July 6, 1948. H. G. BUSIGNIES 2,444,425

ANTENNA ARRAY

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Fig. 1.

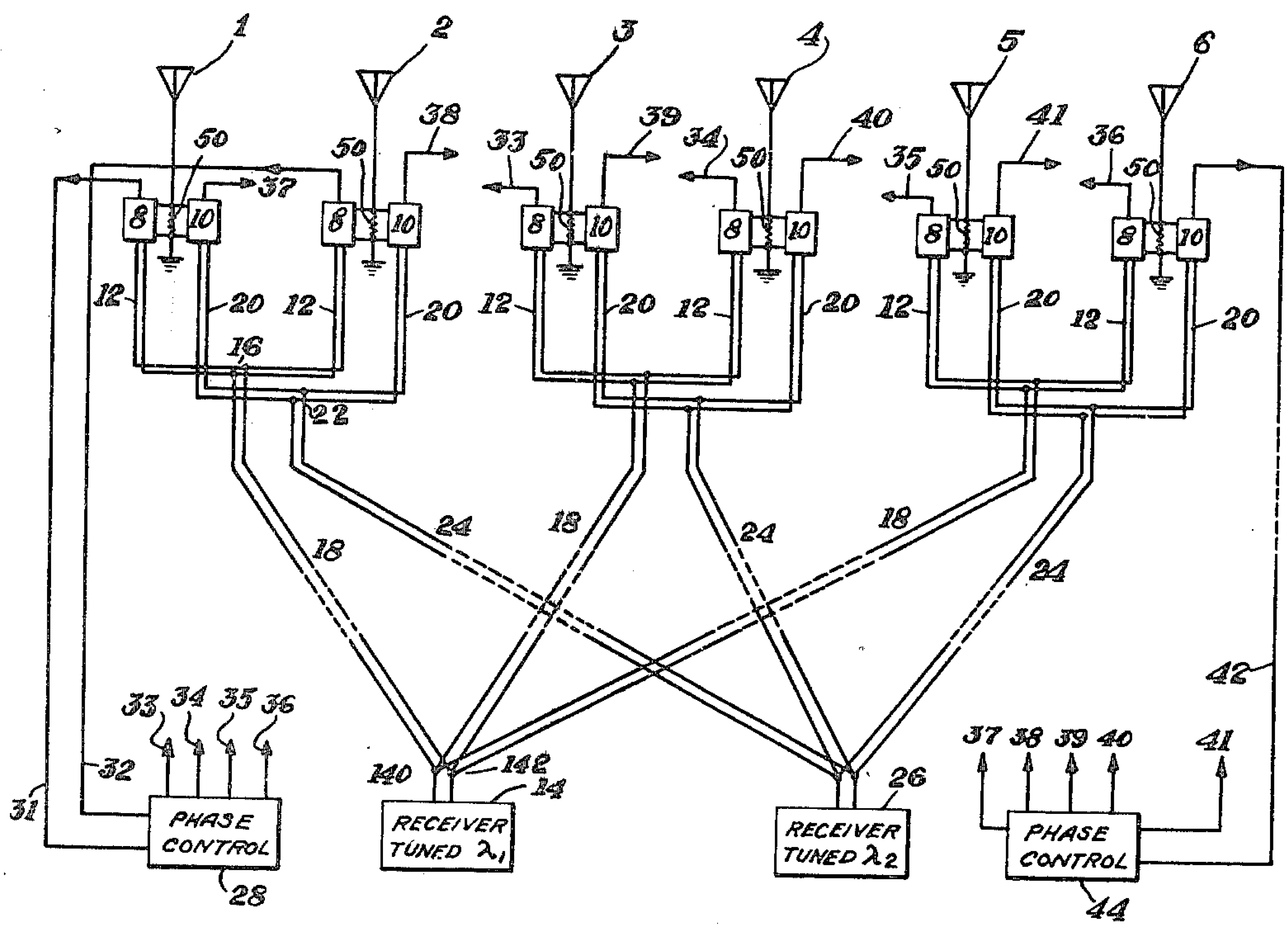

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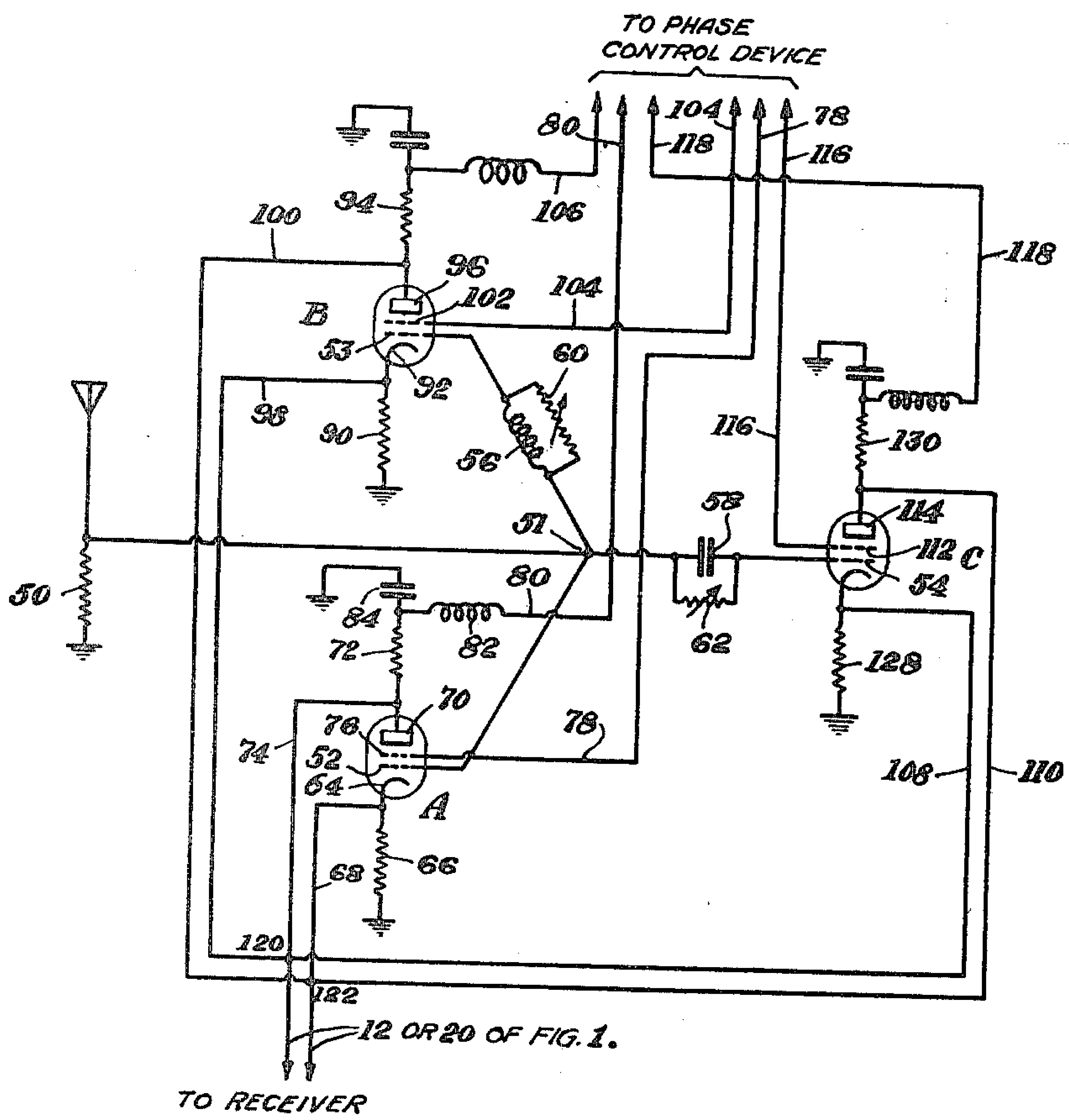
Fig. 2.



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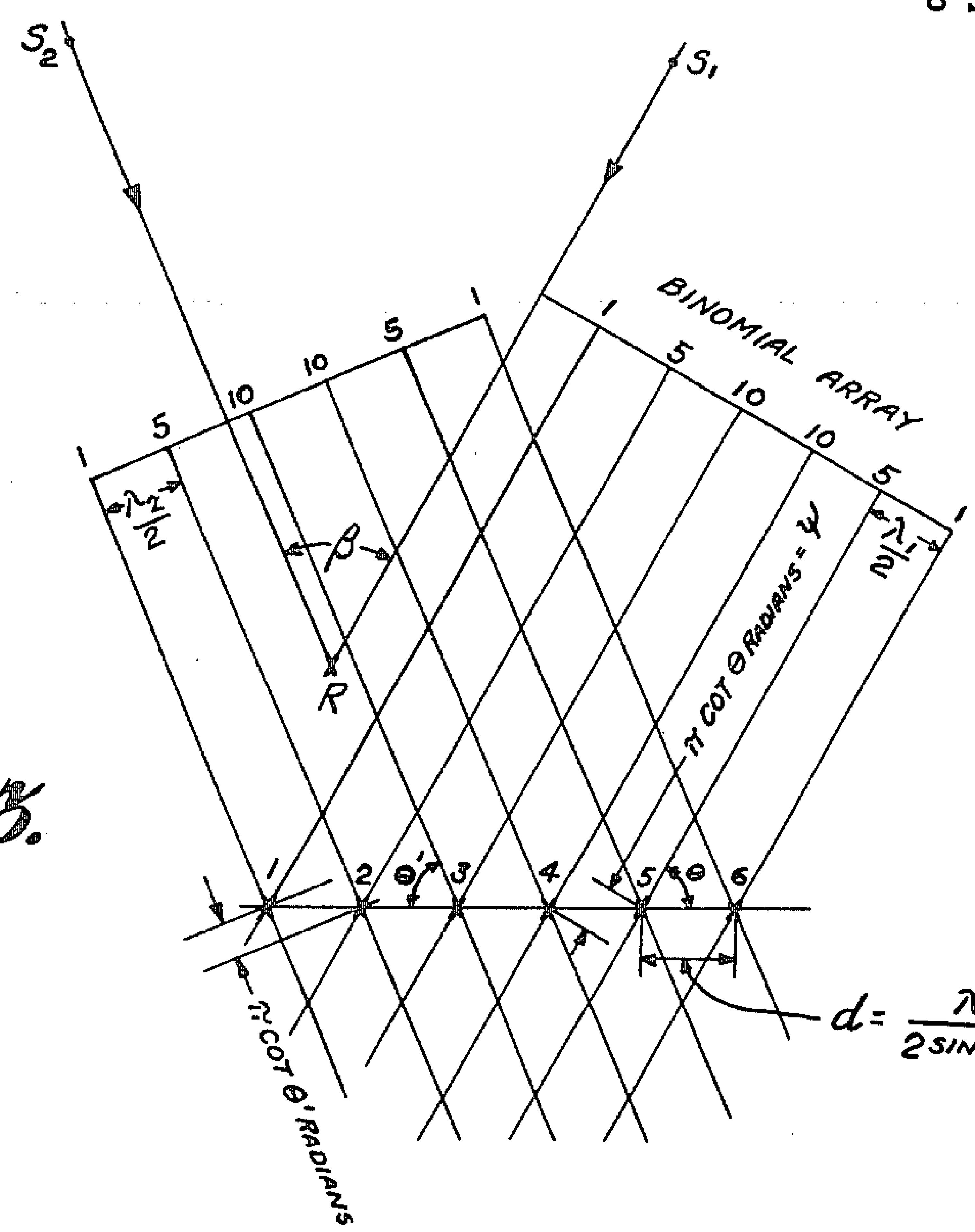

$d = \frac{\lambda_1}{2 \sin \theta} = \frac{\lambda_2}{2 \sin \theta'}$

Fig. 3.

$\theta = 60°$

$\cot \theta = 0.5774$

$\psi = 0.577\pi = 1.81$ Radians

$\psi = 104°$

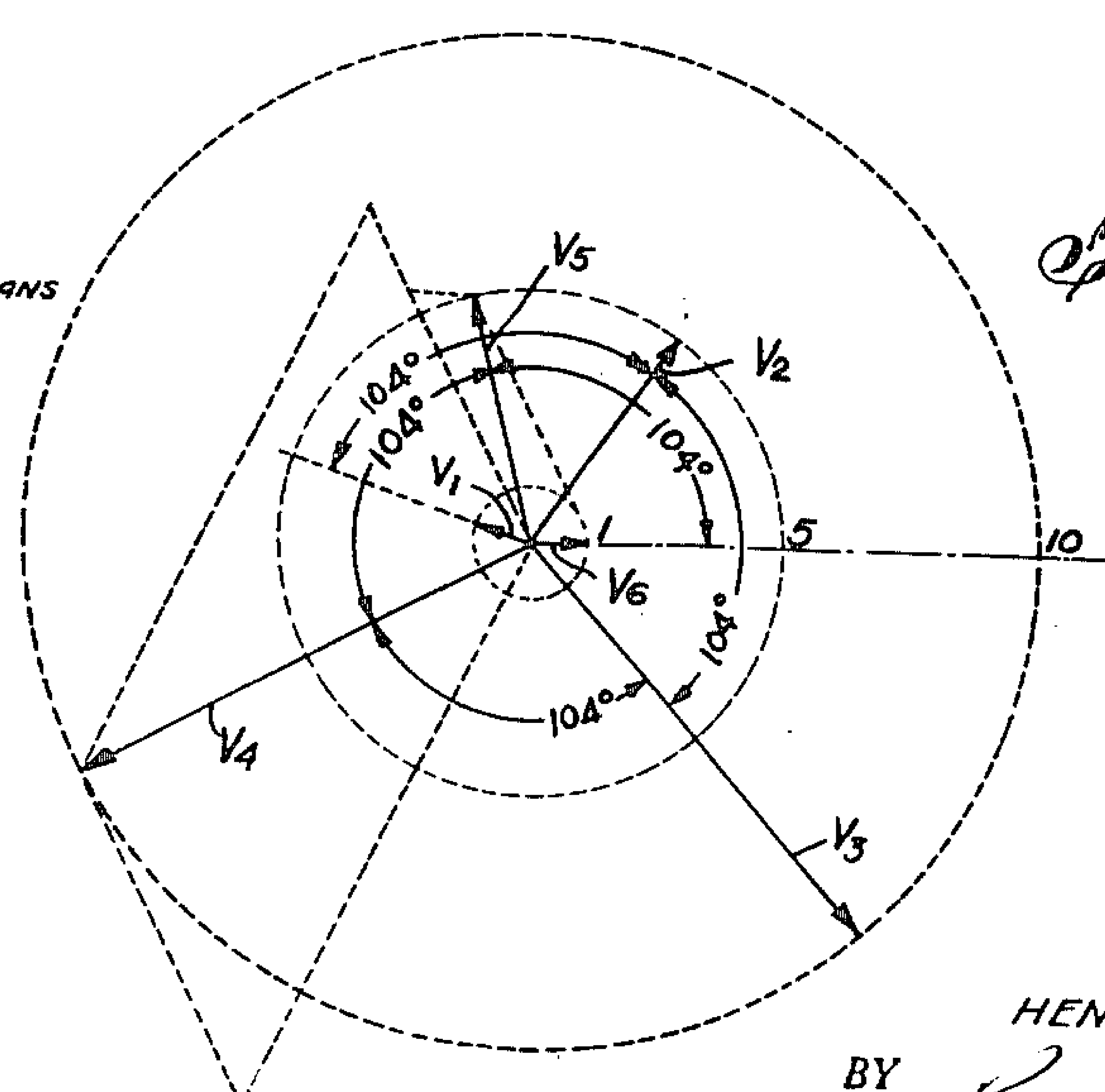

Fig. 4.

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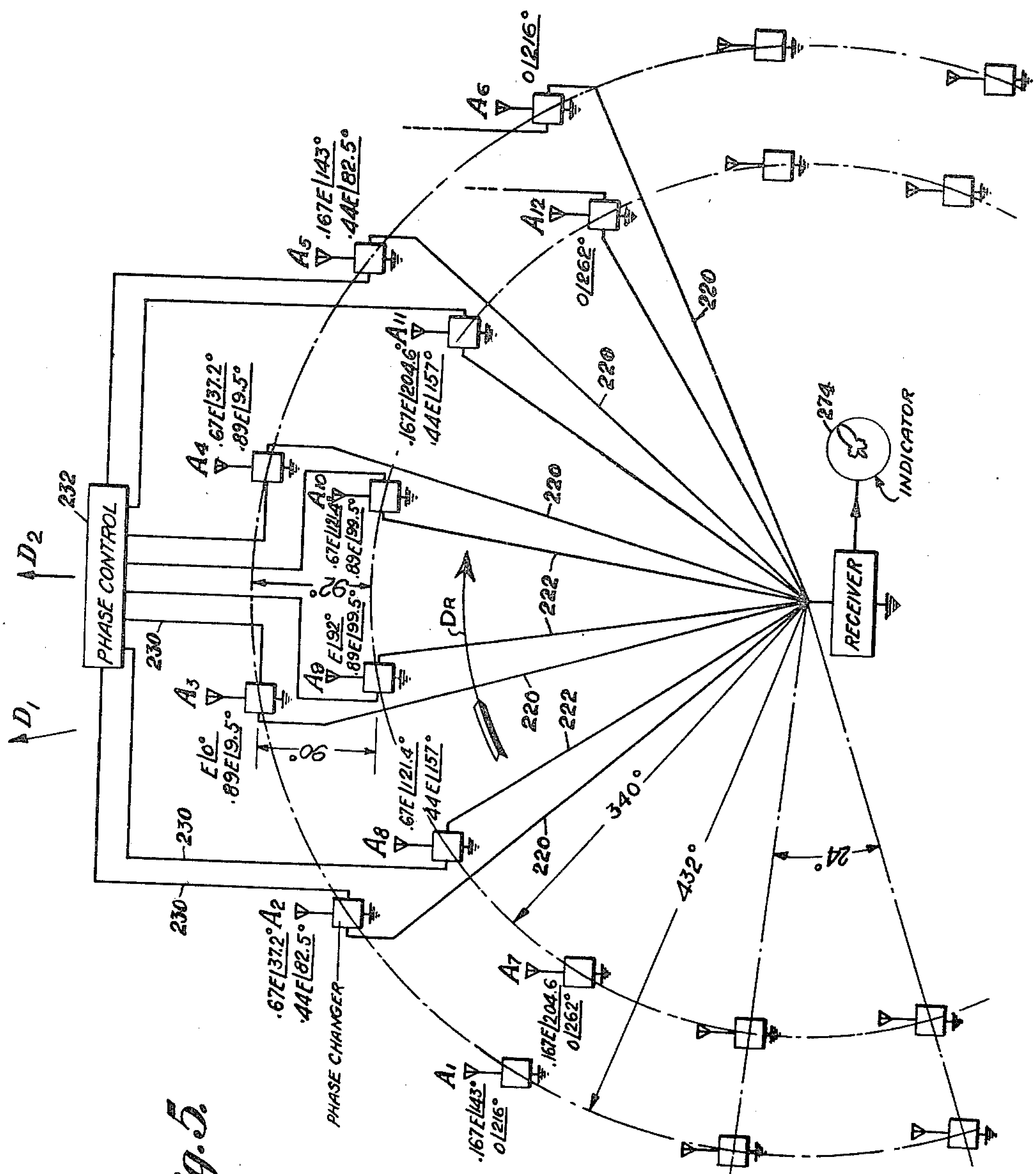

Fig. 5.

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Fig. 6.

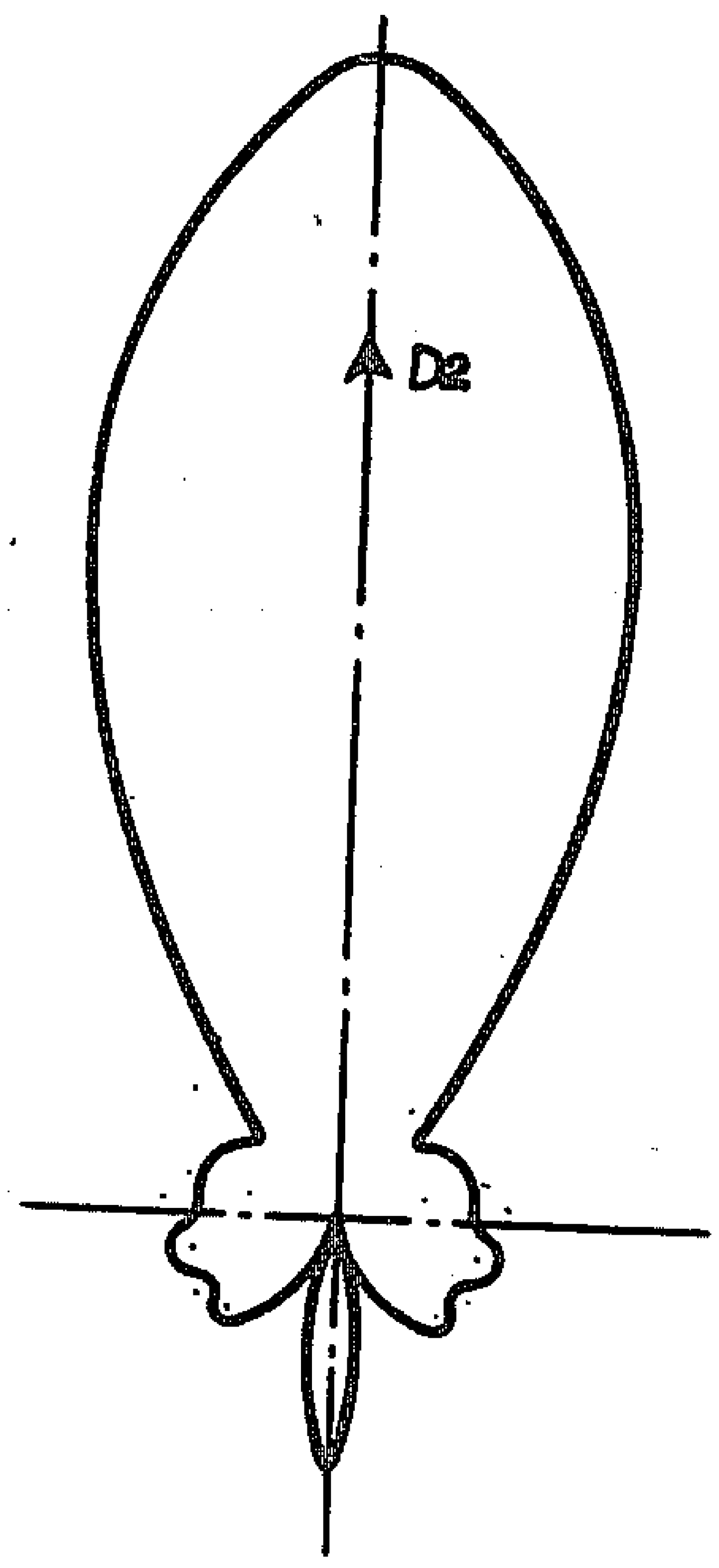
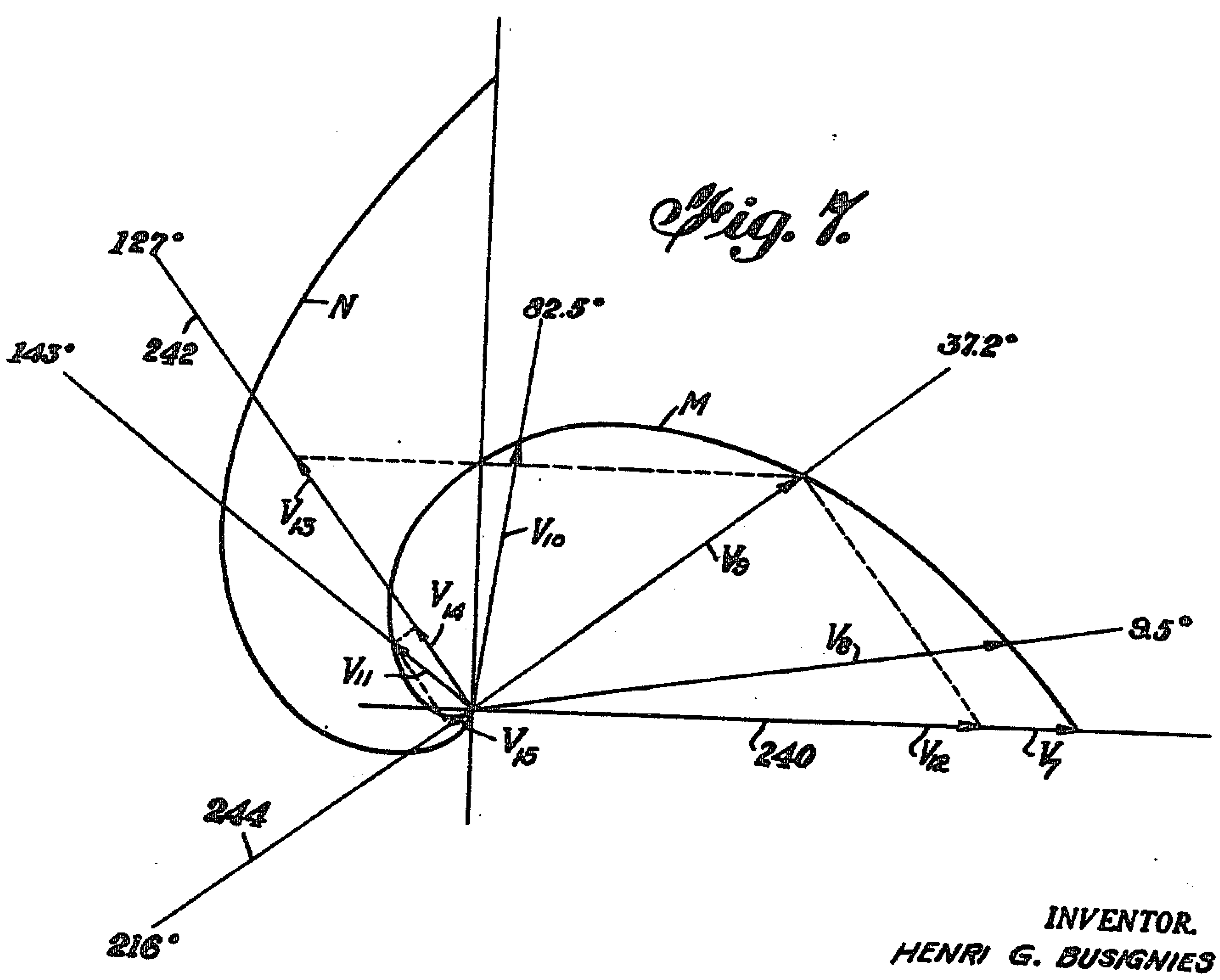


Fig. 7.



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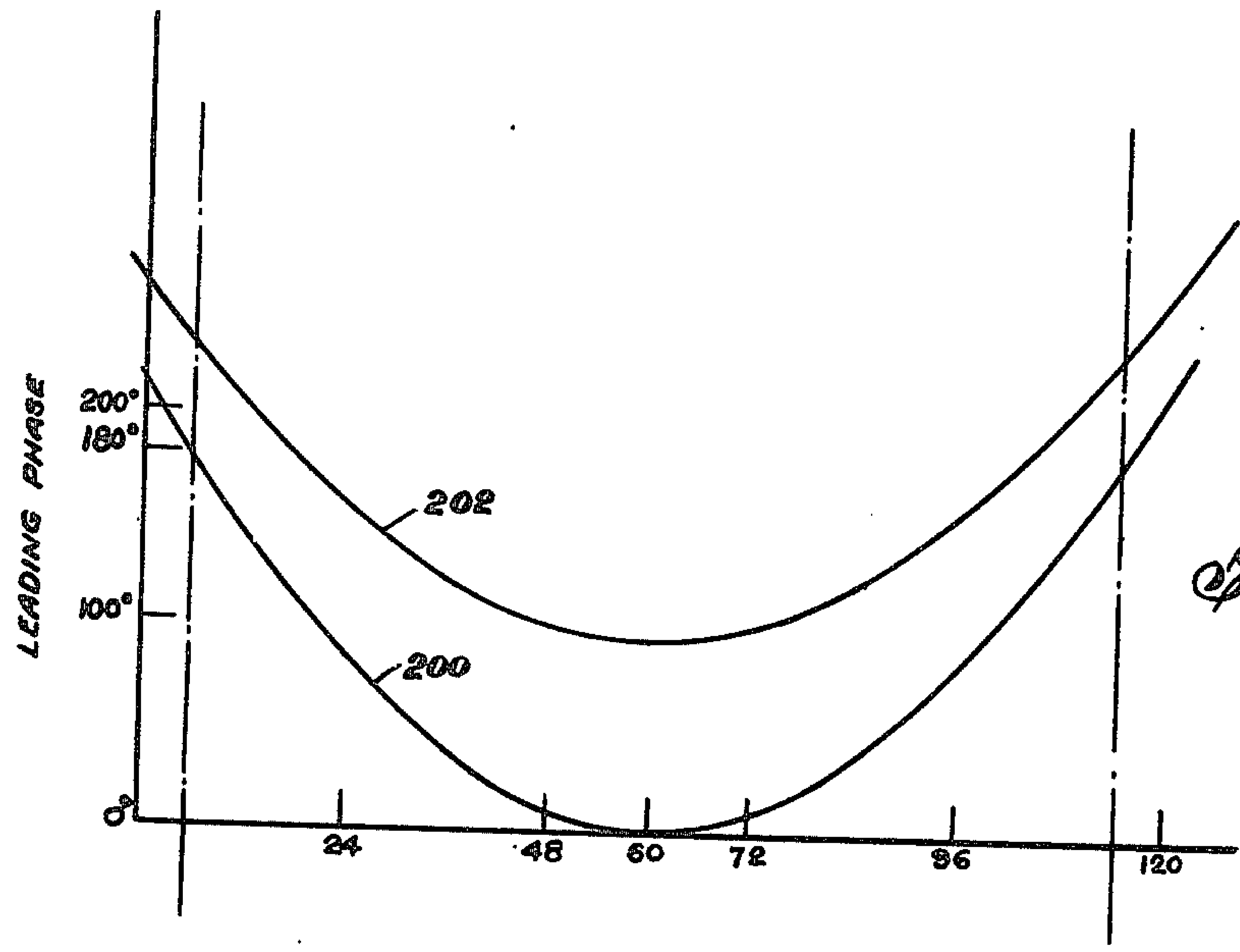

Fig. 8.

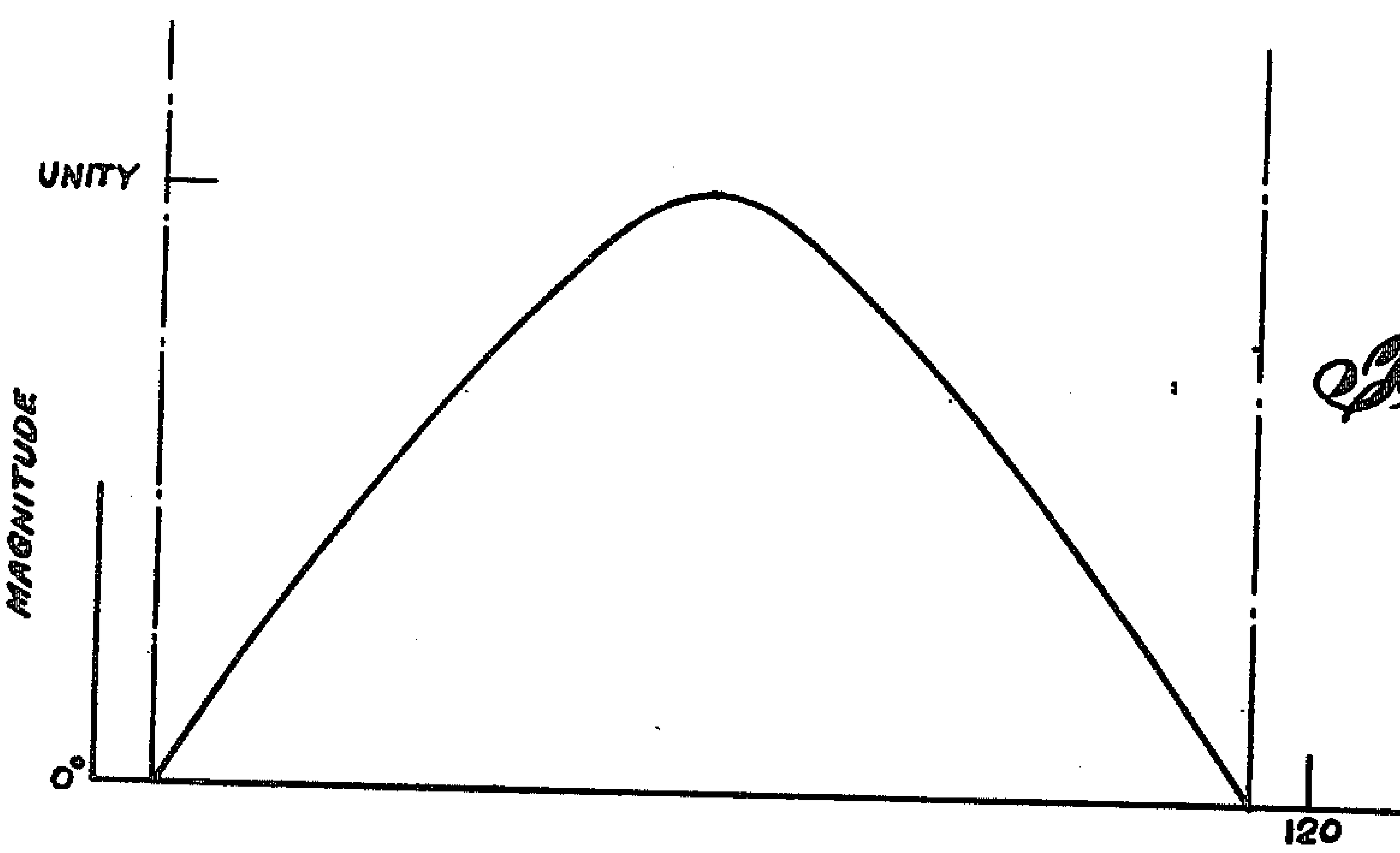

Fig. 9.

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Fig. 10.

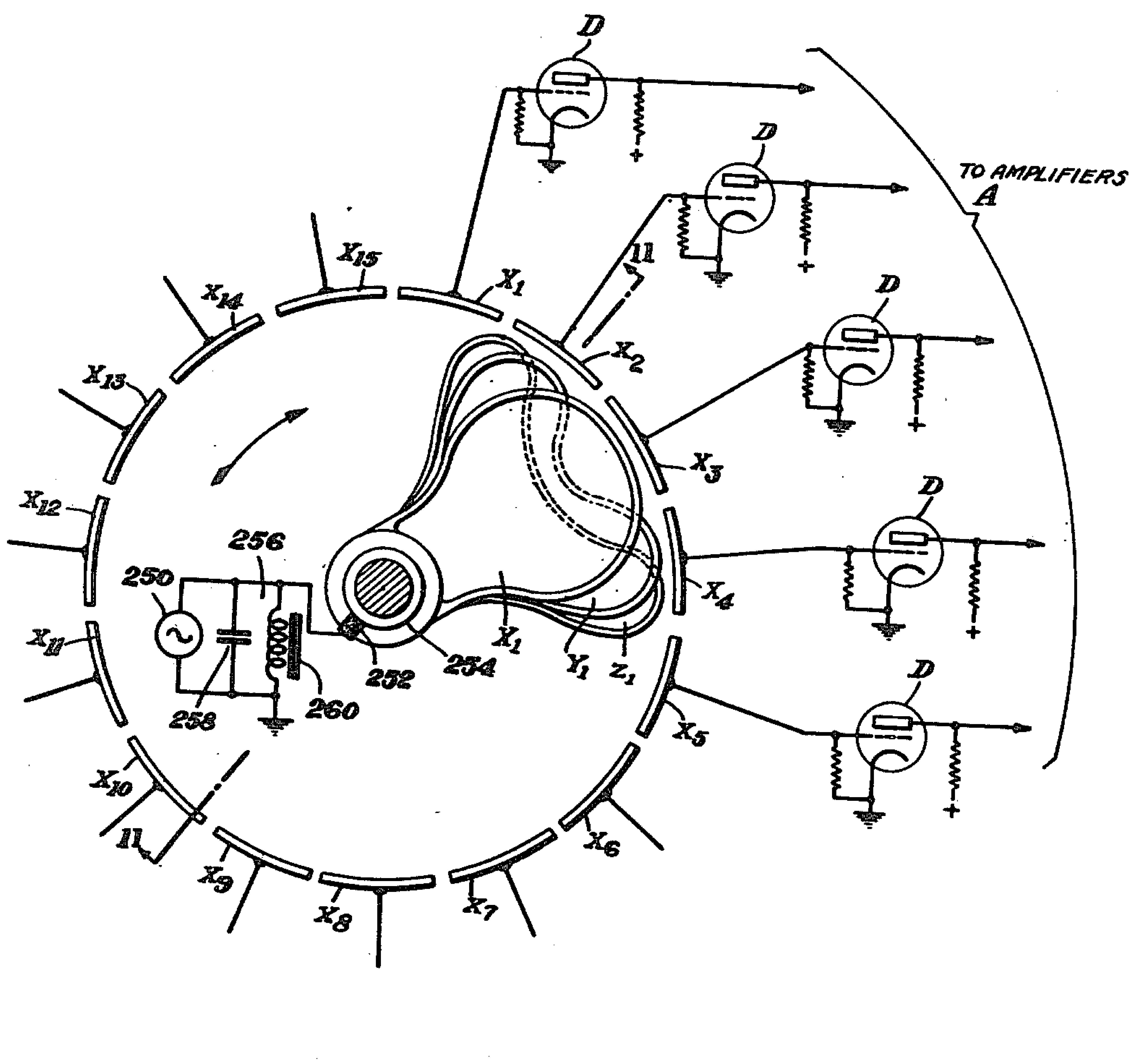

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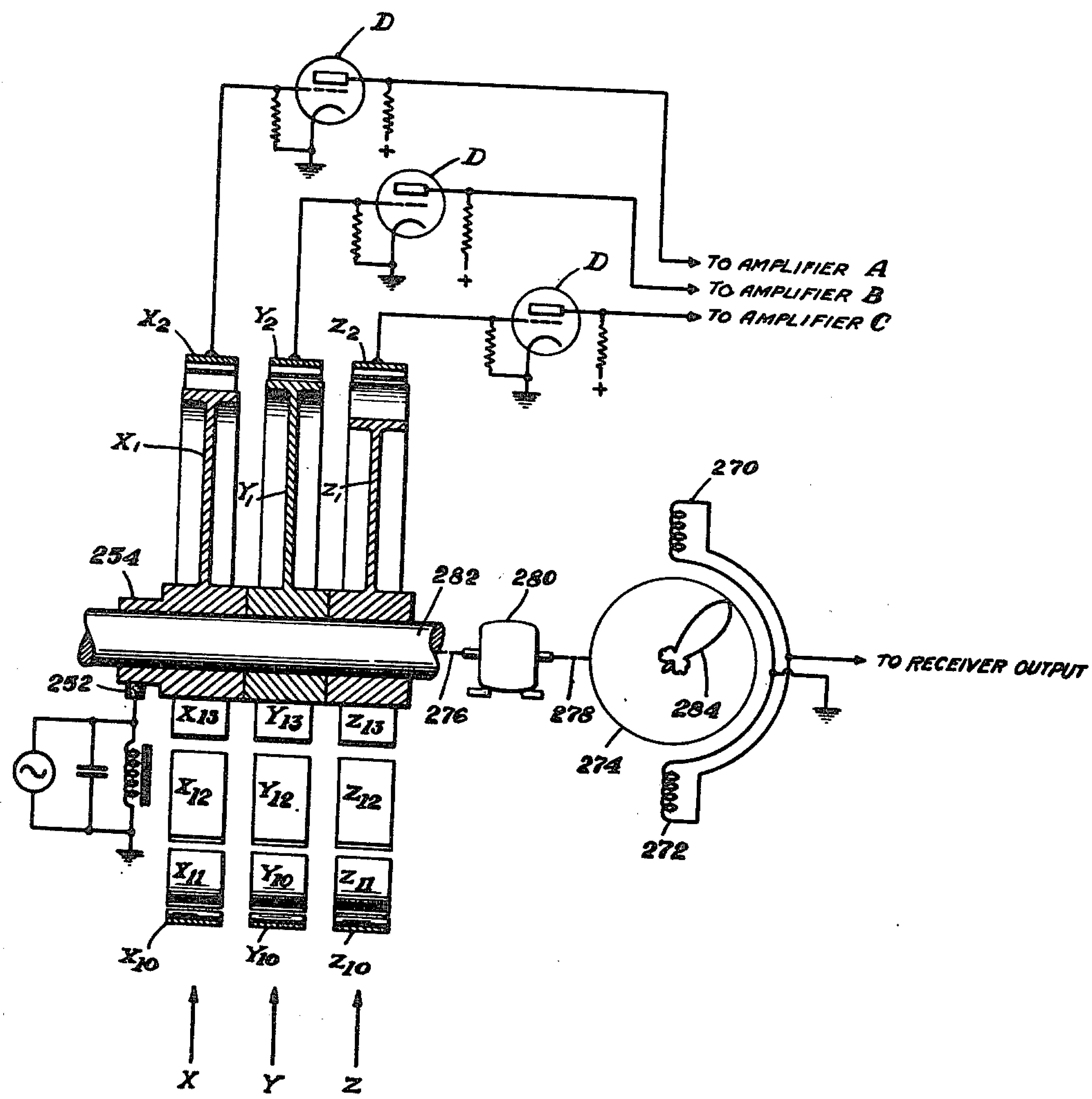
Fig. 11.



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Patented July 6, 1948

2,444,425

UNITED STATES PATENT OFFICE

2,444,425

ANTENNA ARRAY

Henri G. Busignies, Forest Hills, N. Y., assignor to Federal Telephone and Radio Corporation, Newark, N. J., a corporation of Delaware

Application August 9, 1943, Serial No. 497,890

20 Claims. (Cl. 343—115)

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This invention relates to radio antennas and in particular to directive antenna arrays and associated apparatus whereby the directivity of the arrays may be controlled in accordance with predetermined desired conditions or requirements.

The objects of my invention are:

To provide a single antenna array and associated apparatus capable of simultaneously receiving a plurality of radio transmissions either of the same or of different frequencies from different directions.

To provide a single antenna array and associated apparatus capable of simultaneously receiving a plurality of radio transmissions of different frequencies from any one given direction.

To provide a circular antenna array and associated control apparatus by which radio transmissions from any direction in azimuth may be received.

To provide a circular antenna array and associated control apparatus by which the directivity of the array may be rotated in the horizontal plane at substantially any rate.

To provide a completely automatic direction finder capable of determining the direction of a radio transmission in the horizontal plane.

To provide a voltage operated phase changer by which the phase of a voltage or current wave may be advanced or retarded through 360 electrical degrees.

To provide a voltage operated phase changer and control apparatus therefor by which the phase and magnitude of a voltage or current wave may be changed in accordance with a given cycle.

These and other objects and features will become apparent from the following description taken in connection with the attached drawings illustrating several embodiments of my invention, and wherein

Fig. 1 is a schematic circuit diagram showing an antenna array and associated circuits in accordance with one embodiment of my invention;

Fig. 2 is a schematic diagram illustrating a voltage operated phase changer in accordance with my invention;

Fig. 3 is a diagram illustrating one method for determining an antenna array in accordance with my invention;

Fig. 4 is a vector diagram illustrating the magnitude and phase relations of voltages which may be obtained from the phase changer shown in Fig. 1;

Fig. 5 is a second embodiment of my invention wherein a plurality of antennas are arranged in circular array;

Fig. 6 represents the field pattern of the array resulting from a given predetermined set of conditions shown in Fig. 5;

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Fig. 7 is a polar diagram used in explaining the principles of my invention;

Figs. 8 and 9 illustrate respectively the phase and magnitude relations of currents delivered to the transmission lines shown in the antenna array of Fig. 5;

Fig. 10 is a schematic diagram of a phase control device for controlling the phase changer of Fig. 2; and

Fig. 11 is a sectional diagram of the phase control device as viewed from the section line 11—11 of Fig. 10.

Referring to Fig. 1 I have schematically illustrated a six-element linear antenna array together with receiving apparatus and control equipment suitable for receiving a plurality of radio transmissions from different directions as set forth in the first two objects of my invention. In the figure, elements 1—6 represent six antennas arranged in linear array. These antennas are preferably aperiodic and therefore are capable of substantially equal response over a wide frequency band. Connected across an impedance in each antenna are two phase changing devices shown as blocks 8 and 10. Each block represents apparatus for changing the magnitude and phase of the voltage induced in the antenna circuit. The specific circuits for the phase changing devices are illustrated in Fig. 2. One set of phase changers, represented by reference characters 8 for example, is for determining the field pattern of the antenna array for one particular frequency. The other set of phase changers, 10, are for determining the field pattern for another frequency which may have a maximum directivity either in the same or in a different direction from that determined by the phase changers 8. It is to be understood that whereas I have illustrated only two groups of phase changers, any number of groups may be employed each group acting entirely independently from the others and determining a separate field pattern. Extending from the phase changers 8 are a plurality of transmission lines 12. Each line extends from the phase changer to which it is connected at one end to a receiver 14 which may be located at a remote point. The output impedance of the phase changer is matched to the impedance of the line. In the interest of economy of transmission lines it is preferable that adjacent lines, for example those associated with antennas 1 and 2, be connected together at a point 16 and that the combined energies from these lines be transmitted over a single line 18 to receiver 14. The dimensions of the lines are preferably so chosen that an impedance match occurs at the junction point 16. It is preferable though not essential that the electrical length of all of the lines 12 and all of the lines 18 be equal. In a similar manner, transmission lines 20 extending from phase changers 10 are connected together at point 22 and the energies therein are transmitted over a common line 24 to a separate receiver 26.

Associated with receivers 14 and 26 are phase change control devices 28 and 44 respectively. Control channels 31—36 extend from the phase control device 28 to the phase changers 8. In a similar manner control channels 37—42 extend from the phase control device 44 to the group of phase changers 10. Each control channel, 31 for example, is to be considered as representing a number of conductors sufficient to control the operation of a single phase changer.

In general the phase changers, as illustrated by the schematic wiring diagram of Fig. 2, comprise a plurality of vacuum tube amplifiers of the cathode follower phase invertor type. I have illustrated each phase changer as comprising three amplifiers A, B, and C. The input circuits of the amplifiers are connected in parallel across an impedance 50 in the antenna circuit of each of the antennas 1–6. Between the point 51 and the control grids 52, 53 and 54 of amplifiers A, B, and C respectively, there is a connection having electrical characteristics such that the voltages applied to the grids have a predetermined phase separation. The specific value of the phase separation is not critical but in general the voltage applied to grid 53 should lag the voltage applied to grid 52 by approximately 60°. Similarly, the voltage applied to grid 54 should lead the voltage applied to grid 52 by approximately 60°. These phase displaced voltages are obtained as follows: From the point 51 to the control grid 52, there is a non-reactive connection. Any potential at point 51 is therefore impressed on grid 52 with substantially no change in phase. From the point 51 to the grid 53 there is an inductive reactive connection. Any voltage occurring on grid 53 as a result of an applied voltage at point 51, therefore undergoes a lagging phase shift. Similarly, a capacitive reactance is connected between the point 51 and the grid 54 whereby any voltage occurring on the latter grid, as the result of a voltage applied to the point 51, undergoes a leading phase shift. The inductive and capacitive reactive connections are represented by the inductor 56 and the capacitor 58. Shunting the inductor 56 is a variable resistance 60 by which the phase voltage and the grid 53 may be controlled over a predetermined range. Similarly, a variable resistance 62 is shunted across the capacitor 58 for varying the phase of the voltage and the grid 54. It is to be understood that the reactors 56 and 58 may also be made variable for producing phase variations of voltage on the grid to which they are connected.

Between the cathode 64 of amplifier A and ground, there is a resistor 66. The voltage developed across this resistor is in phase with the voltage appearing across the resistor 50 in the antenna circuit. A lead 68 connected to the junction point between the cathode 64 and the resistor 66 has a voltage impressed thereon having a phase relation the same as that across the resistor 66. Between the anode 70 of amplifier A and ground, there is a second resistor 72, and across this resistor a voltage is developed having a 180° phase relation with respect to the voltage impressed across the resistor 50 in the antenna circuit. A lead 74 connected to the junction point of the anode 70 with resistor 72 has the same phase as that developed across resistor 72. It will therefore be seen that the voltages developed across conductors 68 and 74 have a 180° phase relation with respect to ground. The magnitude of this voltage is controlled in part by the value of the voltage appearing on grid 76, and the source of this controlling voltage is in the phase control device 28. A conductor 78 extends between the grid 76 and the phase control device 28, and is one of the conductors making up the channel 31 described in connection with Fig. 1. A second conductor 80 extends between the anode 70 and the phase control device 28 and is for the purpose of impressing a positive potential on the anode. A choke coil 82 prevents radio frequency currents from flowing in the conductor 80. The conductor 80 represents another of the conductors constituting the plurality of conductors of channel 31. The magnitude of the voltage applied to the anode also controls the magnitude of the voltage appearing across the conductors 68 and 74. The capacitor 84 by-passes the radio frequency current to ground and blocks direct current from the conductor 80 from ground.

Referring now to amplifier B, the resistor 90 is connected between the cathode 92 and ground. The resistor 94 is connected between the anode 96 and ground. The phase relation between conductor 98 and ground and the conductor 100 and ground is 180° as will be seen from the description in connection with amplifier A. The phase relation between the voltage appearing across the conductors 68 and 74 and the voltage appearing across the conductors 98 and 100 will have a substantially 60° phase relation as determined by the reactor 56.

The magnitude of the voltage across conductors 98 and 100 is determined by the voltage appearing on the grid 102 and the anode 96. The grid voltage is impressed from the phase control device 28 to the grid 102 over the line 104 which constitutes part of the channel 31. The anode voltage is transmitted over the line 106 extending between the anode 96 and the phase control device 28 and this line 106 likewise constitutes part of the channel 31.

With respect to amplifier C, the phase relation between the voltage across conductor 108 and ground and the voltage across conductor 110 and ground is 180°. However, due to the reactor 58, the voltage between conductors 108 and 110 is displaced substantially 60° from the phase of the voltage across conductors 68 and 74. The magnitude of the voltage between conductors 108 and 110 is determined by the voltages applied to the grid 112 and the anode 114 of amplifier C. The voltages are impressed over lines 116 and 118 respectively from the phase change control device 28. Lines 116 and 118 constitute conductors of the control channel 31. It will be seen that in the illustrated case, the control channel 31 comprises six conductors 78, 80, 104, 106, 116, and 118.

The output conductors 68 and 74 of amplifier A are connected to the output conductors 98 and 100 of amplifier B and to the output conductors of 108 and 110 of amplifier C at the points 120 and 122 in such a manner that the phase relation of the voltages appearing across points 120 and 122 due to the above mentioned conductors are 120° apart. This phase relation may be obtained by inverting the phase of the voltages across conductors 98 and 100 and across 108 and 110 with respect to the points 120 and 122. Under these conditions, if the voltage appearing across each of the resistors 66, 72, 90, 94, 128 and 130 were equal in magnitude, the combined voltage across points 120 and

122 would be zero. However, if a voltage appearing across any of the resistors immediately above mentioned was reduced or increased, the voltage across points 120 and 122 would no longer be zero, but would have a finite value and phase relation dependent upon the magnitude of the voltages appearing across the resistors. Connected across points 120 and 122 are the lines 12 or 20 of Fig. 1 as the case may be.

Referring again to Fig. 1 it will be seen that due to the common connections at points 140 and 142 of the lines 18 of which the lines 12 may be considered as branches, a change of voltage across any of the resistors in any of the amplifiers of the phase changers 8 will result in a change in magnitude and phase of the final voltage impressed upon the receiver 14. Likewise when considering phase changers 10, a change in voltage appearing across any resistor therein will affect the magnitude and phase ultimately impressed upon receiver 26. However, there is no interaction between phase changers 8 and 10 and therefore each receiver will be controlled by the respective phase changers to which it is connected.

In Fig. 3 I have shown the manner in which a single antenna array may be designed to receive radio transmissions from two arbitrary directions in such a manner that the field patterns of the antenna array will be a maximum in the direction from which the transmissions are received. If two different frequencies are being received the directivities of each transmission may be the same and there will be no interaction. If the radio transmissions are of the same frequency, in order to prevent interaction of the receivers it will be necessary for the transmissions to have different directions with respect to the antenna array. I have assumed two transmitters located at points S_1 and S_2 and a receiver located at R. The angle between the transmissions from S_1 and S_2 with respect to R is β.

There are many types of arrays known to the prior art and I have chosen the type known as a binomial array for describing my invention. At right angles to the direction of transmissions from S_1 a six-element binomial array is laid out. As is well known the spacing between the antennas of the array are one-half wavelength at the operating frequency which I have designated in Fig. 3 as

$$\frac{\lambda 1}{2}$$

The relative magnitudes of the voltage outputs from the wave changers associated with each antenna are 1–5–10–10–5–1 sequentially between end antennas of the array. It is of course understood that a one-half wavelength separation is equivalent to a 180° time phase displacement. Construction lines are drawn parallel to the transmissions from S_1 through the antennas of the array. A similar array is constructed at right angles to the transmissions from S_2 and the distance between the antennas are designated

$$\frac{\lambda 2}{2}$$

Through the antennas of the second array, construction lines are drawn parallel to the transmissions from S_2. At points where the two sets of construction lines intersect, the antenna array comprising antennas 1—2—3—4—5—6 in accordance with my invention may be positioned as shown in Fig. 3. It will be seen that projections from the antennas to points on a line at right angles to either directio of transmission will be equal to one-half th wavelength of either transmission.

Considering transmissions from S_1 for exampl it will be observed that there will be a differen in phase between the energies arriving at th various antennas of the array, and that this pha relation for a given wavelength is dependent upo the angle between the array and the direction reception. This angle I have designated θ an the phase between the energies induced in an two adjacent antennas is equal to $\pi \cot \theta$ radian

In order that the antenna array will have field pattern with a maximum directivity in th direction of S_1, it is required that the effecti outputs of wave changers associated with th antennas be cophasal. This result may be at tained as follows:

A wave front passing through the array will in tercept the antenna closest to the transmitter certain number of electrical degrees in spa phase before intercepting the second antenn If the effective output voltage from a pha changer associated with the first antenna is de layed an amount equal to this space phase, th effect upon a receiver would be the same as the receiver were being acted upon by in-pha voltages from both antennas. Applying th principle to all of the antennas of the array, will be seen that by a plurality of suitable pha changing means, the effective output voltag from all antennas can be made cophasal.

In Fig. 4 I have illustrated by a group of ve tors, certain conditions which must prevail order that the antenna array of Fig. 3 have th desired maximum directivity in direction S_1 fro the receiver R. The angle θ between the arr and the direction of reception is assumed to 60°. The vector V_6 represents the output volta from the phase changer associated with anten 6. V_5 represents in magnitude and phase th value of the output voltage from the wa changer associated with antenna 5. The pha relation of the voltage induced in antenna 5 wi respect to that induced in antenna 6 is 104° represented by the angle between V_5 and V_6. Th means that the phase changer associated wi antenna 5 must advance the phase of the inp voltage by 104° in order that the outputs of th two phase changers will be cophasal. A simil analysis applies to all of the remaining vecto V_4, V_3, V_2 and V_1. A detailed example of th manner in which the phase changers operate provide an output of the desired magnitude an phase will be given hereinafter in connection wi a second embodiment of my invention.

Although I have described my invention embodied in the diagram of Fig. 3 as comprisi an antenna having a directivity in two directio it is to be understood that any number of dire tivities could be obtained provided only that th distance between adjacent antennas is substa tially equal to the operating wavelength divid by twice the sine of the angle between the dire tion in which the antenna array extends an the direction of reception. This distance shown in Fig. 3 as

$$d=\frac{\lambda_1}{2 \sin \theta}=\frac{\lambda_2}{2 \sin \theta'}$$

The directivity can therefore be varied over considerable angle without materially affecti the field pattern of the antenna array.

Referring to Fig. 5 I have illustrated anoth embodiment of my invention wherein a plurali of antennas are arranged in two concentric circular arrays. Connected to each antenna is a phase changer of the type illustrated in Fig. 2 and from each wave changer a transmission line extends to a central receiver. At any instant of time a predetermined number of the antennas are conditioned through the medium of their associated phase changers so that as a group they are responsive to radio transmissions from a predetermined direction and substantially non-responsive to transmissions from other directions. Even though the antennas constitute a receiving array, the antenna may be said to have a field pattern having a maximum directivity in a predetermined direction.

In accordance with my invention the field pattern of the directive array is rotated in azimuth. The rate of rotation may have substantially any value, being determined in accordance with my invention by the rate of rotation of a mechanical phase control device to be hereinafter described. The rotation of the field pattern is accomplished by progressively energizing antennas on one side of the group which is active at any given moment and de-energizing antennas on the other side of this group.

In order to describe my invention, it is convenient to discuss a given antenna array which is conditioned to receive in accordance with a predetermined field pattern. For example in Fig. 5 I have illustrated an outer antenna array in which fifteen equally spaced antennas are positioned on the circumference of a circle having a radius of 432 electrical degrees and an inner antenna array positioned on the circumference of a circle having a radius of 340 electrical degrees. One antenna of each array is positioned on a common radius. Adjacent antennas of the array are spaced 24 electrical degrees apart. Considering for the moment the outer array, the adjacent antennas thereof are spaced apart one-half wavelength at the operating frequency or 180 electrical degrees. It is from this given condition that the radius of the array equals 432 degrees.

In Fig. 5 I have not shown all of the antennas constituting the complete array, since so doing would merely complicate the drawing and add nothing to a clear understanding of the operation of my invention. I have assigned reference characters A_1–A_6 to a group of antennas in the outer array and A_7–A_{12} to a group of antennas in the inner array. A discussion of the manner in which these antennas and their associated wave changers are conditioned to operate will be sufficient to completely describe the operation of the system as a whole. Opposite each antenna I have indicated certain voltage values and phase relations to be used in describing its operation. Assuming the direction of maximum reception is rotating in the direction of arrow D_R the upper values indicate certain voltage and phase relations when the antenna array is conditioned to receive from the direction of the arrow D_1 and the lower values indicate conditions when the array is conditioned to receive from the direction D_2. The amplitude and phase relations of the voltages delivered from the phase changers of the array gradually shift from one set of values to the other as the directivity of the array changes from the direction of D_1 to D_2 as will be hereinafter more completely described. When the array is receiving from the direction D_1, the phase changer associated with antenna A_3 is delivering a maximum voltage E having a phase relation of zero degrees taken as a reference. Phase changers associated with antennas A_2 and A_4 on either side of A_3 are conditioned to deliver a voltage of .67E having a phase relation of 37.2°. Similarly, phase changers associated with antennas A_1 and A_5 are conditioned to deliver a voltage of .167E having a phase relation of 143°. It will be observed that the values .167–.67–1–.67–.167 bear the relation of 1–4–6–4–1 respectively, and that these values represent magnitudes corresponding to the effective received voltages in a binomial array of five antennas. As above described in connection with Fig. 3, in order that an antenna array have a maximum directivity in a direction normal to the array, it is necessary that the effective voltages delivered from the antennas have a cophasal relation. Since the antennas of my array are on the arc of a circle, it is necessary that means be provided in the form of a phase changer to develop these cophasal voltages. For example, in order that antenna A_2 deliver a voltage in phase with antenna A_3, the phase changer associated with A_2 must advance the phase of the voltage wave as it strikes the antenna by 37.2°. Similarly, the phase changer associated with antenna A_1 must advance the phase of the voltage wave intercepting the antenna by 143°.

As is known in the prior art, in order that an antenna array have a unidirectional receiving pattern with a maximum directivity normal to the array, it is customary to provide either a second array of reflecting antennas usually spaced one-quarter wavelength from the energized antennas or to provide means for energizing this second array. Due to the fact that the antennas of my invention are aperiodic, it is necessary to provide a second energized array rather than one of the unenergized or reflector type. Accordingly, a second group of antennas A_7–A_{12} is provided to form an inner array. Since the antennas of the arrays are on the arcs of circles, it is impossible to locate all antennas of the inner array so that they will be one-quarter wavelength from corresponding antennas in the outer array. However, the antennas of the inner array may be conditioned to deliver a voltage wave having a phase relation such that substantially the same effect is obtained as if the one-quarter wave phase relation existed. The values of the voltages and phase relations delivered by the output of antennas A_7–A_{12} is recorded in Fig. 5.

The above discussion has dealt with the magnitudes and phase relations of voltages delivered by the antennas under consideration when maximum reception is from the direction D_1. If now the various magnitudes and phase relations of all the antennas be changed in a manner such that they correspond to the lower sets of figures shown adjacent the various antennas, the antenna array as a whole will have a field pattern such that its maximum directivity is in the direction D_2. An examination of the drawing will show that under these conditions antennas A_3 and A_4 for example will deliver equal voltages of .89E having a phase relation of 9.5°. The antennas of a binomial array under these conditions would normally have sequential voltage values of 1–5–10–10–5–1. However, since the outer antennas of a six-element array deliver only $\frac{1}{32}$ of the total voltage developed by the array and the power varies with the square of the voltage, these outer antennas have been disregarded in the computation. By so doing no serious error could be noted in any practical system. For this reason the magnitudes of voltages delivered by antennas A_1, A_6, A_7, and A_{12}, have been considered as zero. The phase relation however of these voltages has been recorded to indicate the phase relation at which voltages would begin to be developed by these antennas during the rotation of the field pattern. The field pattern for the condition in which antennas A_2–A_5 of the outer array and antennas A_8–A_{11} of the inner array are conditioned for reception for the direction D_2 has been computed and is shown on the polar diagram of Fig. 6. It will be seen from this diagram that the field pattern has a very marked directivity in the direction D_2.

I will now describe the manner in which the phase changers are operated so as to deliver output voltages having a desired magnitude and phase in accordance with the conditions indicated on Fig. 5. In Fig. 7 are plotted two curves M and N from the voltage and phase values appearing on Fig. 5. Curve M shows the order of change of the voltage and phase delivered by a phase changer associated with any antenna in the outer array. Curve N shows similar values for a phase changer associated with any antenna of the inner array. These curves are substantially two spirals having a 90° phase relation therebetween. A discussion of the variation in magnitude and phase of voltages from antennas in the outer array only will be given in order to not unduly lengthen the specification and since a similar discussion would apply to antennas of the inner array.

In Fig. 7 I have shown a plurality of vectors extending from the origin to certain points on curve M, these vectors representing the specific values of magnitude and phase of voltages appearing on Fig. 5. Curve M is interpreted as follows:

When the directivity of the array changes from D_1 to D_2, the magnitude and phase relation of the output voltage from antenna A_3 as represented by vector V_7 changes to a value represented by vector V_8. At the same time the magnitude and phase relation of output voltages from antenna A_2 changes from a value represented by vector V_9 to a value represented by vector V_{10}, and likewise the output from antenna A_1 changes from vector V_{11} to zero. It will be observed that during this period there is considerable reduction in magnitude and an increase in phase difference in the voltage outputs from antennas A_3, A_2, and A_1. On the other hand, the output from antenna A_4 increases from a value represented by vector V_9 to a value represented by vector V_8, while the output from antenna A_5 increases from the value represented by vector V_{11} to the value represented by vector V_{10}. It is clear that the changes in output just described occur while the directivity is changing from the direction D_1 to the direction D_2 or through 12°. The manner in which the magnitude and phase of the output voltage from any antenna changes through one complete rotation of the field pattern is shown on Figs. 8 and 9 respectively for that portion of the complete cycle during which any given antenna is conditioned to receive. In Fig. 8 curve 200 shows a variation in phase through which the output of any antenna of the outer array passes during a 120° rotation of the field pattern. Curve 202 shows the change in phase through which the voltage output from any antenna of the inner array passes during the same period.

The phase changer which is associated with any of the antennas of the arrays, is shown in Fig. 2 and has been previously described. The manner in which the output of the phase changer is controlled so that it will deliver a variable voltage having a variable phase in accordance with the requirements of any antenna shown in Fig. 5 will now be described. First, from the wave changer associated with each antenna of the outer antenna array, there extends a transmission line 220 to a central receiver. Preferably these transmission lines are of equal length and have the same electrical characteristics. Other similar transmission lines 222 extend between the phase changers associated with the various antennas of the inner array and the central receiver. These latter transmission lines should also be of equal length and electrical characteristic, but need not necessarily be equal to the first group of transmission lines 220. Each transmission line has been diagrammatically illustrated in Fig. 5 as a single conductor. In reality the line is preferably composed of two conductors extending from the points 120 and 122 in Fig. 2.

In Fig. 5, as well as Fig. 1, I have illustrated each phase changer unit as being connected directly with its associated antenna, and have also illustrated a transmission line extended from the phase changer to the receiver. It is to be clearly understood that each antenna could be first coupled to a transmission line with the far end of the line connected with a phase changer unit. Under these conditions all the phase changers could be centrally located at the receiver. If this type of construction were employed it would of course, be desirable to match the output impedance of the antenna with the input impedance of the transmission line and the output impedance of the transmission line with the input impedance of the phase changer in accordance with known methods.

Also extending between each phase changer and a phase control device is a control channel. Each channel is diagrammatically illustrated in Fig. 5 as a line 230. Each line is actually composed of a plurality of conductors and as shown in Fig. 2 these conductors are identified by reference numerals 78, 80, 104, 106, 116, 118. The phase control device 232 is preferably located adjacent the central receiver but in Fig. 5 it has been drawn at the top of the figure in order to make the diagram less confusing. It is the function of the phase control device to apply voltages to the various grids 76, 102, and 112 of the amplifiers shown in Fig. 2 of such magnitude that the output voltage from the combined amplifiers as it appears across terminals 120 and 122 will have the desired amplitude and phase. As an example when the output from antenna A_3 has an amplitude of E and phase zero, let it be required to produce an output voltage from A_2 of a magnitude .67E and phase of 37.2°.

Considering Figs. 2 and 7 the output of amplifier A varies in accordance with a vector extending from the origin horizontally to the right along a line 240. This line represents the reference from which all phases are measured. The line 242 positioned in the 2nd quadrant of the diagram of Fig. 7 is that along which the voltage output from amplifier B varies. This line bears an angular relation with respect to line 240 of approximately 127° in accordance with this example and for a reason which will be brought out later. This angle of 127° is determined by the reactor 56 in the grid circuit of amplifier B and the polarity in which the output leads 98 and 100 are connected to points 120 and 122. In the third quadrant a line 244 extends in a direction having an angular relation with line 240 of 216° for reasons which will be described later. It is along this line that the vector of the voltage output from amplifier C extends. The direction of line 244 is determined by the capacitor 58 and the polarity in which the output leads 108 and 110 are connected to points 120 and 122.

Digressing for the moment from the particular problem at hand, it will be noted that if the voltages applied to the grids 102 and 112 of amplifiers B and C respectively were such that a current output from these amplifiers were reduced to zero, the vector output from the complete phase changer would be determined solely by the output from amplifier A. The vectors normally extending along the lines 242 and 244 would be reduced to zero, and the output vector from amplifier A would lie on line 240. The magnitude of this vector could be determined by the voltage applied to the grid 76 and to the anode 70. As a matter of fact the output vector from antenna A_3 extends along this line, and may be represented by the vector V_7. At the same instant of time it is desired that the output from antenna A_2 have a magnitude of .67E and a phase relation of 37.2°, as shown by vector V_2. This vector may be obtained by reducing the voltage on the grid 76 of amplifier A to a value where the output is represented by vector V_{12} while at the same time increasing the voltage applied to the grid 102 of amplifier B until the output from this amplifier may be represented by the vector V_{13}. The output from amplifier C is maintained zero during this time. The sum of vectors V_{12} and V_{13} is equal to the desired vector V_9.

At this same instant the output voltage from antenna A_1 should have a value of .167E and a phase relation of 143°. This voltage is shown by vector V_{11} and may be obtained by reducing the output from amplifier A to zero, and maintaining outputs from amplifiers B and C equal to values shown by vectors V_{14} and V_{15} respectively. In a similar manner the desired amplitude and phase relation of any voltage of any antenna of the array may be obtained.

The manner in which the direct current voltages to be impressed on the grids 76, 102, 112, and amplifiers A, B and C respectively may be generated is illustrated in Figs. 10 and 11. In these figures I have represented a plurality of variable capacitors. Each capacitor comprises two electrodes, one fixed and one rotatable. One of these variable capacitors is provided for each phase control grid electrode controlling the output of an amplifier in all phase changers. In the present illustration there would thus be a total of 90 capacitors, three for each phase changer of which there is one for each of the thirty antennas comprising the inner and outer antenna arrays. However, I have illustrated in Figs. 10 and 11 only forty-five of these variable capacitors or a number sufficient to control the outputs of the antennas constituting one of the circular arrays. It is understood that the other forty-five variable capacitors for the other array would be similar to those illustrated in Figs. 10 and 11. As illustrated by these figures the forty-five fixed electrodes of the variable capacitors are divided into groups of 15, each group lying on the periphery of a circle. I have designated these groups as X, Y and Z. Associated with groups X, Y and Z are three rotating electrodes X′, Y′ and Z′ respectively. The rotating electrodes may be likened to cams having predetermined irregular faces as shown in Fig. 10. As the electrodes X′, Y′ and Z′ rotate, it will be seen that the interelectrode capacitance between the surfaces of the rotating electrodes and the fixed electrodes changes due to the irregular shape of the former.

The fixed electrodes X_1–X_{15} are connected to the phase control grids 76 of the amplifiers A associated with the phase changers in the outer antenna array. Similarly, each fixed electrode Y_1–Y_{15} of group Y is associated with the phase control grid 102 of amplifier B of these phase changers and fixed electrodes Z_1–Z_{15} of group Z are connected to phase control grids 112 of amplifier C of the phase changers. It will be observed that the fixed electrodes of group X are connected to that amplifier A whose output is in phase with its input, that the electrodes of group Y are connected to that amplifier having an inductive reactance in its input circuit, and that the electrodes of group Z are connected to that amplifier having a capacitive reactance in its input circuit.

In the lead between each fixed electrode in groups X, Y, Z and a phase control grid in the phase changer, there is a vacuum tube rectifier D. As shown in Figs. 10 and 11 these rectifiers may consist of a triode in which case an amplifying as well as a detecting action is obtained. It is to be understood that any equivalent rectifying device such as a diode or a selenium rectifier may be employed.

A source of high frequency current 250 is connected between the rotating electrodes X′, Y′ Z′ and ground through the medium of a brush 252 bearing on a ring 254 the latter being a part of or electrically connected to the rotating electrodes. The circuit 256, tuned to the frequency of the source and comprising a capacitor 258 and inductor 260, acts as a tank circuit connected across the output of the high frequency source to improve the regulation thereof. The frequency of the source 250 should be high enough to make the capacitance reactance between the rotating electrodes and any fixed electrode relatively low. Sufficient energy may thereby the transferred to the rectifiers to cause them to operate efficiently. The rectified output of the rectifiers is passed over the control circuits, 78, 104 and 116 for example, and impressed on the phase control grids of the phase changer amplifiers. Referring again to Fig. 7 it will be observed that the vector V_7 and therefore the output of amplifier A has a magnitude for a portion of the operative cycle at least, greater than the outputs of either amplifiers B or C at any time. This means that the capacitance between the rotating electrode associated therewith X′ and any fixed electrode X_1–X_{15}, must be proportionately greater than the capacitance between either of the other rotating electrodes and their corresponding fixed electrodes. This is illustrated in Fig. 10 wherein the rotating electrode X′ has a relatively long electrode surface opposite the fixed electrodes. Referring to Fig. 7 it was mentioned that the line 242 was positioned at an angle of approximately 127° from the line 240. This line 242 was drawn parallel to the tangent of curve M at the point A_3'. By such a construction it is seen that the vector V_1 undergoes no abrupt change in magnitude as it rotates from point A_3'. This in turn means that the periphery of rotating electrode X′ has the form of a smooth curve and facilitates its design. For similar reasons the line 244 of Fig. 7 occupies the position of 216° with respect to line

240, and the electrode Z' may have a smooth outer periphery.

With the electrode X' in the position as shown in Figs. 10 and 11, it will be seen that the reactance between it and electrodes X_3 is a minimum, whereas the reactance between electrodes Y', Z', and Y_3 Z_3 respectively is a maximum. This means that only amplifier A of the phase changer associated with electrodes X_3, Y_3, and Z_3 is delivering an appreciable output voltage. The high reactance between electrodes Y', Z' and Y_3 Z_3 respectively prevents energy flow from the source 250 across these electrodes with the result that the phase control grids of amplifiers B and C of the phase changer are biased to cutoff.

However during this period, the reactance between Y' and the two fixed electrodes Y_2 and Y_4 is a minimum, maximum energy is being passed between these electrodes, and the result is that the phase of the output of adjacent antennas is controlled primarily thereby. It must be kept in mind, however, that the voltage output and phase from any antenna is, in general, controlled by the joint action of all energies passing between the rotating electrodes and any group of fixed electrodes X_2, Y_2, and Z_2 for example. As the electrodes X', Y', and Z' rotate, they come into operating relation with other groups of fixed electrodes than those shown in Fig. 10 and in this manner the field pattern of the antenna array is rotated.

The manner in which the output from the receiver may be employed to indicate the direction from which a signal is being transmitted will now be explained. The receiver itself may be of any usual type, for example a superheterodyne employing the usual tuned circuits for selecting the frequency to be received. The output from the receiver is connected to the rotating coils 270, 272 of a cathode ray indicator 274 as illustrated in Fig. 11. The coils of the oscillograph are driven in synchronism with the rotating electrodes of the phase control device. This is illustrated in Fig. 11 by the lines 276, and 278 connecting the motor 280 to the shaft 282 of the phase control device and to the indicator 274.

Normally, when no signal is being received, a fluorescent spot will appear at the center of the oscillograph screen, the position of this spot being controlled by known means. When a signal is being received, current from the receiver passes through the coils 270 and 272 causing the spot to trace on the screen a pattern corresponding substantially to the field pattern of the antenna as shown by the curve 284. From the position of the trace with respect to a scale (not shown) on the indicator, the direction from which the received energy is being transmitted can be observed.

In describing my invention I have chosen specific examples of antenna arrays comprising a given number of antennas. The dimensions of the arrays were also assumed. It is to be clearly understood that these values were assumed for the purpose of illustration and description only since other arrays having a greater or a lesser number of antennas could equally well have been described. In describing the phase changer and phase change control device it has been assumed that the various values of voltage output were controlled by applying suitable voltages to the phase control grids of the amplifiers. These output voltages could also have been controlled in part by applying suitable voltages to the anodes of the amplifiers as taught in my copending application Serial Number 481,760 filed April 3, 1943 which issued January 27, 1948 as Patent No. 2,434,904. Likewise in place of balanced transmission lines extending between the phase changers and the receivers I could have employed unbalanced lines such as the concentric conductor lines disclosed in the above-named copending application. The above description was made by way of example only, and is not to be considered as a limitation on the scope of my invention as set forth in the objects thereof and the accompanying claims.

I claim:

1. A radio receiving system having a directivity variable in azimuth, comprising a plurality of antennas arranged in a predetermined array, a receiver, coupling means connected between said antennas and said receiver, said coupling means comprising a like plurality of phase changers and a plurality of transmission lines, each antenna being coupled to said receiver through one of said phase changers and through said transmission lines, each of said phase changers being controllably adapted to deliver voltages of a selected magnitude and phase, and a control device connected to said phase changers applying a varying control to said phase changers so that said phase changers deliver voltages of varying magnitude and phase to said receiver.

2. A radio receiving system in accordance with claim 1 wherein said plurality of antennas are aperiodic and are arranged in a linear array.

3. A radio receiving system in accordance with claim 1 wherein said plurality of antennas are aperiodic and are arranged in a circular array.

4. A radio receiving system in accordance with claim 1 wherein each of said phase changers comprises a plurality of vacuum tube amplifiers, each amplifier having an input and an output circuit, the phase relation between the voltages of the input and the output circuits of one amplifier being different from the phase relation between the voltages of the input and output circuits of another of said amplifiers.

5. A radio receiving system according to claim 1 wherein each of said phase changers comprises a plurality of vacuum tube amplifiers, each amplifier comprising an input and an output circuit and a control grid said control grid being connected to said input circuit, connection means for supplying voltage from one of said antennas to each of said input circuits, the input circuit of one of said amplifiers having a reactance different from the reactance of the input circuit of another of said amplifiers, the maximum phase difference between a voltage developed on one of said grids and a voltage developed on another of said grids being less than 180°, and circuit connections between the output circuits of said amplifiers to provide output voltages having a minimum phase difference greater than 90°.

6. A phase changer for changing the magnitude of a voltage and simultaneously changing the phase of said voltage through any angle between 0° and 360° comprising a plurality of vacuum tube amplifiers each amplifier comprising an input and an output circuit, an input control grid and a phase control grid, reactive means connecting the input control grids of said amplifiers to said input circuit to provide from a given input voltage a plurality of voltages having a maximum phase difference of less than 180° at said input control grids, circuit connections in said output circuits to provide voltages developed

in said output circuits have a maximum phase difference greater than 180° and control means connected with said phase control grid for applying a variable voltage to said phase control grid.

7. A radio direction finding system having a predetermined directivity continuously variable in azimuth, comprising a plurality of antennas in a circular array, a receiver, coupling means connected between said antennas and said receiver, said coupling means comprising a like plurality of phase changers and a plurality of transmission lines, each antenna being coupled to said receiver through one of said phase changers and through said transmission lines, each of said phase changers being controllably adapted to deliver voltages of a selected magnitude and phase, and a control device connected to said phase changers applying a varying control to said phase changers so that said phase changers deliver voltages of varying magnitude and phase to said receiver.

8. A radio direction finding system having a predetermined directivity continuously variable in azimuth comprising a first plurality of aperiodic antennas arranged in circular array, a second plurality of aperiodic antennas arranged in a circular array concentric with said first named array, the separation of adjacent antennas in said first array being substantially one-half wavelength, the radial distance between the two arrays being substantially one-quarter wavelength, a receiver, coupling means comprising a separate phase changer and a transmission line coupling each antenna of both arrays to said receiver, a phase change control device connected to each phase changer whereby in accordance with predetermined voltage characteristics of said control device the phase changers deliver waves of predetermined magnitude and phase to said receiver in accordance with said directivity and means connected to the output of said receiver for indicating said directivity.

9. A radio direction finding system in accordance with claim 8 wherein said phase control device delivers a control voltage to less than half of the number of phase changers included in said coupling means at any instant of time.

10. A radio direction finding system in accordance with claim 8 wherein each of said phase changers comprises a plurality of vacuum tube amplifiers the outputs of said amplifiers being connected to a single transmission line and connection means from said output circuits to said line whereby the output of each of said phase changers is the vector sum of the voltage outputs of said amplifiers.

11. A radio receiving system comprising a plurality of aperiodic antennas in linear array, a plurality of receivers, a first coupling means comprising a plurality of phase changers, a separate phase changer coupling each of said antennas to one of said receivers, a second coupling means comprising a second plurality of phase changers, a separate phase changer of said second plurality of phase changers coupling each of said antennas to another of said receivers, each phase changer comprising a plurality of vacuum tube amplifiers, each amplifier comprising an input and an output circuit, the phase relation between the voltages of the input and the output circuits of one amplifier being different than the phase relation between the voltages of the input and outputs of another amplifier.

12. A radio receiving system in accordance with claim 11 wherein the phase relations between the voltages of the input and output circuits of all amplifiers included in said first coupling means are such that the antenna array has a directivity in a first direction and wherein the phase relations between the voltages of the input and output circuits of all amplifiers included in said second coupling means are such that the antenna array has a directivity in a second direction.

13. A radio direction finding system having a predetermined directivity continuously variable in azimuth comprising a first plurality of aperiodic antennas arranged in circular array, a like plurality of aperiodic antennas arranged in a second circular array concentric with said first named array, a plurality of phase changers, one phase changer being connected to each antenna of each of said arrays, phase control means connected to said phase changers cyclically conditioning each phase changer to generate from voltage applied thereto by the antenna to which it is connected an output voltage having a predetermined variable amplitude and variable phase, connecting means to combine the output voltages from said phase changers, a receiver, means for connecting said combined voltages to said receiver, and an indicator connected to said receiver for indicating said directivity.

14. In the method of determining the directivity of a radio transmission from energy received by a plurality of antennas arranged in outer and inner circular arrays and in which the output from each of said antennas controls the generation of a voltage in a separate phase changer associated with said each antenna, said phase changer comprising a plurality of vacuum tube grid controlled amplifiers normally biased to cut-off, the steps which include cyclically varying the biases on the grids of the amplifiers of all phase changers associated with the antennas of said outer array to produce a plurality of voltages varying in a predetermined magnitude and phase, simultaneously cyclically varying the biases on the grids of the amplifiers of all phase changers associated with the antennas of said inner array to produce a second plurality of voltages varying in a predetermined magnitude and phase, combining all produced voltages, and determining said directivity from said combined voltages.

15. The method of determining the directivity of a radio transmission from energy received by a plurality of antennas arranged in outer and inner concentric circular arrays comprising cyclically conditioning overlapping groups of adjacent antennas in said outer array to generate a plurality of voltages varying in magnitude and phase, simultaneously cyclically conditioning overlapping groups of adjacent antennas in said inner array to generate a second plurality of voltages varying in magnitude and phase, generating said pluralities of voltages in accordance with said received energy and said conditioning, combining all generated voltages, and indicating the directivity of said transmission from said combined voltages.

16. A radio receiving system having a variable directivity comprising a plurality of antennas arranged in a predetermined array, a receiver, coupling means connected between said antennas and said receiver, said coupling means comprising a plurality of phase changers and a plurality of transmission lines, each antenna being coupled to said receiver through one of said phase changers and through said transmission lines, each of said phase changers adapted to deliver voltages of a selectable magnitude and phase in accordance with the magnitude of the control voltages supplied to said phase changers and a

control device for supplying variable voltages to said phase changers, said control device being connected to said phase changers so that said phase changers deliver voltages of varying magnitude and phase to said receiver.

17. In the method of controlling the directivity of reception of radio transmisison from a plurality of antennas arranged in an array, the steps comprising generating voltages of predetermined magnitude and phase, conditioning the energy received from each of said antennas in accordance with said voltages, and cyclically varying said voltages both in magnitude and phase over a range corresponding to the directivity range.

18. In a method of controlling the directivity of reception of radio transmission from a plurality of antennas arranged in an array, the steps comprising generating voltages of different magnitude and phase, conditioning the energy received from each of said antennas in accordance with a separate one of said voltages, and cyclically varying said voltages both in magnitude and phase over a range corresponding to the directivity range.

19. In a method of controlling the directivity of reception of radio transmission from a plurality of antennas arranged in an array, the steps comprising generating voltages of different magnitude and phase, conditioning the energy received from each of said antennas in accordance with a separate one of said voltages, and cyclically and simultaneously varying said voltages both in magnitude and phase.

20. In a method of controlling the directivity of reception of radio transmission from a plurality of antennas arranged in an array, the steps comprising generating voltages of different magnitude and phase, conditioning the energy received from each of said antennas in accordance with a separate one of said voltages, and simultaneously and continuously varying said voltages both in magnitude and phase.

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