Aug. 9, 1949. B. M. OLIVER 2,478,778

VARIABLE DELAY MEANS

Filed Aug. 1, 1944 7 Sheets-Sheet 1

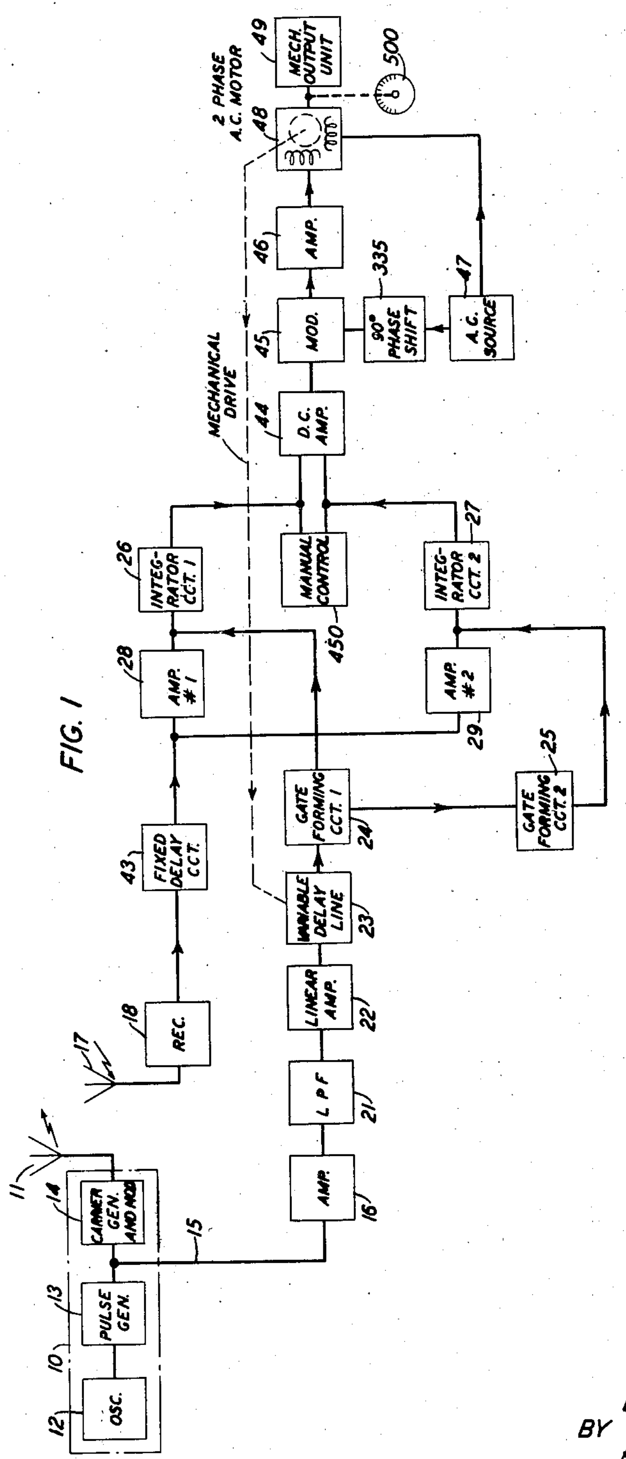

FIG. 1

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VARIABLE DELAY MEANS

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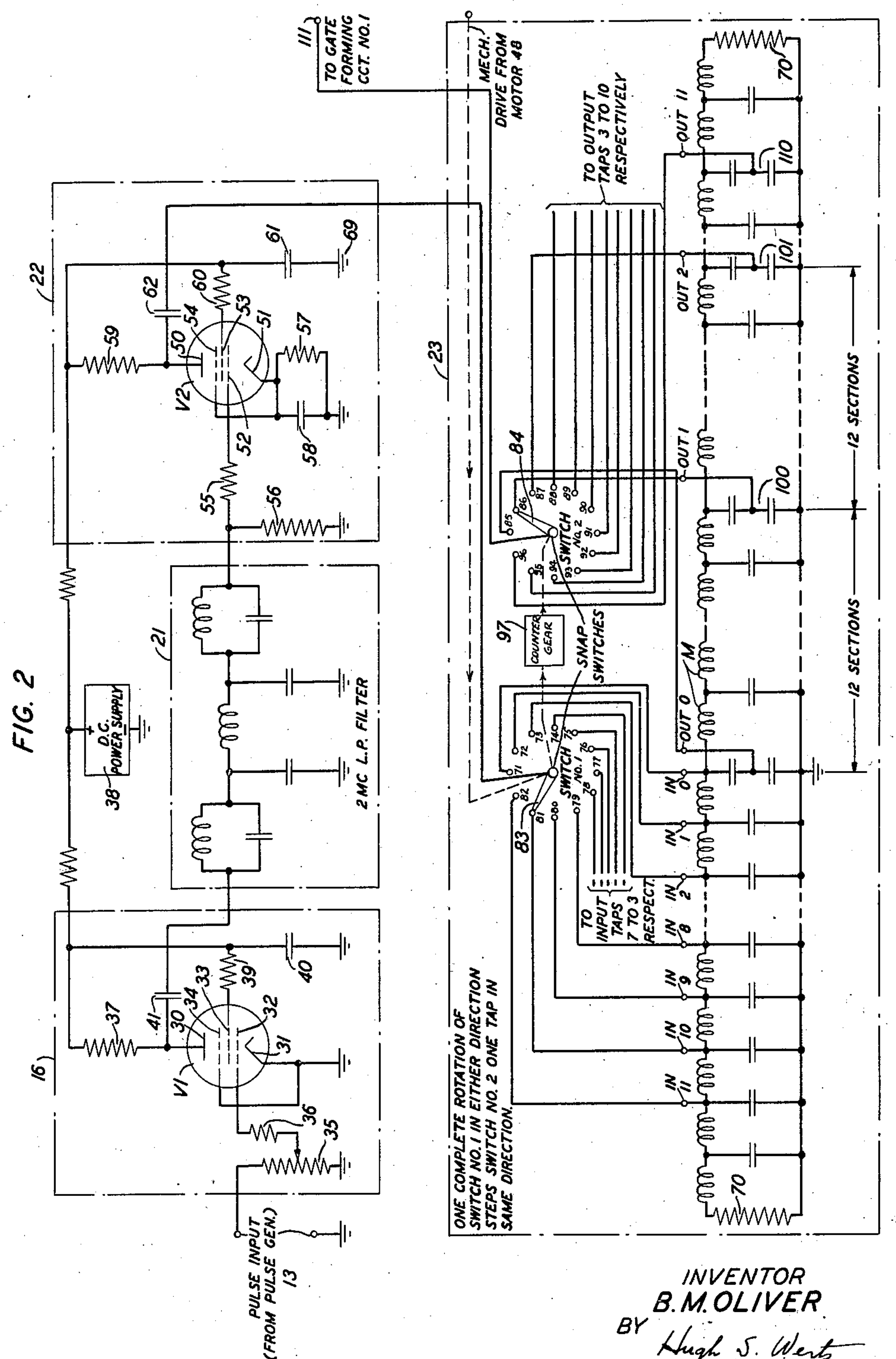

FIG. 2

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VARIABLE DELAY MEANS

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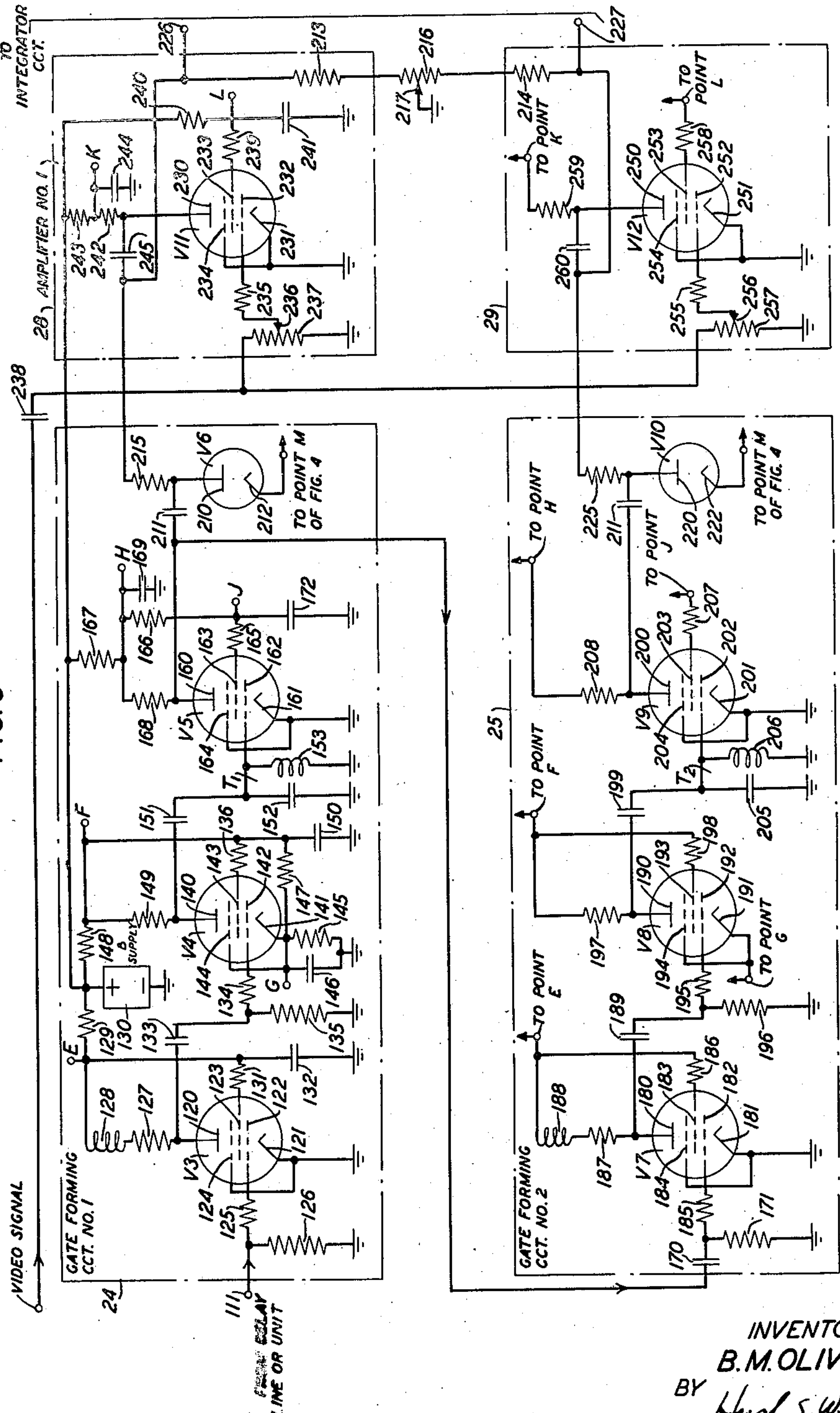
FIG. 3



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VARIABLE DELAY MEANS

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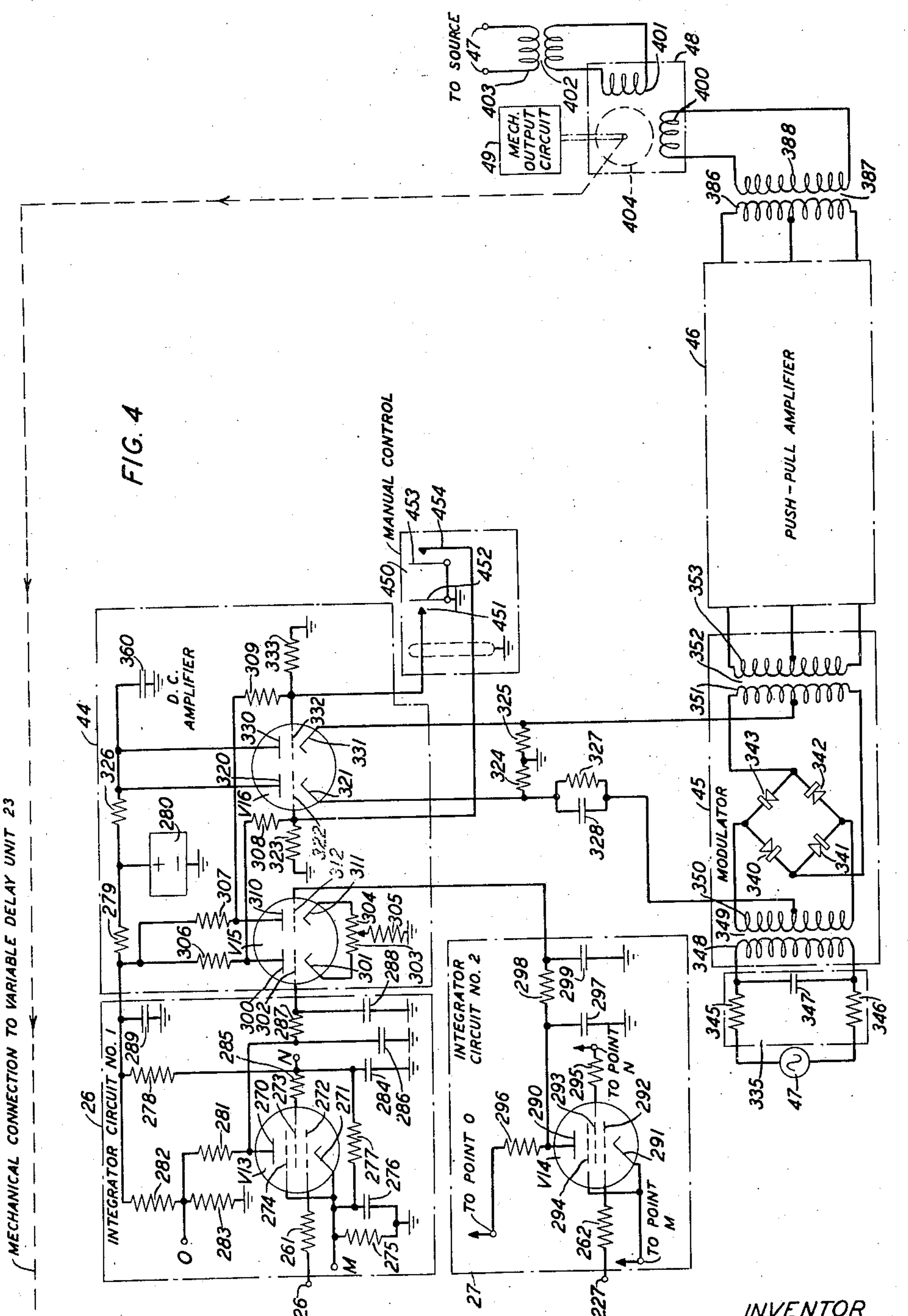

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VARIABLE DELAY MEANS

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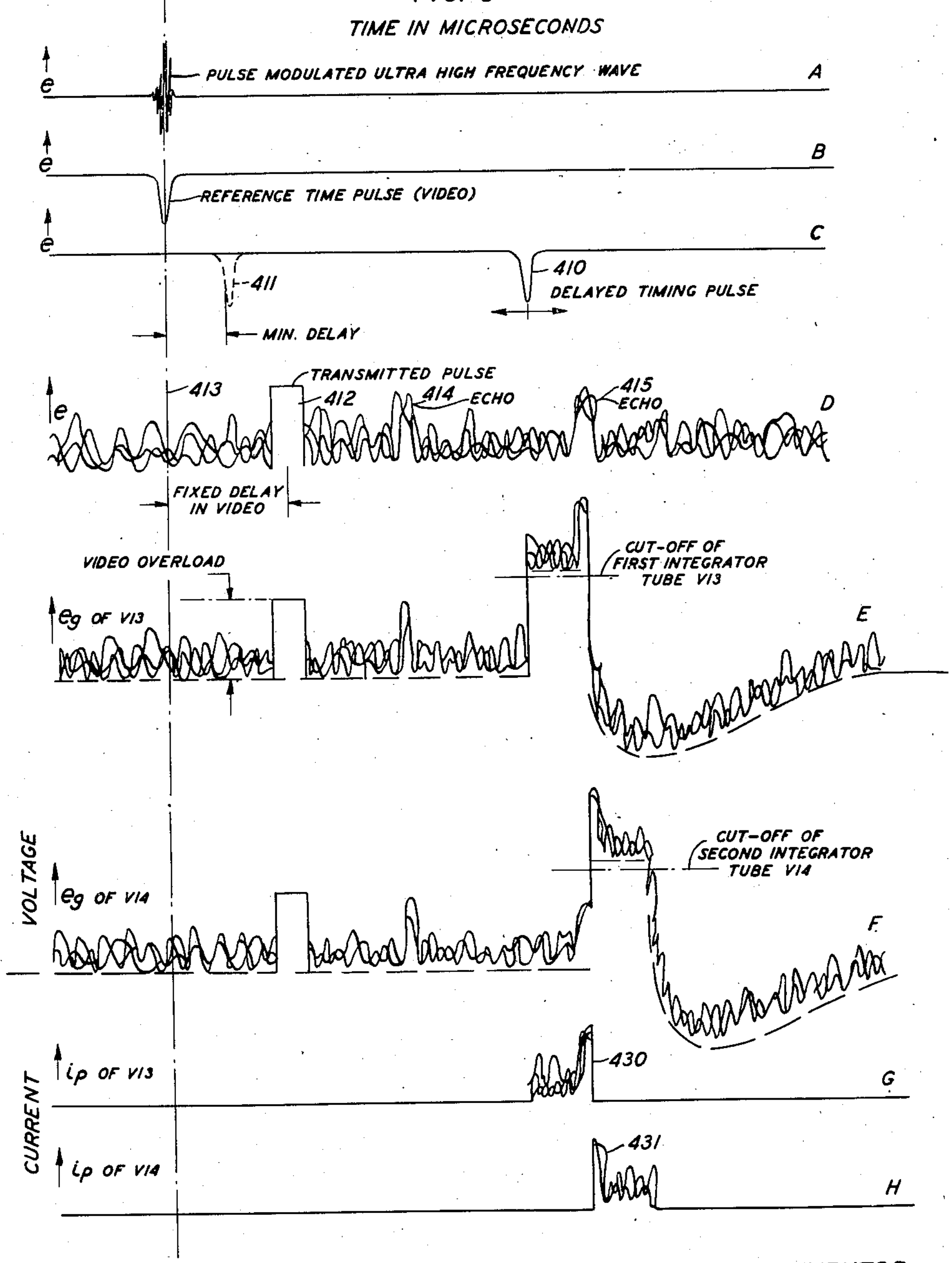
FIG. 5



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VARIABLE DELAY MEANS

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FIG. 6

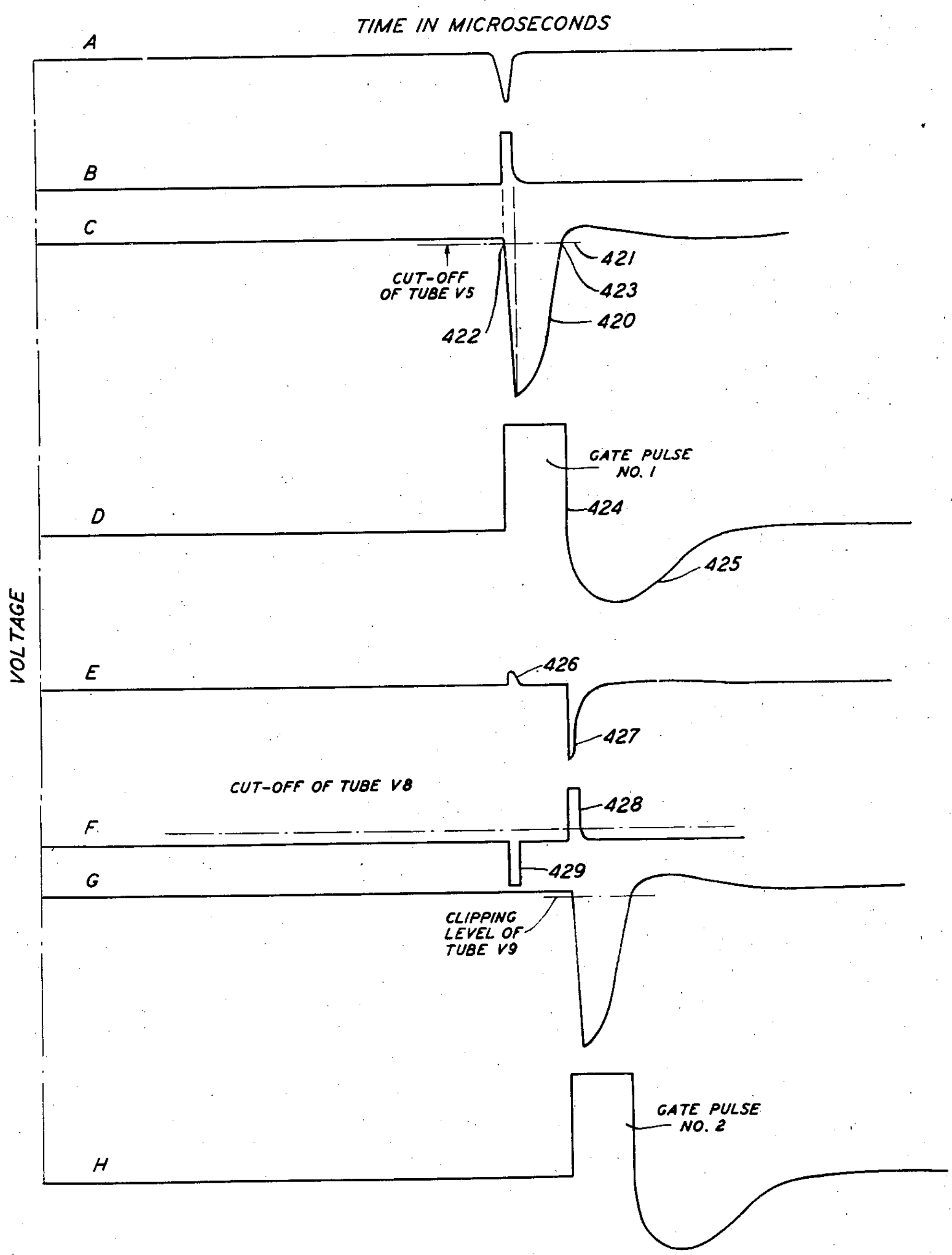

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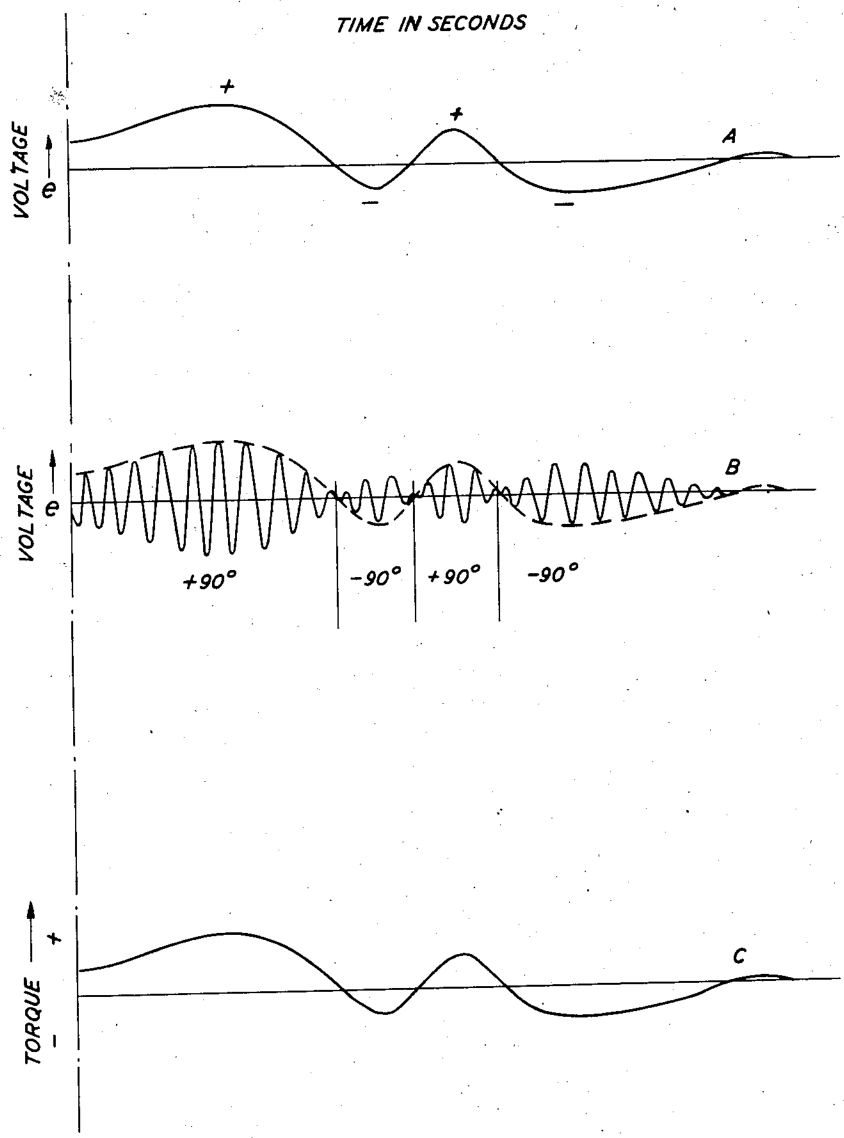
FIG. 7



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Patented Aug. 9, 1949

2,478,778

UNITED STATES PATENT OFFICE

2,478,778

VARIABLE DELAY MEANS

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Application August 1, 1944, Serial No. 547,573

5 Claims. (Cl. 178—44)

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This invention relates to electric transmission and more specifically to delay means for electric waves which is suitable for delaying pulse trains. This application is a continuation-in-part of application Serial No. 491,829, filed June 22, 1943.

It is an object of this invention to provide novel electric circuits adapted to variably transmit pulses or other wave forms.

It is another object of this invention to provide a novel variable transmission line adapted for rapid adjustment.

It is still another object of this invention to provide a novel variable delay line or unit which is suitable for use in radio object locating and distance measuring systems.

It is a further object of this invention to provide a novel transmission line having a variable delay but which has a substantially flat attenuation versus delay characteristic.

While the delay line or unit of this invention will be shown and described in connection with a radio object locating and distance measuring system (frequently called a "radar" system) of the automatic range tracking type, it will be apparent from the description that this line or unit can be used wherever it is desired to delay a wave by different amounts at different times.

In accordance with an illustrative embodiment of the invention, there is provided a variable delay transmission line comprising a number of sections of inductance and capacity, the inductance elements being in one conductor of the line and the capacity elements across the two conductors of the line. All of the inductance elements are of equal inductance and the capacity elements all have the same capacity, there being single sections connected between adjacent ones of twelve contact points of a first or input rotary switch member and twelve sections connected between adjacent ones of the contact points of a second or output rotary switch member. The moving contact arm of the first switch member is actuated in either direction by a servo-motor to cause the arm to snap from one contact or tap to the next and the moving arm of the second switch member, which is similar to the first, is geared to the arm of the first switch member by counter-gear mechanism so as to snap the second arm one tap when the first arm snaps from its last tap to its first or vice versa. The delay introduced by the line is proportional to the number of sections between the input and output taps. The output taps are brought out of capacity voltage dividers each comprising two condensers in series replacing at the tap point, and having the

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same over-all capacity as, the single shunt condenser which would otherwise be present. The output is taken from across the condenser in each output pair farthest removed from the line conductor which contains the inductance elements. The capacity members of each divider are made of such size that the signal in the output path has the same magnitude as in all other output paths. It follows that the ratio of the capacity of the condenser across which the output voltage is taken to the capacity of the two members in series decreases as the output tap number increases by an amount to make the amplitude of the output signal the same regardless of the position from which it is taken. The same voltage-dividing principle may be applied to the input taps but, in the usual practical case, the attenuation between the input taps is not great enough to warrant this refinement. Adjacent inductance members (one in each section) are wound to have mutual inductance between them. By properly adjusting the coefficient of coupling, a flatter delay characteristic can be obtained than with no mutual inductance, i. e., the delay can be made constant (for a particular setting) to higher frequencies.

This transmission line is utilized in the embodiment of the invention chosen by way of example for illustrative purposes to impart a delay to a radar synchronizing pulse bearing a fixed time relation with the radar transmitted pulse. The delayed pulse causes the formation of a pair of gating pulses which are used to "unblock" one of two tubes to both of which is also applied the video or "echo" signal from the radar receiver. If each selected "echo" pulse (the one corresponding to the target being tracked) is not symmetrically positioned in time with respect to the corresponding two gating pulses, a differential current is produced which is utilized to drive a motor to vary the position of the switch arms of the variable delay transmission line to change thereby the time displacement between the gating pulses and the corresponding transmitted pulses. The motor operates until the differential current is zero, for which condition the pairs of gating pulses are symmetrically positioned with respect to the corresponding selected "echo" pulses. The dial indicator on the variable delay transmission line then indicates the range of the selected target and continues to indicate accurately the range even though there is relative movement between the target and the observing station.

The invention will be more readily understood by referring to the following description taken in connection with the accompanying drawings forming a part thereof, in which:

Fig. 1 is a schematic block diagram of an object detecting and distance measuring system of the pulse reflection type employing a variable delay line in accordance with the invention;

Figs. 2, 3 and 4 are detailed circuit diagrams of portions of the system schematically shown in Fig. 1, the variable delay line of this invention being shown in Fig. 2; and

Figs. 5 to 7, inclusive, are various schematic and graphical representations to aid in understanding the invention.

Referring more specifically to the drawings, Fig. 1 shows, by way of example to illustrate the invention and in block diagram form, a variable delay line used in an object detecting and distance measuring sytem of the pulse reflection type which is adapted to automatically "track" (in range) a desired target by continuously indicating the range of the target from the observer's station on a dial or dials to provide a mechanical motion representative of the distance between the target and the observing station. Briefly stated, the system comprises means for radiating pulses which are aimed in a desired direction by means of a proper antenna system, means for receiving the original pulses and also reflections ("echoes") from one or more objects or targets, means for producing by the variable delay line of this invention a delayed pulse a variable period of time after the formation of each transmitted pulse, and apparatus responsive jointly to the delayed pulses and the received signals (including the "echo" pulses corresponding to a target it is desired to "track") to vary the delay period of time so that a predetermined relationship is maintained between the time of occurrence of a reflected ("echo") pulse representative of the selected target and the delayed pulse corresponding thereto. The length of the delay interval is utilized to indicate the range of the target and if, as in this invention, the means for producing the delay is continuously operable, properly calibrated readings of the delay interval give the range of the target at all times.

In the arrangement of Fig. 1, a transmitter 10 is provided to supply ultra-high frequency radio waves which can be directed at a particular object by means of an antenna 11. Any suitable transmitter and antenna can be provided. For example, the transmitter 10 can comprise an oscillator 12 for providing a sine wave having a suitable periodicity which can conveniently be 400 cycles per second, for example. This oscillator energizes a pulse generator 13 of any of several suitble types well known in the art. For example, see United States Patent 2,117,752, issued May 17, 1938, to L. R. Wrathall which provides an energy pulse at a particular point of each cycle of the input wave provided to it. The pulse from the member 13 is then applied to a carrier generator and modulator 14 of any suitable type. The member 14 may, for example, generate a carrier wave of approximately 3300 megacycles and this carrier wave is modulated by the pulses from the pulse generator 13 and the modulated wave applied to the antenna 11. Unmodulated pulses from the generator 13 are also applied by means of the connection 15 to the amplifier 16. The purpose of this connection will be explained more fully below.

Waves reflected from one or more objects within the range of the transmitting antenna 11 are received by a receiving antenna 17. While the antennas 11 and 17 can be of any suitable type, preferably they are of the polystyrene "polyrod" type disclosed in an application of G. E. Mueller, Serial No. 469,284, filed December 17, 1942, and which issued as Patent No. 2,425,336 on August 12, 1947. Connections to the transmitting antenna 11 and from the receiving antenna 17 are made by coaxial cable. The reflected waves picked up by the receiving antenna 17 (and also the transmitted waves) are applied to a receiver 18 of any suitable form wherein it is amplified, rectified and fed into two amplifiers 28 and 29 the input circuits of which are in parallel. If desired, a fixed delay circuit 43 can be included in the circuit between the receiver 18 and the amplifiers 28 and 29, the purpose of which will be described more fully below.

At this point it is advisable to leave the received signal temporarily and describe the formation of timing pulses which are generated at the same periodicity as the transmitted pulses but are delayed by a variable period of time from the corresponding transmitted pulses. Reference will also be made to Fig. 2 which is a more detailed drawing of an amplifier 16 for pulses from the pulse generator 13, a low-pass filter 21 connected to the amplifier 16, a linear amplifier 22 following the low-pass filter, and a variable delay line 23 connected to the linear amplifier. The so-called timing pulses appear in the output of the variable delay line.

Pulses from the pulse generator 13 (which ordinarily are in phase with the transmitted pulses but which may lead or lag them, if desired) are applied to the input circuit of the amplifier 16 which is shown as a single tube V1. The tube V1 includes an anode 30, a cathode 31, a control grid 32, a screen grid 33, and a suppressor grid 34. The circuit between the control grid and the cathode 31 includes a portion of a potentiometer resistor 35 connected across the input terminals and an "anti-sing" resistor 36 (to prevent parasitic oscillations) connected between an inner terminal of the resistor 35 and the control grid 32. The cathode 31 and the suppressor grid 34 are connected to ground in accordance with well-known practice. The plate 30 is connected through an anode resistor 37 to the positive terminal of the power supply 38 (represented schematically by a box), the negative terminal of which is grounded. The screen grid 33 is connected through the resistor 39 to the positive terminal of the source 38, the end of the resistor 39 remote from the screen grid being connected through a by-pass condenser 40 to ground. If the pulses applied to the input circuit of the tube V1 from the pulse generator 13 are negative, there appears in the output circuit of the tube V1 a succession of positive pulses. The anode 30 of the tube V1 is connected through a coupling condenser 41 to one terminal of a low-pass filter (the other terminal being connected to ground) which is used as an interstage coupling between the tube V1 and the tube V2 to prevent any component above 2 megacycles, for example, from being applied to the grid of the tube V2 which is a linear amplifier for the positive pulses. Since V2 is a linear amplifier, its output will contain no new frequencies, and the input to the delay line will contain only frequencies below the cut-off of the low-pass filter. If this cut-off is chosen low enough so that the delay line has negligible delay distortion over the pass-band, there will be no asymmetrical distortion of the pulse by the lines. The low-pass filter 21 can be of any suitable form.

The tube V2 includes an anode 50, a cathode 51, a control grid 52, a screen grid 53, and a suppressor grid 54. The circuit between the control grid 52 and the cathode 51 includes an "anti-sing" resistor 55, a leak resistor 56 connected between the output terminals of the filter 21, and the parallel-connected resistor 57 and condenser 58 which are connected both in the input and in the output circuits of the tube V2 to provide bias for the tube. Resistors 37 and 56 also serve to terminate the filter 21. The anode 50 is connected through the usual anode resistor 59 to the positive terminal of the source 38 while the screen grid 53 is connected to this terminal through the "anti-sing" resistor 60. A by-pass condenser 61 is provided between the outer terminal of the resistor 60 and ground 69.

The output negative pulses of the tube V2 are fed to the variable delay line 23 through a coupling condenser 62. The delay line 23 is designed to be substantially flat in gain and of constant delay (linear in phase) up to about 2 megacycles and is terminated at each end by a resistor 70. It comprises a number of sections of inductance and capacity, there being single sections between adjacent ones of the contact points 71, 72 . . . 81, 82 of the input snap switch member (switch No. 1 in the drawing) and there being twelve sections between adjacent ones of the contact points 85, 86 . . . 95, 96 of the output snap switch member (switch No. 2 in the drawing). Moving contact member 83 which, as will be described more fully below, is actuated in either direction by a servo-motor, is adapted to contact members 71 to 82, inclusive, while moving contact member 84 is adapted to contact the members 85 to 96, inclusive. The contact members 71 to 82, inclusive, are preferably arranged in a closed circle (as in the drawing) in such a way that contact member 83 if it is going in that direction) contacts successively 71, 72 . . . 81, 82 and then 71 again. The member 83 can also contact these elements in the reverse direction. When rotary contact member 83 moves in a clockwise direction from the contact element 82 to the contact 71, by means of any suitable counter gear mechanism 97, the rotary switch member 84 is adapted to move one tap (corresponding to twelve sections like that between 71 and 72, 72 and 73, etc.) in a clockwise direction. The switch members 83 and 84 preferably employ micro-switch blades having snap action between contacts. Any suitable gearing 97, such as that in the well-known Veeder counting mechanisms, may be utilized for this purpose. As an alternative, the contact elements 71, 72 . . . 81, 82 can be arranged in a line and the contact member 83 moved in a linear path, the design being such that when the contact member 83 is moving towards the left and passes the contact element 82 (the last one), a suitable return mechanism returns the member 83 to the contact element 71 and at the same time snaps the contact member 84 one tap to the right. The same thing applies, but in the opposite sense, when the contact member 83 is moving toward the right. As in the case where the contact elements are arranged in circles, the rotary contact members 83 and 84 are actuated in either direction by a servo-motor which is controlled in a manner which will be described hereinafter. In the position shown in the drawing, the pulses from the tube V2 are delayed by a period corresponding to the length of time it takes a pulse to traverse the delay sections between contact elements 81 and 71 (that is, between the terminals of the transmission line marked IN—10 and IN—0), and also the delay sections between contact elements 85 and 86 (that is, between the terminals of the transmission line marked OUT—0 and OUT—1). The input pulses propagate both ways down the line from the point of injection (point IN—10 if switch element 83 is in the position shown in the drawing) and are absorbed at either end by the resistors 70. The output is to a high impedance load which merely samples the voltage of the passing pulse. The delay introduced by the line is accordingly proportional to the number of sections between the input and output taps. While a number of equally spaced taps can be utilized, the arrangement shown in Fig. 2 is preferred as by means of this arrangement the number of leads is minimized. The input taps, twelve in number (IN—0 to IN—11 connected respectively to switch elements 71 to 82, inclusive) are separated by one section each and the output taps (OUT—0 to OUT—11 connected respectively to switch elements 85 to 96, inclusive) are, as pointed out above, each separated by twelve sections. The rotary switches are, of course, reversible and can be rotated continuously in either direction. In this way delays each of one section per step, are obtained, there being 144 steps but requiring only 24 leads. Each section includes an inductance member and a capacity member, adjacent inductance members having mutual inductance between them. This mutual inductance may be obtained by winding all of the inductances series aiding on a long form and is then in such a sense as to introduce an equivalent negative inductance in series with the shunt condenser between the coils. By properly adjusting the coefficient of coupling a flatter delay characteristic can be obtained than with no mutual inductance, i. e., the delay can be made constant to higher frequencies.

To compensate for the changing attenuation introduced by the line as the number of intervening sections is changed, the output taps are brought out of capacity voltage dividers 100, 101 . . . 110, each of two capacity members, the capacity members of each divider being of such size that their attenuation plus that of the line up to them is constant. In other words, the ratio of the capacity of the lower capacity member (from which the output voltage is taken) in each divider to that of the overall capacity of the two members in that divider decreases as the output tap number increases by an amount to make the amplitude of the output signal the same regardless of the position from which it is taken. The output pulse is therefore merely delayed without having any appreciable variable change in shape. The attenuation between the input taps is usually not great enough to warrant the provision of capacity dividers of this type.

The delayed pulse (called also the "marking" or "timing" pulse and shown in Fig. 6A) at the output terminal 111 (connected to the contact member 84) is applied to a first gate-forming circuit 24 comprising (see Fig. 3) the tubes V3, V4, V5 and V6. The tube V3 acts as an amplifier and includes an anode 120, a cathode 121, a control grid 122, a screen grid 123, and a suppressor grid 124. The control grid 122 is connected through an "anti-sing" resistor 125 and a grid leak 126 to ground, this being the potential of the cathode 121 and of the suppressor grid 124. The anode is connected through resistor 127, inductance member 128 (to provide high frequency equalization), and resistor 129 to the positive terminal of the direct current source 130 (or to the source 38, if desired), while the screen grid is connected through the "anti-sing" resistor 131 and the resistor 129 to the same terminal. The end of the resistor 131 remote from the screen grid is connected through the by-pass condenser 132 to ground.

The anode of the tube V3 is connected to the control grid 142 of the tube V4 through a coupling condenser 133 and an "anti-sing" resistor 134. The grid voltage of this tube V4 is shown in Fig. 6B. The terminal of the resistor 134 remote from the control grid is connected to ground through the grid leak resistor 135. The tube V4 also includes an anode 140, a cathode 141, a screen grid 143 and a suppressor grid 144. The suppressor grid 144 and the cathode 142 are connected to ground through the parallel-connected resistance member 145 and capacity member 146 which serve to provide bias for the control grid. The "bleeder" resistor 147 is also connected between the cathode and the positive terminal of the source 130 through the resistor 148 to place the cathode 141 at a positive potential even when no current is flowing through the tube. In the absence of signal pulses, the tube V4 is adapted to be cut off. The suppressor grid 143 is connected through the "anti-sing" resistor 136 and the resistor 148 to the positive terminal of the source 130 while the anode 140 is connected through the resistor 149 and the resistor 148 to the same terminal of the source 130. A by-pass condenser 150 is provided between the screen grid 143 and ground.

The anode 140 is connected through a coupling condenser 151 to the control grid 162 of the tube V5, this tube also including an anode 160, a cathode 161, a screen grid 163, and a suppressor grid 164. A tuned interstage circuit comprising the condenser 152 and inductance member 153 is connected in parallel between the control grid 162 and ground. One or more of the members 152 and 153 may be variable, if desired. The interstage coupling, which is designated the tuned circuit T_1, is shock-excited by pulses from the tube V4 but the oscillation initiated by the shock excitation is damped within one-fourth of an oscillation cycle by means of the tube V5 which starts to draw grid current when the oscillation potential passes the cut-off bias point of tube V5. The cathode 161 and the suppressor grid 164 are connected to ground. The screen grid 163 is connected through an "anti-sing" resistor 165 and resistors 166 and 167 to the positive terminal of the source 130. The terminal of the resistor 165 remote from the screen grid is connected to ground through the condenser 172, while the plate 160 is connected through the resistor 168 and the resistor 167 to the positive terminal of the source 130. A filter condenser 169 is connected between the common terminal of the resistors 166 and 167 and ground. The tube V5 is conducting current at a substantially constant rate prior to the appearance of a negative pulse on its grid (due to the oscillation of the tuned circuit T_1) but this pulse is of sufficient magnitude to cause the tube V5 to be cut off. The positive portion of the voltage oscillation set up in the tuned circuit T_1 (see Fig. 6C), however, causes the tube again to conduct and the plate voltage to go to a lower value than it had been prior to the arrival of the pulse on its grid, and this voltage gradually changes to substantially the same value it had before the appearance of the pulse in the tube V4, as shown in Fig. 6C. The positive rectangular pulse portion of the wave shown in Fig. 6D is used as the first "gate" pulse.

The anode 160 of the tube V5 is connected to a circuit including the small condenser 170, of the order of 2.5 micromicrofarads, for example, and the resistor 171, which acts to differentiate the voltage wave applied thereto to form the two voltage pulses shown in Fig. 6E. The negative pulse shown in Fig. 6E then excites the circuit comprising tubes V7, V8 and V9 exactly as the pulse (shown in Fig. 6A) at the terminal 111 excited the circuit comprising tubes V3, V4 and V5 to form the second "gate" pulse.

The tube V7 includes an anode 180, a cathode 181, a control grid 182, a screen grid 183 and a suppressor grid 184. An "anti-sing" resistor 185 is connected between the control grid 182 and the condenser 170 while a similar "anti-sing" resistor 186 is connected between the screen grid 183 and the resistor 129 the other terminal of which is connected to the positive terminal of the source 130. The suppressor grid 184 and the cathode 181 are connected to ground while the anode 180 is connected through the resistor 187 and inductance member 188 (for high frequency equalization) and the resistor 129 to the positive terminal of the source 130.

The anode 180 is connected through the coupling condenser 189 to the control grid 192 of the tube V8 which also includes an anode 190, a cathode 191, a screen grid 193 and a suppressor grid 194. The control grid voltage of the tube V8 is shown in Fig. 6F. An "anti-sing" resistor 195 is also connected in the lead to the control grid 192 and a leak resistor 196 is connected between the coupling condenser 189 and ground. The anode 190 is connected through the resistor 197 and the resistor 148 to the positive terminal of the source 130 while the screen grid 193 is connected through the "anti-sing" resistor 198 and the resistor 148 to the same terminal of the source 130. The suppressor grid 194 and the cathode 191 are connected through the parallel-connected resistance member 145 and capacity member 146 to ground, these last two members providing bias for the control grid 192. The bleeder resistor 147 is also utilized as the cathode of the tube V8 is connected to point G which is connected to the cathode of the tube V4. It will be apparent from the drawing that many of the resistor and capacity members of the gate-forming circuit No. 1 are utilized also in the gate-forming circuit No. 2 in order to save parts.

The anode 190 is connected through the coupling condenser 199 to the interstage tuned circuit T_2 and also to the control grid 202 of the tube V9 which also includes an anode 200, a cathode 201, a screen grid 203, and a suppressor grid 204. The tuned circuit T_2 comprises a capacity member 205 and an inductance member 206 connected in parallel between the control grid 202 and ground. The action of the tuned circuit T_2 is similar to that of the tuned circuit T_1 in the gate-forming circuit No. 1. The cathode 201 and the suppressor grid 204 are connected to ground while the screen grid 203 is connected through an "anti-sing" resistor 207 and the resistance members 166 and 167 to the positive terminal of the source 130 while the anode 200 is connected through the resistor 208 and the resistor 167 to the positive terminal of source 130. A wave, such as that shown in Fig. 6G, is produced at the plate of the tube V9 which, it will be noted is like that produced (see Fig. 6C) by the tubes V3, V4 and

V5 except that it is displaced in time by a period substantially equal to the duration of the positive pulse in the wave shown in Fig. 6D. The positive pulse of the wave shown in Fig. 6H forms "gate" pulse No. 2. "Gates" 1 and 2 are effectively rectangular since only the positive part of each of the waves shown in Figs. 6D and 6H is utilized.

The function of diodes V6 and V10 is to limit the height of the positive portion of the gate pulses to a fixed value. The plate 210 of the tube V6 is connected to the plate 160 of the tube V5 through a coupling condenser 211 while the cathode 212 is connected to the cathodes 271 and 291 of tubes V13 and V14 to be hereinafter described. The plate 210 is connected through the resistance 215, the resistance 213, the top half of the resistance 216 and the movable tap 217 to ground. Similarly, the anode 220 of the diode V10 is connected through a coupling condenser 211 to the plate 200 of the tube V9 while the cathode 222 is also connected to the cathodes 271 and 291. The plate 220 is connected through the resistor 225, the resistor 214, the bottom portion of the resistor 216, and the movable tap 217 to ground. When the gating pulse No. 1 causes the plate 210 to exceed the potential of the cathodes of V13 and V14 the tube V6 conducts and the top of the gating pulse is limited. A similar action takes place with respect to gating pulse No. 2 in tube V10. The two gating pulses are then applied to integrating circuits 26 and 27 through terminals 226 and 227. The gate pulses as they appear in the grid circuits of tubes V13 and V14 can be made to have the same amplitude by varying the position of the movable tap 217, which varies the potentiometer action of the associated resistors.

Also applied to the terminals 226 and 227 are the output voltages of the amplifiers 28 and 29. The amplifiers 28 and 29 have applied thereto, in parallel, the video signal from the receiver 18, either directly or through the fixed delay circuit 43, the purpose of which is to compensate for the minimum delay of the variable delay line or unit 23 plus the delay represented by the width of one gate pulse if it is desired to track down to very low ranges.

The amplifier 28 preferably comprises a tube V11 including an anode 230, a cathode 231, a control grid 232, a screen grid 233, and a suppressor grid 234. The control grid is connected through an "anti-sing" resistor 235 to an inner terminal 236 of the leak resistor 237 connected between the coupling condenser 238 and ground. The suppressor grid 234 and the cathode 231 are connected to ground while the screen grid 233 is connected through an "anti-sing" resistor 239 and a resistor 240 to the positive terminal of the source 130. The by-pass condenser 241 is connected between the terminal of the resistor 239 remote from the screen grid 233 and ground. The anode 230 is connected through resistors 242 and 243 to the positive terminal of the source 130, a filter condenser 244 being connected between the common terminal of the resistors 242 and 243 and ground. The anode is connected through coupling condenser 245 to the terminal 226.

Tube V12 includes an anode 250, a cathode 251, a control grid 252, a screen grid 253, and a suppressor grid 254. The control grid 252 is connected to an inner terminal 256 of the grid leak resistor 257 through an "anti-sing" resistor 255. The screen grid 253 is connected through an "anti-sing" resistor 258 and the resistor 240 to the positive terminal of the source 130, while the anode 250 is connected through the resistor 259 and the resistor 243 to the same terminal. The cathode 251 and the suppressor grid 254 are connected to ground. By means of the coupling condenser 260 the anode 250 is connected to the terminal 227.

The amplified video signals from the amplifiers 28 and 29 are applied to the control grids of the tubes V13 and V14, along with the gate pulses produced by the gate-forming circuits 24 and 25, respectively, through "anti-sing" resistors 261 and 262, respectively. V13 includes an anode 270, a cathode 271, a control grid 272, a screen grid 273, and a suppressor grid 274. The suppressor grid 274 is connected to the cathode and through parallel-connected resistance member 275 and capacity member 276 to ground which combination provides bias for the control grid. A bleeder resistor 277 is provided between the cathode 271 and the resistor 278 which is connected to the positive terminal of the power supply 280 for direct current (which may be replaced by the power supply 38 or 130, if desired). The plate 270 is connected through resistor 281 to the voltage divider, consisting of the resistors 282 and 283. An "anti-sing" resistor 285 is connected between the screen grid 273 and the resistor 278, the common terminal of the resistors 285 and 278 being connected through a by-pass condenser 284 to ground. Connected to the plate 270 is an integrating circuit having a comparatively long time constant, the integrating circuit comprising a condenser 286, of, for example, .01 microfarad connected between the plate 270 and ground and the resistor 281 of, for example, 1 megohm. A resistor 287 of, for example, 1 megohm, is connected between the plate 270 and the control grid 302 of the tube V15 and a condenser 288 is connected between the control grid 302 and ground, this latter condenser being of the order of .005 microfarad. The resistor 287 and the condenser 288 filter out high frequency variations.

The tube V14 includes an anode 290, a cathode 291, a control grid 292, a screen grid 293 and a suppressor grid 294. The suppressor grid and the cathode are connected together and to the cathode 271 of the tube V13, thus making use of the resistor 275 and the condenser 276 to provide bias for the control grid 292. The screen grid 293 is connected through an "anti-sing" resistor 295 and resistors 278 and 279 to the positive terminal of the source 280. A filter condenser 289 is connected between the common terminal of the resistors 278 and 279 and ground. The anode 290 is connected through resistance 296 to the common terminal of the resistors 282 and 283. The anode 290 is also connected to the integrating capacity member 297 similar to the capacity member 286. A resistance member 298 similar to the resistance member 287, and a capacity member 299 similar to capacity member 288 are also provided to filter out high frequency variations. The resistance member 298 is connected to the control grid 312 of the double triode V15.

Tubes V13 and V14 are biased so far beyond cut-off, in the absence of the gating pulses, that even the signal overload peaks (positive) in the video signal are inadequate to cause them to pass any plate current. However, when gate No. 1 is applied to the control grid 272, tube V13 is made conducting to an amount depending on the video signal then present. Similarly, when gate No. 2 is applied to the control grid of tube V14 it is made conducting to an amount depending on the video signal then present. The integrating condensers 286 and 297 in the output circuits of the tubes V13 and V14, respectively, are charged up negatively as these tubes become conducting during each pulsing interval and retain the charges for several cycles. The voltages across the condensers 286 and 297 are the result of integrations of the signals occurring during the corresponding gate intervals over the past several cycles. Noise present in the signal, because of its random nature, tends to integrate equally between the two gate-controlled circuits. If an echo pulse from the object or target it is desired to "track" is centered, that is, if it lies half within the time span of gate pulse No. 1 and half within the time span of gate pulse No. 2, it also will integrate equally into the two channels, but if the echo pulse drifts off into the time span of one or the other of the two gates, the integrated charge on the integrating condenser in the plate circuit of the tube V14 will increase or decrease with respect to that on the one in the plate circuit of the tube V13. A voltage unbalance will then be developed between the grids 302 and 312 of the double triode V15 which comprises one of the two tubes of a direct current amplifier 44.

The tube V15 includes an anode 300, a cathode 301, and a control grid 302 for one section and an anode 310, a cathode 311, and a control grid 312 for the second section. The two cathodes 301 and 311 are connected by a potentiometer 303, the variable tap 304 of which is connected through a resistor 305 to ground. The variable tap 304 makes it possible to create an unbalance voltage between the cathodes of V15 which can be used for moving the gate pulses with reference to the corresponding transmitted pulses for "scanning" purposes, as will be pointed out more fully below. Anode 300 is connected through the resistors 306 and 279 to the positive terminal of the source 280 while anode 310 is connected through resistors 307 and 279 to the same terminal of the power supply 280. The anode 300 is connected through a voltage dropping resistor 308 to the control grid 322 of the double triode tube V16 serving as a second stage of the direct current amplifier 44, while the anode 310 of the tube V15 is connected through a voltage dropping resistor 309 to the control grid 332 of the right-hand section of the tube V16. The tube V16 also includes an anode 320 and a cathode 321, and an anode 330 and a cathode 331. A grid leak resistor 323 is connected between the grid 322 and ground while a similar resistor 333 is connected between the grid 332 and ground. The cathodes 321 and 331 are connected to ground by means of similar resistors 324 and 325. The anodes 320 and 330 are connected through the resistor 326 to the positive terminal of the source 280. The cathodes 321 and 331 are connected to a balanced modulator 45, the parallel connected resistance member 327 and capacity member 328 being connected in one of the leads to the modulator. It will be seen that the entire system, including the motor 48, the gear train between the motor and switch No. 1 of the variable delay unit 23, the unit 23, the gate-forming circuits 24 and 25, the integrator tubes and circuits 26 and 27, the direct current amplifier 44, modulator 45, and the alternating current amplifier 46 follows it, comprises one large feedback loop structure, forming what is commonly known as a "servo-mechanism." The resistor 327 and capacity 328 are included to provide the frequency characteristic required to stabilize this loop.

The modulator 45 comprises a bridge structure of four rectifier elements 340, 341, 342 and 343. An alternating current from a suitable source 47, which preferably is of the same frequency and phase as that of the oscillator 12, is applied through a 90-degree phase shifting network 335 comprising the resistors 345 and 346 in series with the line and the condenser 347 across it, to the primary winding 348 of a transformer 349, the secondary winding of which is connected to one diagonal of the bridge, the other diagonal being connected to the primary winding 351 of a transformer 352, the secondary winding 353 of which is connected to a push-pull amplifier 46. The leads from the cathodes of the tube V16 are connected to the mid-points of the windings 350 and 351, respectively. The modulator 45 operates in accordance with the description in Patent 2,025,158 issued December 24, 1935, to F. A. Cowan to suppress the carrier from the source 47 and transmit to the output circuit substantially only the upper and lower side-bands produced by the amplitude modulation of this carrier by the signal input. The output wave of the modulator is shown in Fig. 7B and will be explained more fully below. This output wave from the modulator is applied to the input of a conventional push-pull amplifier 46, having the required amplification and a sufficient output power at the proper impedance level to drive one winding 400 of any suitable two-phase low inertia motor 48. An unmodulated 400-cycle voltage is applied to the winding 401 of the motor 48 by means of a transformer 402, the terminals of the primary winding 403 of which are connected to the source 47. Since the carrier input to the modulator 45 is shifted 90 degrees by the phase shifter 335, the output of the amplifier 46 will bear a plus or minus 90-degree phase relation to the fixed phase excitation of the motor depending on the direction of the direct current unbalance which drives the modulator. Any unbalance voltage resulting from the received signal not occurring symmetrically with respect to the two gating pulses thereby causes rotation of the motor armature 404 which is mechanically connected to the variable delay unit 23 to drive switch No. 1 thereof in one direction or the other. The rotation is in a direction to center the gates about the received signal, reducing the unbalance of the driving voltage to zero. A dial, calibrated in thousands of yards of range, for example, indicates the delay introduced by the unit 23 and is an accurate indication of the range. If desired, the dial may be connected directly to the motor 48, as indicated by the reference character 500 in Fig. 1.

A mechanical output unit 49 is shown mechanically connected to the motor 48. This unit comprises a low inertia motor similar to the motor 48 and means for causing this motor to "follow" the motor 48. The motor in the output unit can be used to operate an optical range finder or to provide a component of motion to a computer. A suitable follow-up system is shown in Patent 2,056,348 issued October 6, 1936, to M. A. Edwards.

The operation of the system shown in Fig. 1 will now be described, reference being made also to the circuit diagrams of Figs. 2, 3 and 4 and to the diagrammatic and graphical representations of Figs. 5, 6 and 7. A pulsed ultra-high frequency radio wave is directed at an object by means of the antenna 11. The reflected wave is received by antenna 17, amplified and rectified by the receiver 18 and sent to the fixed delay circuit 43 in which it is delayed by an amount corresponding to the minimum delay of the variable delay line 23 plus the time span of one of the gate pulses (formed by circuit 24). This delay line, as pointed out above, may be omitted, if not desired. The high frequency pulse (shown in Fig. 5A) comprises, for example, a wave of a radio frequency of 3300 megacycles per second, the duration of a pulse being approximately one-fourth of a microsecond and the pulses being repeated four hundred times per second. The antennae by which this pulse is radiated and received are preferably of a directional type and are aimed at the target. Reflections (echoes) from the target are picked up by the receiving antenna and passed to the receiver 18 over a coaxial cable.

The video signal from the amplifier in the receiver 18 is passed either directly or through the fixed delay circuit 43 into the two amplifiers 28 and 29 connected in parallel.

At this point it is desirable to leave the received signal temporarily and describe the formation of timing pulses which have the same periodicity as the transmitted pulses but which have a variable time relationship with respect thereto, as will be clear from the decription below. The timing pulses are formed at the output of the variable delay line 23 and are used to initiate the formation of the gating pulses in the gating circuits 1 and 2. Fig. 5A represents a pulse modulated ultra-high frequency wave applied to the antenna 11 while Fig. 5B shows a corresponding reference-time pulse which can be generated in the pulse generator 13, for example, and which is fed to the delay line or unit 23 to form a timing pulse at a controllable period of time thereafter. Fig. 5C shows a timing pulse 410 produced at the output of the variable delay line or unit 23. It will be understood that the pulse 410 may occupy positions to the right or left of that of the pulse shown in Fig. 5C, its position being dependent on the delay of the unit 23. Pulse 411 shown by dotted lines represents the output pulse as generated at the minimum delay setting of the delay device. Fig. 5D shows a received video signal as it might be seen on a cathode ray oscilloscope, the significant portions of several pulsing cycles being shown superimposed. The transmitted pulse 412 is shown removed from the reference line 413 by a distance corresponding to the fixed delay introduced by the circuit 43. Echo pulses 414 and 415 are also shown. In this drawing the echoes shown are fairly weak ones and the receiver gain is assumed to be turned up so high that the signal produced by thermal agitation in the input circuits and commonly called "thermal noise" is visible as a random waviness in the oscilloscope trace. The delayed pulse or timing pulse produced by the variable delay line 23 is amplified by the tube V3 and applied to the normally cut-off tube V4. The tuned interstage circuit T_1 following the tube V4 is shock-excited and describes an oscillation as shown in Fig. 6C. Apparatus for and the method of forming oscillations of the type shown in Fig. 6C are more completely disclosed in a copending application of B. M. Oliver, Serial No. 486,780, filed May 13, 1943, and which issued as Patent No. 2,433,863 on January 6, 1948. The dotted line 421 in Fig. 6C represents the cut-off bias level of the tube V5. It will be seen that V5 is cut off for a period of time corresponding to the time between the points 422 and 423 in Fig. 6C. V5, being cut off during this interval, forms at its plate a rectangular positive gate pulse 424 (the upper part of Fig. 6D) and a curved lower portion 425. The positive rectangular portion of the wave shown in Fig. 6D is designated gating pulse or gate No. 1 and is later used to unblank tube V13. The output pulse from the tube V5 is differentiated by the circuit comprising the elements 170 and 171 to form a wave such as that shown in Fig. 6E having a positive pulse 426 and a larger negative pulse 427. The grid voltage of the tube V8 is shown in Fig. 6F and comprises a positive pulse 428 which is similar to the pulse in Fig. 6B except that it is displaced by a period of time very nearly equal to the width of the positive rectangular portion of the gate pulse No. 1 shown in Fig. 6D. The negative pulse 429 has no effect on the tube V8 as it is already cut off. The voltage applied to the grid of tube V9 is shown in Fig. 6G. This voltage causes an output wave in the tube V9 of the shape shown in Fig. 6H which, it will be noted, is similar to the wave shown in Fig. 6D except that it is displaced in time by a period of time very nearly equal to the width of the positive pulse of the wave shown in Fig. 6D. The positive rectangular pulse shown in Fig. 6H forms gate pulse No. 2. In point of time, gate pulse No. 2 is contiguous to gate pulse No. 1, that is, the trailing edge of the rectangular top of gate No. 1 is simultaneous with the leading edge of gate No. 2.

The received signal is introduced to the amplifiers 28 and 29 in parallel and after amplification therein, is applied to the integrating circuits 26 and 27, respectively. Tubes V13 and V14 which supply the integrating circuits are biased so far beyond cut-off normally (that is, when no gate pulse is applied to the grid) that even the highest signal peaks (positive) which can be obtained even under overload conditions are inadequate to cause them to pass any plate current. (It is indicated in Fig. 5E that the video overload level is set at a value such that even the maximum signal output is insufficient to make the tube V13 conducting.) When gate No. 1 is applied to tube V13, however, the plate of the diode V6 is brought up to, but not appreciably above, the cathode potential of tube V13 whose control grid 272 is accordingly elevated to (or a little above) cut-off as determined by the associated resistor potential dividers. The signal occurring during this interval thus causes plate current to flow in the tube V13. The video signal of Fig. 5D (including transmitted pulse 412, echo pulses 414 and 415 and random voltage variations due to noise, etc.) and the first gate pulse shown in Fig. 6D are shown as a combined wave in Fig. 5E. The plate current in the output of tube V13 is shown in Fig. 5G, all portions of the wave of Fig. 5E below the cut-off line in that figure not being reproduced in the output signal of this tube. Fig. 5F shows a wave similar to that of Fig. 5E except that it represents the grid voltage of the tube V14 rather than that of the tube V13, while Fig. 5H shows the plate current of the tube V14. It will be noted that a portion 430 of the energy of the echo pulse 415 appears in Fig. 5G and a portion 431 thereof appears in Fig. 5H. In the plate circuits of the tubes V13 and V14 are the long time constant integrating circuits which collect whatever negative charge is passed by the tubes V13 and V14, respectively, during the selected interval of each pulsing cycle and store it for several cycles. Naturally, being a linear network all the charge contributions ever contributed are superposed, and each contribution may be thought of as dying away exponentially as time progresses, so that the state of charge of the condensers is at all times determined by the few most recent cycles. Noise present in the signal, because of its random nature, tends to integrate equally into the two gates. If the echo pulse being tracked, that is, for example, the pulse 415 of Fig. 5D which represents a selected target, is centered, that is, if it occurs half within the time span of gate No. 1 and half within the time span of gate No. 2, as indicated in Figs. 5G and 5H, the charges integrated into the two channels will be (on the average) equal. If, however, the pulse drifts, for example into the time span of gate No. 2, the integrated (negative) charge on the integrating condenser in the plate circuit of the tube V14 will increase with respect to that on the condenser in the plate circuit of the tube V13. An unbalance voltage will then be applied to the grids of the direct current amplifier V15, the grid 302 going positive with respect to the grid 312. The aplified unbalance on the plates of the tube V15 is applied to the grids of the tube V16 acting as a dual cathode follower. The potential difference on the cathodes of the tube V16 is used to develop a control current which unbalances the copper-oxide balanced modulator comprising the bridge of rectifier elements 340, 341, 342 and 343. This bridge has applied across one diagonal a 400-cycle alternating current obtained through the 90-degree phase shifter 335. The copper-oxide modulator then applies a 400-cycle signal to the amplifier 46 whose output power is used to drive the motor 48 in the proper direction to adjust the contacts on the delay line 23 so as to re-center in time the gate pulses on the selected echo pulse. It will be apparent that increasing the delay in the delay line 23 increases the time interval between the transmitted pulse and the corresponding gating pulses and decreasing the delay interval produced by the line 23 will have the opposite effect on the gating pulses' position with respect to the transmitted pulse. The variation with respect to time of the input signal voltage applied to the modulator 45 is represented in Fig. 7A, while Fig. 7B represents the output of the amplifier 46 which is applied to the motor winding 400. It will be noted that the portions of the wave designated −90 degrees in Fig. 7B are 180 degrees out of phase with those designated +90 degrees. (The plus or minus 90-degree relationship is with respect to the unmodulated wave of 400-cycle frequency applied to the winding 401 of the motor 48 from the alternating current source 47.) When the phase of the current in the winding 401 is +90 degrees with respect to that of the current in the winding 400, the motor 48 is driven in one direction while if it is −90 degrees with respect to the current in the winding 400, the motor is driven in the opposite direction. Fig. 7C represents the torque on the motor 48, corresponding to the input wave shown.

The delay of the echo pulse 415 in Fig. 5D from the transmitted pulse 412 is (when the echo is centered with respect to the two gate pulses) equal to the delay of the line 23 plus the duration of one gate (gate No. 1). Range to the selected target can therefore be read from the setting of the delay line switch or the revolutions of the spinner motor shaft.

By unbalancing the potentiometer in the cathode circuit of the tube V15, the device can be made to scan in the absence of any echo, that is, move the two gating pulses in either direction in search of an echo. However, for manual drive or "slewing," a double push-button unit shown in Fig. 4 is provided (the push-buttons themselves have not been shown in the drawing but one is arranged to actuate contact member 451 to the right and the other one is arranged to actuate contact member 454 to the left when the respective buttons are depressed). When neither push-button is depressed the equipment will follow an echo, or lacking one scan as indicated above until the target is picked up. Depressing one button of the manual control equipment 450 closes the contacts 451 and 452 while depressing the other button closes the contacts 453 and 454. This shorts to ground one or the other of the control grids 322 and 332 of the tube V16 and the severe unbalance which this produces at the amplifier input overpowers any signal unbalance which may be present, and drives the motor in the indicated direction at top speed, thereby moving the gating pulses in a direction corresponding to a greater or a lesser range and at maximum speed. This is known as "slewing."

The manual drive control keys of the equipment 450 must be accessible to the pilot or gunner sighting the target. In addition to sighting the target, the pilot or gunner must then estimate the distance to the target, slew the equipment past undesired targets into a range in the vicinity of the range of the desired target and then allow the equipment to scan, preferably at a constant rate of speed, to the desired target whereupon it will automatically follow the target until pulled off by the manual drive control 450. If the equipment is adjusted to scan in, it must be slewed to a range greater than the target, or conversely, if adjusted to scan out, it must be slewed to a range less than the target. Visibility to the operator of a range dial is a great convenience in this type of operation.

It is obvious that the variable delay means of this invention can have many other uses other than in connection with a radar system. It can be used for delaying signals or pulses in telephony or in television or in pulse position modulation systems, for example.

Various changes may be made in the embodiment described above without departing from the spirit of the invention as indicated by the claims.

What is claimed is:

1. A variable delay transmission line for pulses comprising input and output terminals, a group of similar signal delay sections connected in tandem, a switch member movable in two directions and connected to one of the terminals of said transmission line, a group of contact members positioned to be contacted one at a time by said switch member, means for connecting an input terminal of said tandem arrangement to one of said contact members and for connecting an output terminal of each section to others of said contact members in order, a second group of signal delay sections each producing a signal delay which is substantially equivalent to that of one of said first group of delay sections multiplied by the number of sections in the first group, the sections of said second group being connected in tandem with an input terminal of said second tandem arrangement being connected to an output terminal of the tandem arrangement of said

first group of delay sections, a second switch member movable in two directions and connected to the other terminal of said transmission line, a second group of contact members positioned to be contacted one at a time by said second switch members, means for connecting an input terminal of said second tandem arrangement to one of the contact members of said second group and for connecting an output terminal of each section in said second group to others of the contact members of said second group in order, and means including counter-gear mechanism for causing the second movable switch member to snap from one contact member in the second group to an adjacent contact member in that group in one direction when the first movable switch member snaps from the first to the last contact in the first group and for causing the second switch member to snap from one contact member in the second group to an adjacent contact member in that group in the opposite direction when the first movable switch member snaps from the last to the first contact member in the first group.

2. The combination of elements as in claim 1 in which said two movable switch members are driven by a reversible motor.

3. The combination of elements as in claim 1 in which each of said delay sections comprises a series inductance member and a shunt capacity member.

4. The combination of elements as in claim 1 in which each of said delay sections comprises a series inductance member and a shunt capacity member, all of the inductance members in a group of sections being wound on a common form in series aiding direction thereby providing mutual inductance between the inductance members of adjacent sections.

5. The combination of elements as in claim 1 in further combination with a plurality of voltage dividing means connected respectively at the terminations of the sections of said second group, the voltage dividing means serving to attenuate the output pulse of the section connected to the terminal of the transmission line through said second movable switch member, the attenuation being progressively less as the number of sections connected between the terminals of said transmission line increases.

BERNARD M. OLIVER.

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