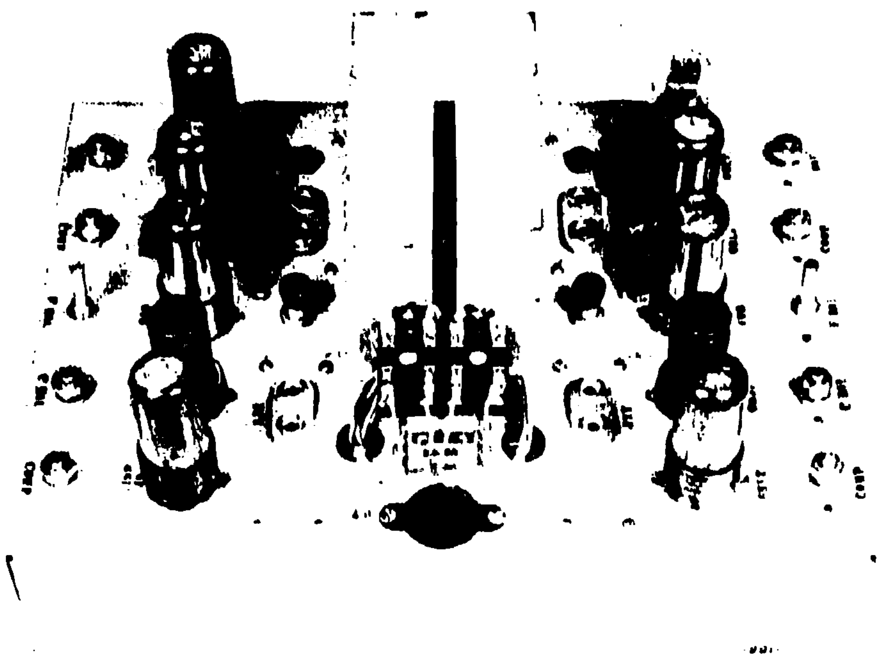

Figure 3 - Computing amplifier chassis

or 'X' coordinate. The two coordinates and their corresponding components of velocity are represented as dc potentials so scaled between positive and negative maximums that both magnitude and direction are given.

An early experimental model of a tracking integrator is shown in Figure 2. The speed and course controls, and meters for indicating altitude and X and Y target coordinates are shown on an experimental control panel. The computing amplifier chassis of a refined model of tracking integrator is shown in Figure 3. The circuitry for both components is contained on a single chassis, and represents the results of research and development in applying electronic integrating amplifiers to this specific problem.

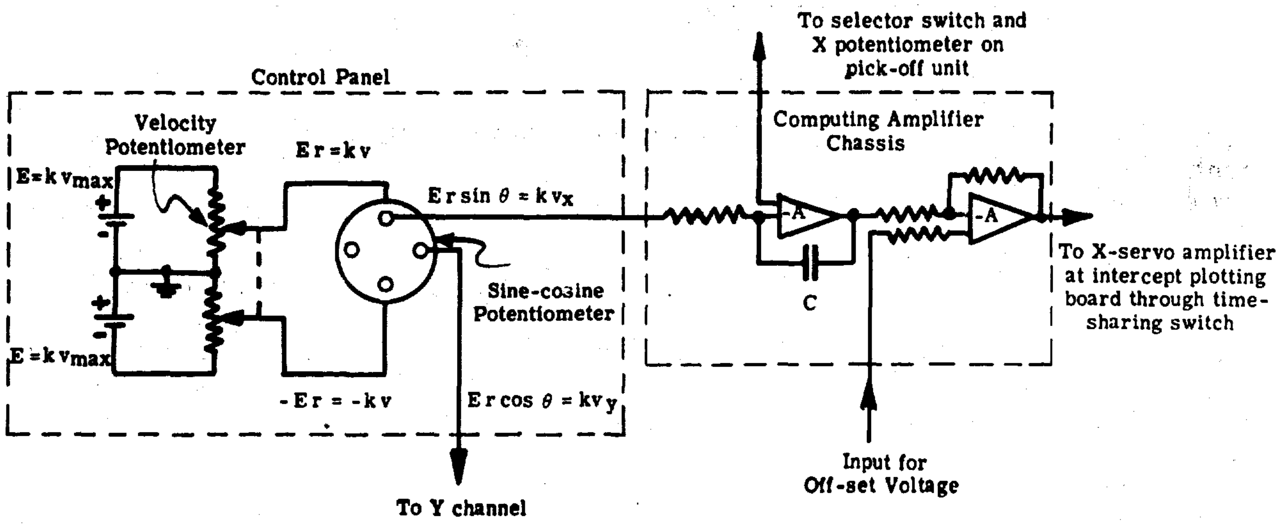

Figure 4 - Simplified tracking integrator schematic

Figure 4 shows the simplified circuit for one component, say X. A voltage E, corresponding to the maximum target velocity which the system is designed to handle, is applied across each section of the velocity potentiometer. The factor k is the constant of proportionality relating voltage to velocity. The sliders on this linear potentiometer may then be adjusted to give voltages $\pm Er$ proportional to any velocity between zero and the maximum. The balanced arrangement of voltages and potentiometers permits targets to be tracked in both the positive and negative directions. Here, r is that fraction of the maximum velocity which is equal to the target velocity. The voltage Er is applied to a sine-cosine potentiometer which gives voltages proportional to the sine or cosine of the angle to which its shaft is set, depending upon which output tap is used. This pair of potentiometers gives voltages proportional to the X and Y components of the target velocity which may be expressed as

$$v_x = Er \sin \theta \tag{1}$$

$$v_y = Er \cos \theta \tag{2}$$

wherein θ is the course angle taken clockwise from north. Integration of the velocity components in the tracking integrators yields X and Y components of position. The instantaneous target position, as defined by these components, is then automatically plotted by the intercept plotting board. If the velocity and sine-cosine potentiometers are properly adjusted to correspond to the speed and course of the target, and if the proper voltages are initially put into the tracking integrators to correspond to the target's position when tracking is begun, the intercept plotting board will produce a continuously lengthening line, the progressing end of which will correspond at every instant to the target's position.

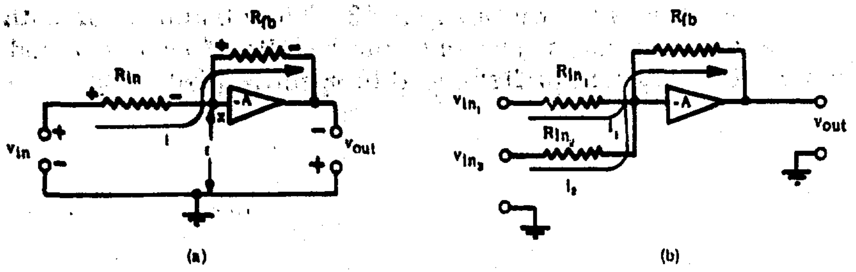

Figure 5 - Sign-changing and summing amplifiers

The computing amplifiers are electronic analog computers which perform the operations of integration, summation, and sign changing. Figure 5a shows the arrangement of a sign-changing amplifier. The triangular-shaped block represents an amplifier of amplification -A. The input resistance, R_{in}, and the feedback resistance, R_{fb}, are considered equal in this case. The amplifier design is such that a negligibly small current flows into the amplifier at point x and the amplification $|A|$ is high (5000 or more). By virtue of the high amplification, only a very small voltage, ϵ, must be applied to the amplifier input terminals to produce any desired output voltage within the useful range of the amplifier (±100 volts). Now, since the same current flows through R_{in} and R_{fb} and since these two resistors are equal in value, the voltage drops across them must be equal, if the small error voltage, ϵ, is neglected. Further, since the potential at point x is considered to be negligibly different from ground potential, the voltage across R_{in} is equal to the voltage applied to the input terminals and the voltage across R_{fb} is equal to the output voltage. The output voltage is, therefore, equal to the input voltage although opposite in sign. The output voltage may be made equal to the negative of the input voltage multiplied by a constant factor, if the ratio of R_{fb} to R_{in} is chosen equal to the desired constant multiplier. Figure 5b shows the connection for adding two or more voltages. Here the individual input voltages cause currents proportional to these voltages to flow through the corresponding input resistors. These currents add together to flow through the resistor R_{fb} and thus produce across R_{fb}, and therefore across the output terminals, a voltage which is equal to the negative of the sum of the input voltages. This feature permits offset voltages to be added to the target position voltages in order to refer the target position to a taskforce center or to any other fixed or moving point.

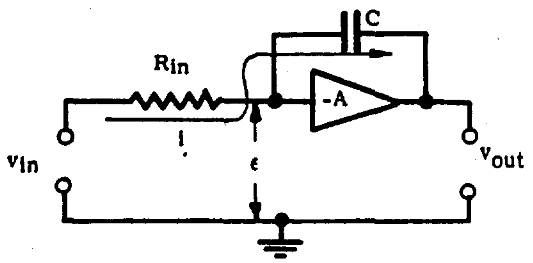

Figure 6 - Integrating amplifier

Figure 6 shows the connection of an integrating amplifier. This circuit may be understood by analogy to the sign-changing amplifier above. Here again the voltage ϵ is negligibly small and the same current which flows through the input resistor R_{in} flows into the condenser C. The voltage across R_{in} is again equal to the input voltage, and the voltage across C is equal to the output voltage. The difference in the two connections lies in the fact that the voltage across C is not proportional to the current as in the case of a resistor, but rather is proportional to the integral of the current. Expressed mathematically

$$v_c = \frac{1}{C} \int_0^t i\,dt. \tag{3}$$

Now, since the current i is equal to the input voltage v_{in} divided by the input resistance R_{in}, Equation (3) may be written

$$v_c = \frac{1}{C}\int_0^t \frac{v_{in}}{R_{in}}\, dt = \frac{1}{C R_{in}}\int_0^t v_{in}\, dt. \quad (4)$$

Therefore,

$$v_{out} = -\frac{1}{C R_{in}}\int_0^t v_{in}\, dt. \quad (5)$$

In words, the output voltage is equal to the integral of the input voltage multiplied by a scaling factor $-1/CR_{in}$. Thus far, nothing has been said about a voltage which may have existed across the condenser at the beginning of the integration process. If such a voltage exists, the integrator will function as before, and the integral of the input voltage will simply be added to the initial condenser voltage. In the tracking integrators this initial voltage is made to represent the position of the target at the time tracking is begun.

DATA SMOOTHING WITH TRACKING INTEGRATORS

Let it be assumed that a raid has been detected and tracked on the summary plotting board for a sufficient time for the evaluator to decide upon a course of action, assign an interceptor, and assign the interception to a particular intercept control officer. An initial estimate of the raid's speed and course may be made from the summary plotting-board track, or may be delayed until the track begins to form on the intercept plotting board. If the initial estimate is delayed, and if the tracking integrator's speed and course circuit is switched off or the speed control set to zero, no integration will take place; and the intercept plotting board will plot only the discrete data points fed into the tracking integrator by the pick-off operator. From the first two or three of these points an initial estimate of the target speed and course may be made. These estimated values are then set on the tracking integrator controls and the integrating process is begun.

A predicted target course will now be generated and plotted. Because of probable errors in the initial course and speed estimates, this predicted course may be in error. Therefore, a new target position determined by the pick-off operator may not coincide with the predicted position. If an error exists when this new target position is obtained, the tracking integrator output will immediately change from the predicted value to the value determined by the pick-off unit, and a discontinuity will appear in the track on the intercept plotting board. This is illustrated in Figure 7a in which the speed and course dials remain uncorrected and the cycle repeats itself.

After the first such cycle appears, the speed and course dials may be corrected as illustrated in Figure 7b. By imagining a circular arc drawn with center at 1, passing through 3, and cutting the predicted course, the proportion by which the speed control setting should be reduced may be estimated. The angle by which the bearing control should be increased is observed from the plot. If further correction of the control settings is necessary, the plot will show the magnitude and direction of correction needed when the next point is determined by the pick-off operator. A target maneuver will produce an effect similar to that described above, the discontinuities in the track showing the corrections which must be applied in order to follow the target through the maneuver. Since the usual two-dimensional maneuver consists only in a change of course, only the course dial must be adjusted during the maneuver. The loss of speed resulting from the turn is quickly regained after the maneuver and the history of speed as stored on the plotting board is still available to the smoothing operator.

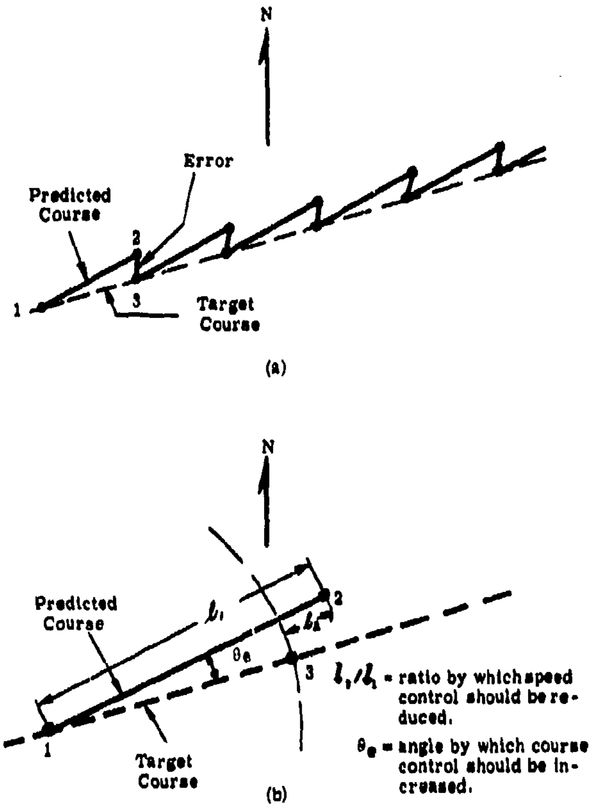

Figure 7 - Plotted tracks with course and speed errors

With experience in performing these operations the operator should develop a high degree of skill in making the initial estimate of speed and course and in making the correct control settings in a minimum number of tries. Experience will also show which track discontinuities are to be corrected and which are due to random errors in the target data.

A different procedure for track smoothing is made possible by using differential metering circuits which show on meter indicators the amount and direction of correction needed. These are simple devices which operate on the output of the tracking integrators and will not be described here.

Determination of the best way of performing some of the functions required in the interim system will probably have to await sufficient experience in operating the entire system. One factor to be determined is where the smoothing should be done. Two possibilities suggest themselves. The intercept control officer might do the smoothing on his own targets by watching the tracks on his intercept plotting board. This, of course, would add to his duties and limit the number of interceptions which he could handle. The other possibility is to locate all tracking integrators in a central panel and have a smoothing operator whose sole duty would be to smooth the tracks for a number of control boards either by watching the control boards or by observing differential error meters. The intercept control officer would then have only to determine the intercept course and might be able to handle two or more interceptions simultaneously.

Another modification of the system which should facilitate the intercept course computation would be to have the data fed to the intercept plotting board based on either the bomber's position or the interceptor's position. In this case one aircraft would always be at the center of the plotting board and the other aircraft's position and track would be shown in relation to this center. The two possibilities are fundamentally the same, the choice between them resting primarily upon psychological factors.

As an example, take the case of bomber-based data. It is well known that if the interceptor flies a course which maintains the bomber's relative bearing constant a collision will occur. Let a transparent cursor be pivoted at the center of the board and rotated to cross the interceptor's position at the beginning of the interception. The cursor is locked in this position. The intercept control officer then manipulates the interceptor's course and speed controls to keep the interceptor position under the cursor, relaying the necessary data to the pilot whenever a change is made in the controls. With experience, the intercept control officer will learn to compensate for the time lag which exists between his manipulation of the controls and the interceptor's response. An automatic data-relay link with the interceptor would reduce this time lag and tighten the control loop. Offsets could be applied to the bomber's position to make the plot center represent the point for beginning a final turn rather than the bomber's position.

The two methods of data smoothing mentioned previously are still possible. The second method involves a separate smoothing operator to smooth data for several intercept plotting boards. For the first method, let a switch be provided to change the plotting board from the conventional two-track plot to the bomber-base plot. At intervals the board could be switched to the two-track type of plot to allow the intercept control officer to check the integrator control settings. Alternatively, the two-track plot could be used exclusively until late in the interception; then the board could be switched to the bomber-based plot for the final phase, in which greater accuracy and speed are required.

The equipment is sufficiently flexible to permit easy adaptation to any of the forms described. Actual operation of the complete system under realistic conditions will be necessary to determine its proper final form. This form must provide optimum utilization of both the equipment and its human operators.

SOME CONSIDERATIONS IN THE DESIGN OF TRACKING INTEGRATORS

The fundamental theory upon which the tracking integrators are based has been well presented,[7,8] and will not be repeated here other than the simple discussion already given. Certain additional relations which are of particular interest in the application considered in this report will, however, be developed.

Drift

As in all dc amplifier applications, one of the chief causes of concern in the design of the tracking integrators is the problem of drift, a more or less slow change in the amplifier output due to causes within the amplifier. The phenomenon results from the direct conductive coupling existing between stages of the amplifier, which permits the operating conditions of one stage to be influenced by variations in the preceding stage. Changes in the resistance values of resistors with aging and temperature, aging of tubes, and changes in cathode emission are among the contributing factors. Change in cathode emission is the most important single factor producing short-term drift. Over short periods of time this is of a somewhat random nature; over longer periods a downward trend is noticeable. Another important source of drift, which, however, is not directly attributable to the amplifier itself, is due to changes in heater temperature resulting from changes in the heater voltage supply. All of these effects are most serious when occurring in the first stages of the amplifier, since the large gain then existing in the later stages causes a large amplification of the drift. For this reason the first stage of the amplifier receives the greatest attention. If the first stage can be madedrift-free and can also be made to have a large gain, drift occurring in the later stages will be negligible in magnitude when compared to the useful signal output.

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[7] Ragazzini, J. R., Randall, R. L., and Russell, F. A., "Analysis of Problems in Dynamics by Electronic Circuits," I.R.E., Proc. 35, 444-452, May 1947

[8] Hagelbarger, D. W., Howe, C. E., and Howe, R. M., "Investigation of the Utility of an Electronic Analog Computer in Engineering Problems," Engineering Research Institute, University of Michigan, External Memorandum No. 28, 1 April 1949

Probably any attack upon the drift problem must eventually come to the use of an electronic compensation device[9] which samples the error due to drift, converts it to an ac voltage, amplifies it by means of a stable high gain ac amplifier, and after rectification reinserts the amplified result into the dc amplifier in such a manner as to compensate the error. A high degree of stabilization may be obtained in this manner. However, it is anticipated that a sufficient degree of stabilization for the present purpose may be obtained through less drastic measures.

It has been shown[10] that most of the drift due to the aging of tubes usually occurs during the first hundred hours of operation. The type 6SL7 tubes used in the first stages of the integrating and sign-changing amplifiers of the tracking integrators (see schematic, Figure 8) were accordingly aged 100 hours prior to use in the amplifier.

A number of methods are available for reducing the effects of heater voltage change.[11] The method used in the tracking integrator is illustrated in Figure 9. Figure 9a shows the circuit in a form for describing its operation while the final circuit is given in Figure 9b. It can be shown that a change in heater voltage is equivalent in effect to a small ideal voltage generator inserted in series with the cathode. In Figure 9a, let this equivalent generator be represented by the voltage e. Then

$$\Delta v_1 = -e + (\Delta i_1 + \Delta i_2) R_1 \qquad (6)$$

$$\Delta v_2 = (\Delta i_1 + \Delta i_2) R_2 \, . \qquad (7)$$

If the input signal is zero,

$$\Delta i_1 = -gm_1 (\Delta v_1 + \Delta v_2) \qquad (8)$$

$$\Delta i_2 = -gm_2 \, \Delta v_1 \qquad (9)$$

where gm is the transconductance of the tube. By eliminating the incremental currents in (6) and (7), adding the resulting equations and rearranging the result

$$\Delta v_1 + \Delta v_2 = \frac{\Delta v_1 - gm_2 \Delta v_1 R_2}{1 + gm_1 R_2} \, . \qquad (10)$$

If R_2 is made equal to $1/gm_2$, this reduces to

$$\Delta v_1 + \Delta v_2 = 0 \qquad (11)$$

and the effect of the heater voltage change is cancelled.

It is possible to bring about the required condition ($R_2 = 1/gm_2$) by varying R_2 or by varying gm_2 by any of several means. The present system was chosen because it permits a wide variation of gm_2 with only a small change in the quiescent value of the plate voltage of T_1. As the 5-K potentiometer (Figure 9b) is reduced in value, the increase in total

[9] Goldberg, E. A., "Stabilization of Wide-Band DC Amplifiers for Zero and Gain," RCA Review, 11, pp. 296-300, June 1950

[10] Valley, G. E., and Wallman, H., "Vacuum Tube Amplifiers," Appendix C, New York, McGraw-Hill, 1948

[11] Ibid, Section 11-12

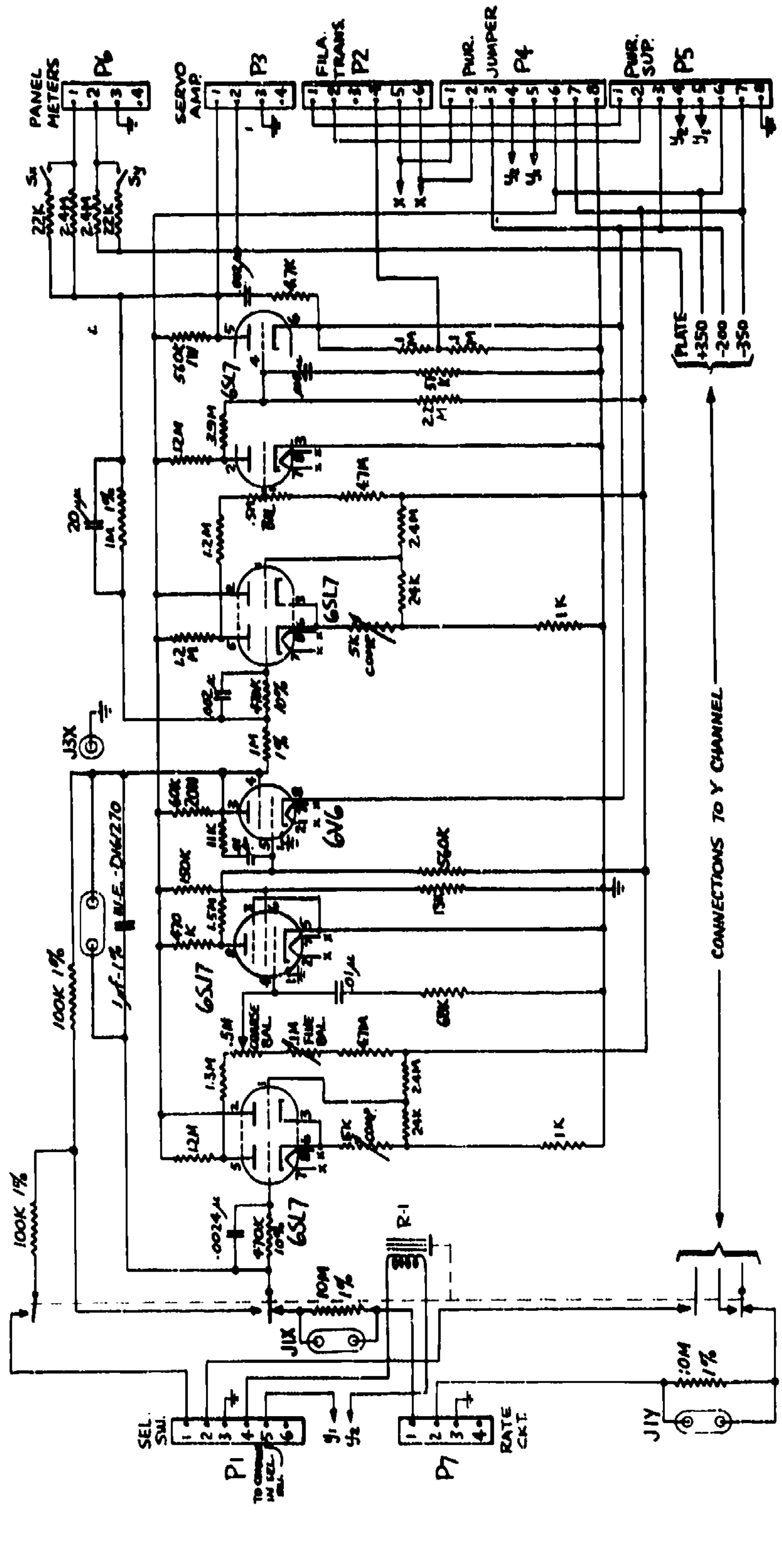


Figure 8 - Computing amplifier

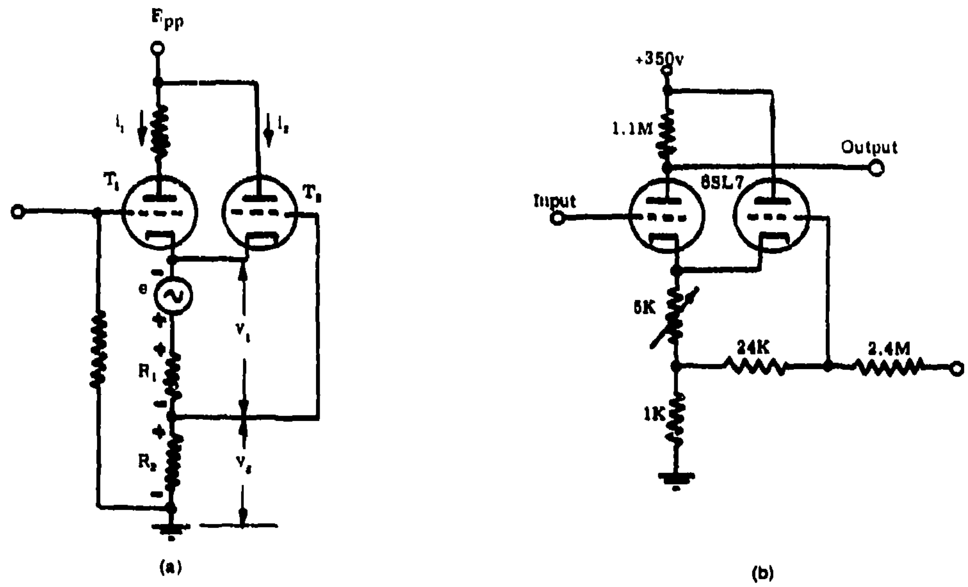
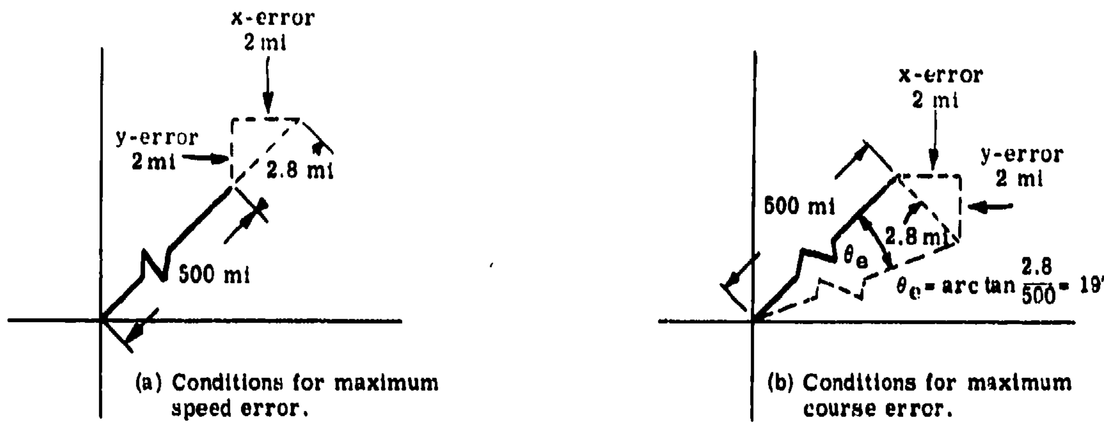


Figure 9 - Circuit for compensating for the effects of heater voltage change

current tends to keep the cathode voltage of T_1 constant. Actually, the cathode voltage passes through a minimum and causes the plate voltage of T_1 to pass through a maximum. This folded effect limits the total excursion of the plate voltage of T_1 to 20 or 25 volts and reduces the requirement on the balancing controls.

Plate current - grid voltage characteristics of the 6SL7 show that for a plate voltage of 350 volts the range of possible transconductance is covered by bias voltages between -3.5 volts and -6.0 volts. The 24 K - 2.4 megohm divider provides the -3.5-volt minimum bias for the second section and the 5 K-potentiometer is capable of increasing the total bias to -6 volts. R_2 is made 1000 ohms which requires a value of 1000 microhms for gm_2. This value of transconductance occurs at a bias voltage of approximately 4.5 volts.

Of the applications of dc amplifiers considered in this report, that in the integrating circuit is most seriously affected by drift since in this case the error accumulates because of the integrating action. By the use of the methods discussed above, it has been found possible to build tracking integrators having an integrated drift of less than 1 volt per hour under normal operating conditions. This represents an actual unbalance voltage of less than 0.0028 volts referred to the input terminals. If the figure of one volt drift per hour is taken as a maximum, the maximum values of speed and angular error may be computed. A scale factor of 0.5 volt per mile is used at present in the interim system. For a plane flying at 500 miles per hour, the plotted course would go through a voltage range of 250 volts if continued for one hour. Both errors are greatest when the course is at 45° to one of the coordinate axes. To be specific, assume a plane flying in the northeast direction (see Figure 10). The maximum speed error will then occur if both the x and y integrators drift either in the positive direction or in the negative direction. The accumulated X and Y errors will each be one volt or 2 miles. The total position error accumulated in an hour will then be $2\sqrt{2} = 2.8$ miles and the speed error will be 2.8 miles



(a) Conditions for maximum speed error.

(b) Conditions for maximum course error.

Figure 10 - Determination of speed and coarse errors

per hour. The maximum course error will occur if the x and y integrators drift in opposite directions. The maximum course error is given by

$$\theta_e = \text{arc tan}\,\frac{2.8}{500} = 19 \text{ angular minutes.}$$

These errors are small in magnitude and their effect is suppressed by the fact that a correction for them, as a result of the closed-loop nature of the system, occurs, as a hidden part, in the instructions which the intercept control officer gives to the interceptor pilot in the latter phases of the interception.

Amplifier Gain and Integrating Capacitance Leakage

It is interesting to determine the influence of amplifier gain and of a high-resistance leakage path shunting the integrating capacitance upon the operation of the integrator. Figure 11a shows the integrating circuit wherein r is a leakage resistance and R_o is the output load resistance. The amplifier input voltage, ϵ, is

$$\epsilon = i_1 R \tag{12}$$

and the output voltage is

$$v_o = -i_1 RA. \tag{13}$$

This output voltage is equal to the voltage which would result from the current i_1 flowing through an equivalent resistance RA. Combining this resistance with the input resistance, R, the equivalent circuit becomes as shown in Figure 11b, since the amplifier output impedance is negligibly small owing to the high gain and large voltage feed-back ratio. From this equivalent circuit, it may be seen that the time constant (tc) of the discharge of C is

$$tc = \frac{(1 + A)R\,r}{(1 + A)R + r}\,C. \tag{14}$$

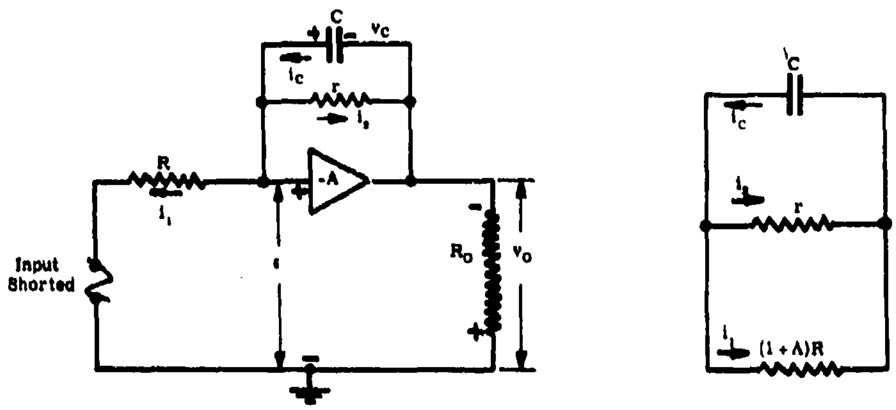


Figure 11 - Discharge paths in the integrating amplifier

If A>>1,

$$tc = \frac{ARr}{AR + r} C. \qquad (15)$$

When r in Equation 15 is allowed to approach infinity, the time constant becomes, in the limit,

$$tc = ARC \qquad (16)$$

from which it is seen that the amplifier increases the time constant for discharge by a factor approximately equal to its gain when leakage is absent.

Leakage between the contacts of the relay presents a troublesome problem. A leakage path between contacts a and b, a and d, or a and f, Figure 12, results in a resistance directly across the condenser terminals. Also, since contact e is permanently connected to the pick-off unit voltage, a leakage resistance between contacts e and d, e and f, or e and b causes a current to flow in the 10-megohm input resistor. This current produces a voltage which is integrated and results in an output error. The resistance required between these points is greater than can be easily maintained in service. On the other hand, the minimum resistance required between any of the relay contacts and ground may be readily maintained.

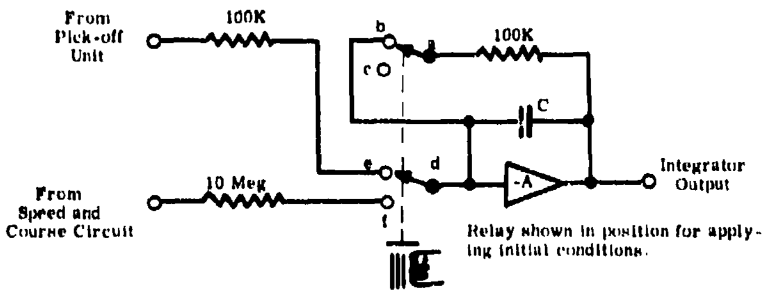


Figure 12 - Method of applying initial conditions

The solution to the problem, therefore, is to construct the relay in such a manner that there are no direct leakage paths between the critical contacts. This may be done by supporting the contacts on separate pieces of insulation. A relay having stacked contact construction may be modified by placing two pieces of insulation between each pair of critical contacts, with grounded metal strips between the pieces of insulation. The relay shown in Figure 3 is not of the construction described. This relay will be replaced. The principle just described should be applied to critical portions of the circuit wiring as well as to the relay.

To appreciate the importance of a large value for r, let it be assumed that the integrator is required to store a voltage of 100 volts for one hour with a maximum error, due to discharge of the capacitance, of 2 volts. This corresponds to a maximum bearing error of approximately 0.6 degree.

Let $A = 20{,}000$; $R = 10$ megohms; $C = 1\mu f$.

If the discharge curve is approximated by a straight line, the requirement stated in the previous paragraph calls for a time constant of 3000 minutes. Inserting these values in (15) yields a value for r of 1,800,000 megohms. Thus, it is seen that the integrating condenser must be of the highest quality and that extreme caution must be exercised in the use of insulation in all possible shunting paths. The jack shown shunting the condenser in the schematic diagram (Figure 8) is desirable to permit shorting the condenser during the adjustment procedure. National FWJ jacks have been found satisfactory here, after trouble had been experienced with lower quality phenolic insulation and fibre washers. The integrating condensers used are Western Electric D161270. These condensers have polystyrene dielectric and insulation. Checks on the leakage resistance existing in completed tracking-integrator units have shown a resistance well in excess of 50,000 megohms, which was the highest calibrated point of the available megohm meter. Indirect measurements of r by measuring the rate of discharge of a stored voltage have given values considerably in excess of the requirement.

Data Insertion

The method chosen to insert data from the pick-off unit may result in inaccuracy of the integrated output if due precautions are not observed. In the original model of the tracking integrator new data was put into the integrator simply by momentarily paralleling the potentiometers on the pick-off unit with the integrating condensers of the tracking integrator. The condenser voltage then quickly changed to the new value (when there was a tracking error) and integration was resumed when the switch was released. However, connecting the potentiometer directly across the condenser in this manner produced a transient in the integrator output with a corresponding jag in the plotted track. In addition, unless the two poles of the switch opened at exactly the same time the unbalanced condition imposed upon the circuit resulted in extraneous voltages which were integrated for the length of time that the unbalance existed. Since a very small voltage applied to the first grid of the amplifier may be large compared to the error voltage, ϵ, this extraneous voltage may produce the effect of integration of an extremely large input voltage, and the integrator will thus be left in error at the end of the switching operation.

The method of data insertion used in the present integrators is illustrated in Figure 12. The relay is shown in the position for inserting new position voltages from the pick-off unit. If the condenser were not present, the circuit would be a simple sign-changing amplifier in which the output would change immediately to the applied input voltage. The presence of the condenser in the circuit causes the output to change exponentially to the input value with a time constant of 0.1 second. The relay contacts are adjusted to make contact a operate a short time before contact d. This prevents discharge of the condenser through the 100-K resistor. Integration of the pick-off voltage occurs during this time but the relay operation is sufficiently rapid to make its effect insignificant. In order that the time constant involved in the charging of the integrating condenser be small, it is necessary that the associated resistors be small. The integrating amplifier must, therefore, be capable of supplying a larger load current than is required of the sign-changing amplifier. This is the reason for the power tube in the output stage of the integrating amplifier.

Miscellaneous Considerations

Means must be provided for balancing the dc amplifiers used in the tracking integrators. Balancing consists of adjusting the circuit to give a zero output voltage with zero input. The balancing method used should permit reducing the unbalanced output to a value small compared to other system errors. Because of its integrating action, the integrating amplifier must be capable of a very close balance. Convenient plugs and metering circuits are provided to expedite balancing of the tracking integrators. Some experimental evidence has indicated the desirability of making a final balance adjustment of the over-all system.

In Figure 4, the voltage E is determined by the plotting scale factor and the multiplying constant, $1/R_{in}C$ (Equation 4), of the integrator. In order to make the noise voltage resulting from rotation of the speed and course potentiometers small compared to E, the integrator multiplying constant has been made 1/10 and E increased by a factor of ten. The voltage E is obtained from dry cells and series dropping-resistors. As an example, for a system designed for a maximum speed of 750 miles per hour, with a plotting scale factor of 0.5 volt per mile:

$$0.5 \times 750 = 0.1\,E \times 3600 \qquad (17)$$
$$E = 1.042 \text{ volts.}$$

The power supplies used with the tracking integrators must be well filtered and regulated. The supplies developed for the present tracking integrators supply voltages of +350, -350, and -200; have less than 0.01 volt peak-to-peak ripple; and have regulation of 0.1 percent for a 20-percent change in line voltage, and 0.05 percent for a 50-percent change in load current.

SUMMARY

Available evidence indicates that a marked improvement in air defense can be made by the incorporation of the interim system. This improvement is brought about by eliminating many of the manual steps now necessary and by revising the remaining functions to easier, more accurate, and more rapid forms. Interceptor control may thus be given greater reliability and a considerably increased capacity.

A detailed description of the over-all system is given in the previously referenced report, "A Method of Data Pick-Off and Display."[12]

Most of the units, with the exception of the intercept control boards, have been constructed in somewhat refined experimental forms and tested individually. One intercept control board

[12] Wedding, P. L., loc. cit.

is sufficiently complete to permit determination of many of its characteristics. Since the intercept control boards are essentially reduced size replicas of the summary board, many of their characteristics are known. Operational and simulated tests of a partial system not including the tracking integrators or intercept control boards have been conducted. Eighteen tracking integrators and their power supplies are nearly complete. Construction of additional intercept control boards will be pushed as soon as needed materials become available. Tests of a complete system are planned at an early date. These tests must await final assembly of all units and a period of experimentation to effect the inevitable revisions and modifications.

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Naval Research Laboratory. Report 3968.
AN ELECTRONIC METHOD OF SMOOTHING TARGET DATA, by G. C. Winston. 19 pp. & figs., April 16, 1952.

A brief introductory description of a previously proposed interim intercept control system to precede the Automatic Aircraft Intercept Control System (AAICS) is given, together with a discussion of some of the requirements for such a system. It is endeavored to show wherein the proposed system can effect a material improvement over the present method of interceptor control at a date considerably in advance of the completion of AAICS. The effectiveness of the interim system may be improved by the inclusion of components

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1. Aircraft intercept control systems - Design
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