June 10, 1947. L. E. NORTON 2,422,123

DIRECTION FINDER

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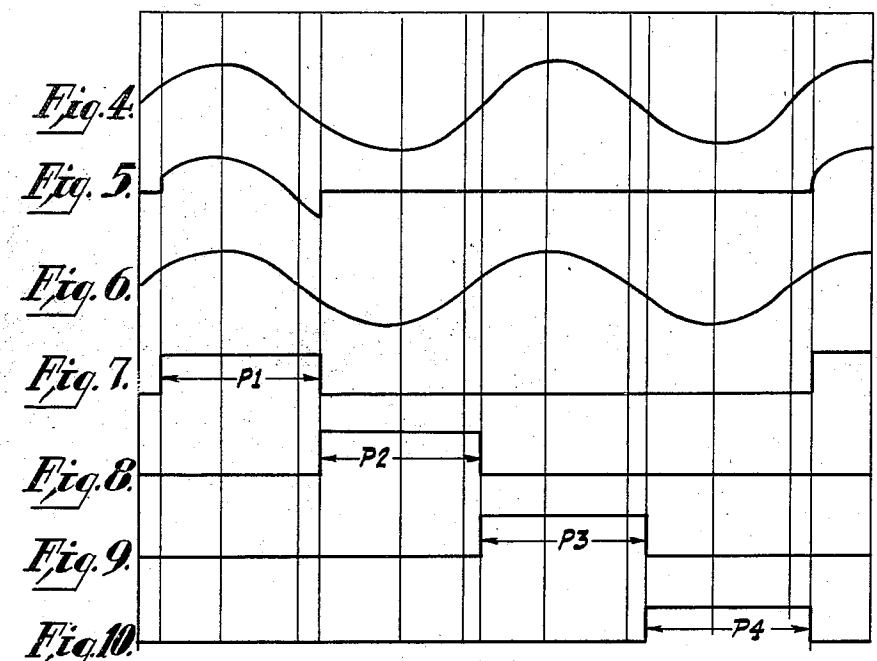


Fig. 1.

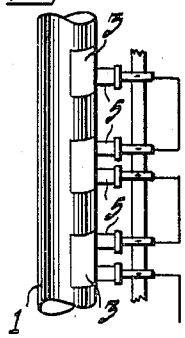


Fig. 16.

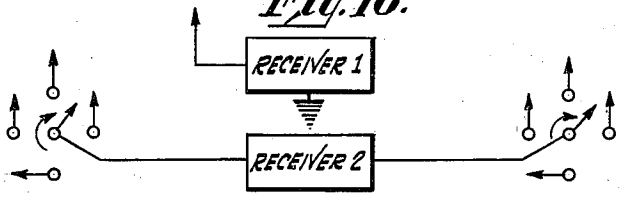


Fig. 2.

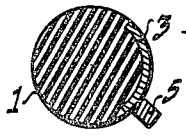


Fig. 13.

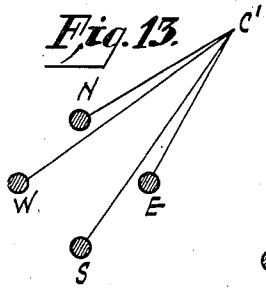


Fig. 14.

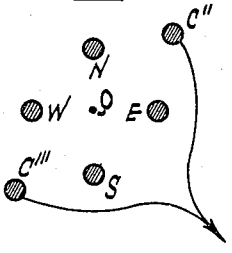
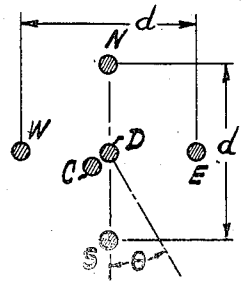


Fig. 15.



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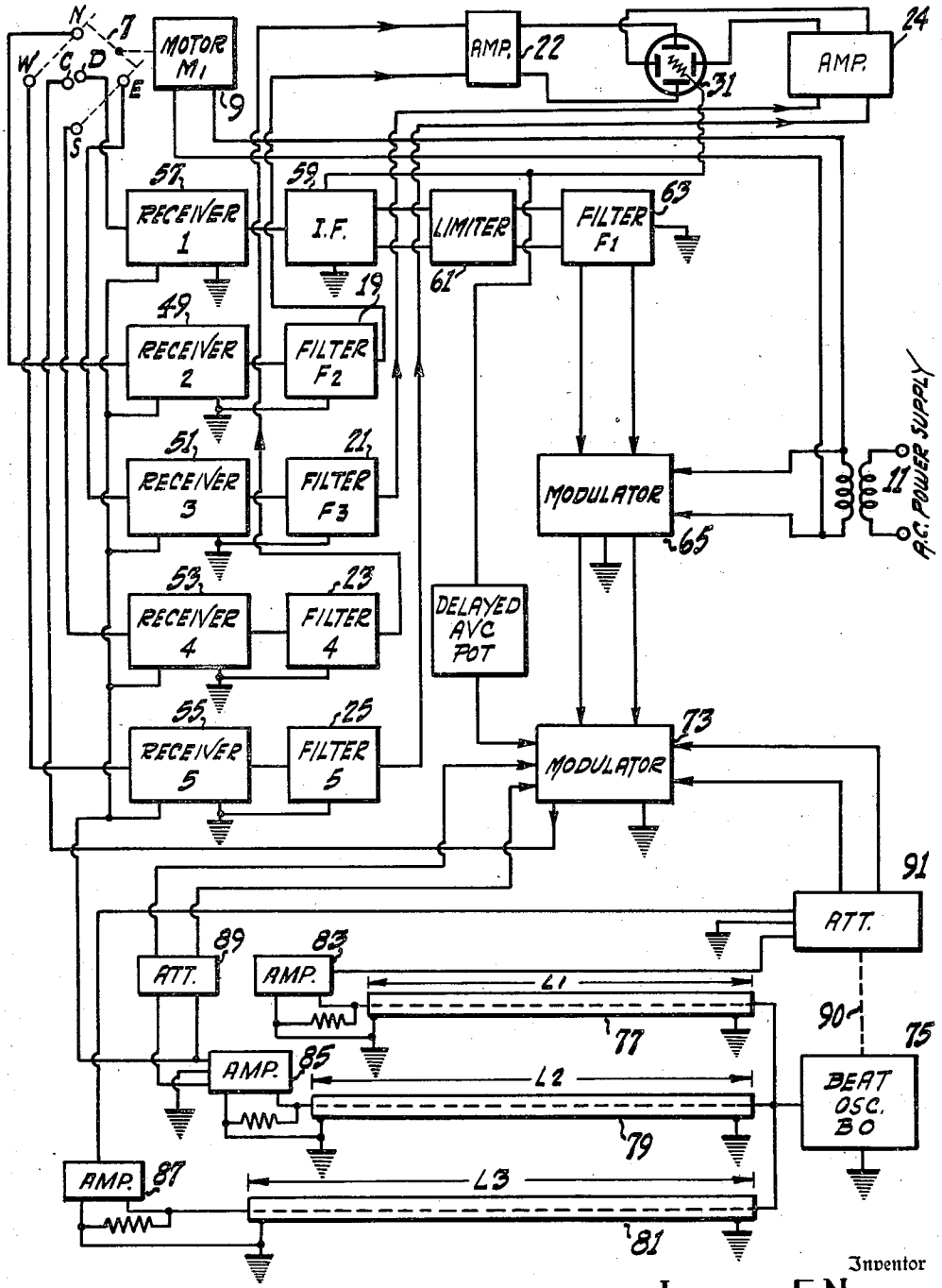


Fig. 3.

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DIRECTION FINDER

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Fig. 11.

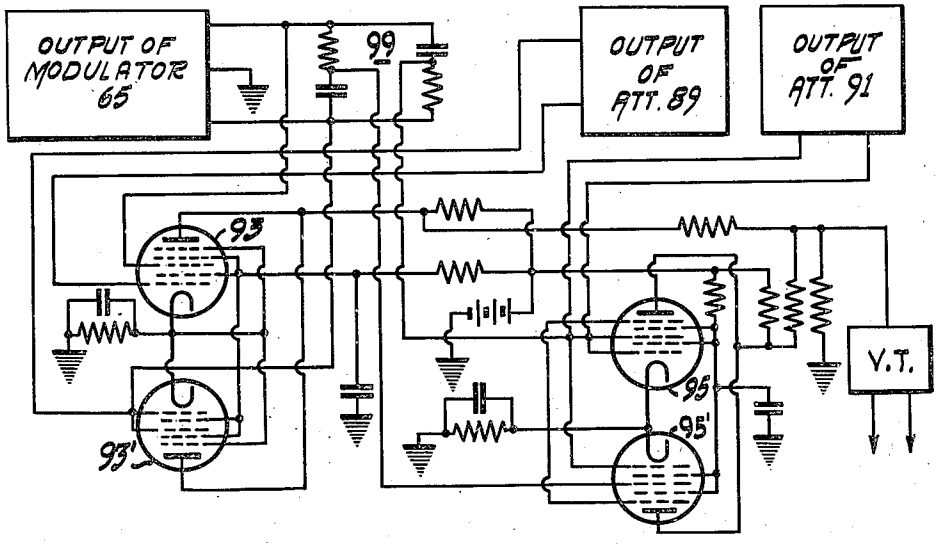
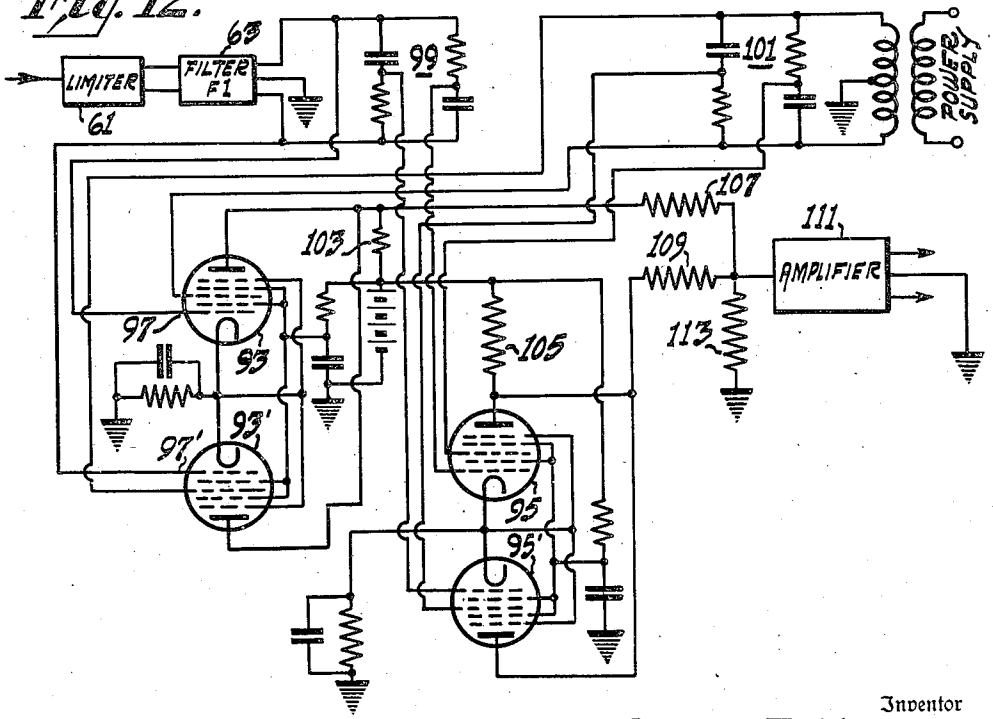


Fig. 12.



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UNITED STATES PATENT OFFICE

2,422,123

DIRECTION FINDER

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Application December 31, 1942, Serial No. 470,861

4 Claims. (Cl. 250—11)

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This invention relates to direction finders, and more particularly to improvements in the art of determining the front of a radio wave by using spaced vertical antennas and comparing the phases of voltages induced in the several antennas by a radiation field.

This method has been practiced in the past by using pairs of antennas interconnected in opposition to each other and to a common load circuit, as in the well known Adcock system. Owing to the fact that the voltages from the individual antenna pairs are combined in opposition, their resultant amplitude is substantially proportional to their phase difference. Thus a phase comparison is obtained directly in the antenna circuits and the amplitude of the resultant antenna output is substantially proportional to the cosine of the angle between the wave front of the radio wave and the perpendicular bisector of the line between the antennas. The principal reason for using systems of this type is to avoid response to other than vertically polarized waves, and so obtain freedom from so called polarization error or night effect. In order to utilize the full advantage of this arrangement it is necessary to take elaborate precautions to avoid pickup of horizontally polarized field components by any part of the antenna circuit. It has been found impossible in practice to achieve this result completely even when all horizontal surfaces in the system are either removed or shielded.

Thus by process of elimination it appears that the residual response to other than vertically polarized energy must be a result of proximity of the antenna elements, since a single isolated vertical antenna will exhibit no such response. According it has been proposed to sample the radiation field at spaced points while avoiding antenna proximity effects, by means of a plurality of sectionalized antenna structures. During the time that each of the antennas is operative, all of the other antennas are divided into relatively small segments so that they are in effect removed from the field. Said antenna structures and a circuit organization for direction finding therewith, is described and claimed in copending application, Serial Number 470,859, filed on December 31, 1942, by L. E. Norton, and entitled Direction finders.

The principal object of the present invention is to provide an improved method of and means for direction finding, employing antenna structures of the above mentioned type. Another object is to provide an improved method of and means for producing radiation injection signals

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for direction finder systems. These and other and incidental objects will become apparent to those skilled in the art upon consideration of the following description with reference to the accompanying drawing of which Figs. 1 and 2 are elevational and sectional views respectively of a commutated antenna structure, Fig. 3 is a schematic block diagram of an embodiment of the invention, Figs. 4 through 6 are graphical representations of voltages occurring in the operation of the system of Fig. 3, Figs. 7 through 10 are graphical representations of the antenna commutation cycles of the system of Fig. 3, Fig. 11 is a schematic diagram of a single side band modulator system, for the direction finder of the instant invention, Fig. 12 is a schematic circuit diagram of a balanced modulator system, for the direction finder of the instant invention, Figs. 13, 14 and 15 illustrate alternative arrangements of the spaced antennas of Fig. 3, and Fig. 16 illustrates a modified system for comparing the commutated antenna outputs.

Referring to Fig. 1, a vertically disposed shaft 1 of insulating material is provided with a plurality of arcuate conductive segments 3 spaced apart longitudinally from each other and arranged to cooperate with stationary brushes 5. Each of the segments 3 extends through an arc of 90° around the shaft 1, so that if the shaft is rotated past the brushes the segments 3 are connected together and the assembly functions as a continuous vertical conductor during one-fourth of each revolution. During the remainder of the revolution of the shaft 1 the segments 3 are disconnected from each other. The segments 3 and the connections between the brushes 5 are made so short that the natural resonance of each conductor is higher than the highest frequency at which the system is to operate. Four antennas of the above described type are provided at corners of a square as in the familiar Adcock system. Each of the insulated shafts may be driven by an individual motor, or all may be driven together by means of suitable mechanical connection to a single motor, as schematically illustrated in Fig. 3. The antenna shafts are angularly displaced with respect to each other so that the structures are successively connected for operation in sequence. Since the antennas are operated successively, producing outputs in the form of staggered trains of fractional waves, a direct phase comparison is not possible. Hence it is necessary to synthesize voltages which are related in phase to each other in the same way as the outputs of

the antennas would be related if they were coexistent.

Fig. 4 represents a low frequency sinusoidal potential, whose frequency is the difference in frequency between an arriving signal and a locally injected signal. As explained below, the potential represented in Fig. 4 is:

$$E_e = C_1 E_a E_b \cos\left(\beta t + \frac{2\pi d \cos\alpha \cos\psi}{\lambda} + \phi\right)$$

when all the directional information is in the phase angle

$$\frac{2\pi d \cos\alpha \cos\psi}{\lambda}$$

hereinafter referred to as γ, thus

$$E_e = c_1 E_a E_b \cos(\beta t + \gamma + \phi)$$

The frequency $\beta/2\pi$ will be referred to as the modulation frequency. Assuming that the antenna switching repetition frequency is one half the modulation frequency, each antenna will be operative for a period equal to that of one half wave of the modulation. Referring to Fig. 5, if an antenna is made operative at a time $a\pi$ after the initiation of a modulation cycle, the ouput, after demodulation, will comprise a fractional wave repeated at intervals corresponding to the switching repetition period. This wave includes a fundamental frequency which is the same as the switching repetition frequency, a second harmonic of the same frequency as the modulation frequency, and numerous higher harmonics. The modulation frequency components or second harmonics may be isolated by means of a filter comprising reactive elements arranged to reject all other components. The selected second harmonic component of the wave of Fig. 5 will be of the same form as the modulation frequency component Fig. 4. The filter output is illustrated in Fig. 6. A similar filter may be provided for each antenna channel, and the phases of the filter output voltages compared to provide bearing indications. Since there is no assurance that the switching cycle will remain in a constant phase relation with the modulation cycle, it is necessary that the phase of the modulation component of the wave of Fig. 5 be independent of the angle $a\pi$. Expressing the voltage E_5 of Fig. 5 in terms of a Fourier series:

$$E_5 = a_c + a_1 \sin\left(\frac{\beta t+\alpha}{2}\right) + A_2 \sin(\beta t+\alpha) + \ldots a_n \sin n\left(\frac{\beta t+\alpha}{2}\right) + b_1 \cos\left(\frac{\beta t+\alpha}{2}\right) + b_2 \cos(\beta t+\alpha) + \ldots b_n \cos n\left(\frac{\beta t+\alpha}{2}\right)$$

where $\beta/4\pi$=the switching frequency, the terms $a_2 \sin(\beta t+\alpha)$ and $b_2 \cos(\beta t+\alpha)$ represent the second harmonic or modulation frequency component. The constant a_2 may be evaluated by multiplying the series by $\sin(\beta t+\alpha)$ and integrating over one cycle of the repetition frequency:

$$a_2 = 1/a\pi \int_0^{a\pi} 0 \sin(\beta t+\alpha) d\left(\frac{\beta t+\alpha}{2}\right) + 2/\pi \int_{a\pi}^{a\pi+\pi/2} \sin(\beta t+\alpha)\sin(\beta t+\alpha) d\left(\frac{\beta t+\alpha}{2}\right) + \frac{2}{(3-2a)\pi} \int_{a\pi+\pi/2}^{2\pi} 0 \sin(\beta t+\alpha) d(\beta t+\alpha) = \tfrac{3}{4} = \tfrac{1}{2}$$

The constant b_2 may be similarly determined:

$$b_2 = 1/2\pi \int_{a\pi}^{a\pi+\pi/2} \sin(\beta t+\alpha)\cos(\beta t+\alpha) d\left(\frac{\beta t+\alpha}{2}\right) + \frac{2}{(3-2a)\pi} \int_{a\pi+n/2}^{2\pi} 0 \cos(\beta t+\alpha) d\left(\frac{\beta t+\alpha}{2}\right) = 0$$

The phase angle between E_5 and E_6 is

$$\tan^{-1} b2/a2 = \tan^{-1} 0 = 0$$

Thus the phase angle between the modulation and the second harmonic of the wave of Fig. 5 is zero when the switching cycle starts at a time $a\pi$ later than the modulation cycle. Since this is true for any value of a, it is apparent that the phase relation E_5 to E_6 is independent of the switching phase.

Referring to Fig. 3, four antennas N, E, S and W are arranged at corners of a square and mechanically connected, as indicated by the dashed line **7**, to a synchronous motor **9** which is electrically connected to an A.-C. supply **11**. Receivers **49**, **51**, **53** and **55** are connected to the antennas N, E, S and W respectively. Two relatively small vertical antennas C and D of conventional type are provided at the center of the square. The antenna D is supported vertically above the antenna C and slightly offset with respect thereto, as illustrated in Fig. 15. The antenna D is connected to a receiver **57**. The output circuit of the receiver **57** is connected through a limiter **61** and a filter **63** to a modulator circuit **65**. The A.-C. supply **11** is connected to a second input circuit of the modulator. The output circuits of the receivers **49** and **53** are connected through filters **19** and **23** to an amplifier **22** in the vertical deflection circuit of a cathode ray tube **31**. The receivers **51** and **55** are similarly connected through filters **21** and **25** to an amplifier **24** in the horizontal deflection circuit of the tube **31**.

The output circuit of the modulator **65** is connected to a second modulator circuit **73**. A beat oscillator **75** is connected through transmission lines **77**, **79** and **81**, amplifiers **83**, **85** and **87** respectively and attenuators **89** and **91** to the modulator **73**. This network constitutes a phase splitter, as described more fully below. The output circuit of the modulator **73** is connected to the injection antenna C.

The modulators **65** and **73**, and the beat oscillator **75** cooperate to produce a potential differing in frequency from an arriving wave by a fixed amount, independent of the frequency of said arriving wave. As will appear from the description of the operation of the entire system, the output of the filter **63** comprises a voltage of the I.-F. frequency of the receiver **57**.

Referring to Fig. 12, the circuit of the modulator **65** of Fig. 3 comprises a pair of balanced modulators **93**, **93'** and **95**, **95'**. The I.-F. frequency output of the filter **63** is applied directly to the inner grids **97** and **97'** of the tubes **93** and **93'**. The voltage from the power supply is applied directly to the outer control grids of the tubes **93** and **93'**. The inner control grids of the tubes **95** and **95'** are connected to the filter **63** through a 90° phase shifting network **99**. The outer control grids of the tubes **95** and **95'** are

similarly connected through a 90° phase shifter 101 to the power supply. The anodes of the tubes 93 and 93' are connected together through a common load resistor 103. The tubes 93 and 93' are likewise provided with a common load resistor 105. The load resistors 103 and 105 are connected through resistors 107 and 109 respectively to the input of an amplifier 111, which is shunted by a resistor 113. The resistor 113 is of relatively low resistance compared to the resistors 107 and 109. The amplifier 111 includes a phase inverter arranged to provide push-pull output.

The operation of the circuit of Fig. 12 is as follows:

Denoting the frequency of the arriving wave as $\omega/2\pi$, the oscillator frequency as $\alpha/2\pi$ and the power frequency as $\beta/2\pi$, the I.-F. frequency is $(\alpha-\omega)/2\pi$. Voltages of $E_\omega[1+m_3 \sin (\alpha-\omega)t]$ and $E_w[1m_7 \sin (\alpha-\omega)t]$ and $E_c[1-m_4 \sin \beta t]$ are applied to the inner control grids 97 and 97' of the tubes 93 and 93' respectively.

Voltages $E_c[1+m_4 \sin \beta t]$ are applied to the outer control grids of the tubes 93 and 93' respectively. The output of the tube 93 will be

$$E_j=K_1E_hE_i[1+m_3 \sin (\alpha-\omega)t+m_4 \sin \beta t+m_3m_4/2 \cos (\alpha-\omega-\beta)t-m_3m_4/2. \cos (\alpha-\omega+\beta)t]$$

In similar fashion, the output of the tube 93' is

$$E_k=K_1E_hE_i[1-m_3 \sin (\alpha-\omega)t-m_4 \sin \beta t+m_3m_4/2. \cos (\alpha-\omega-\beta)t-m_3m_4/2 \cos (\alpha-\omega+\beta)t]$$

Since the anodes of the tubes 93 and 93' are connected together the voltages E_j and E_k are combined in phase addition, producing a resultant voltage:

$$E_m=2K_1E_hE_i[1+m_3m_4/2+ \cos (\alpha-\omega+\beta)t-m_3m_4/2 \cos (\alpha-\omega-\beta)t]$$

The voltages applied to the grids of the tubes 95 and 95' are the same as those applied to the corresponding grids of the tubes 93 and 93', but shifted 90° with respect thereto. The output of the modulator 95, 95' is

$$E_n=2E_hE_i[1+m_3m_{4/2}. \cos (\alpha-\omega+\beta)t+m_3m_4/2+ \cos (\alpha-\omega-\beta)t]$$

The voltages E_m and E_n are added in the network comprising the resistors 107, 109 and 113 and applied to the input of the amplifier 111. The output of the amplifier

$$E_p=k_2E_hE_i[1+m_3m_4/2+ \cos (\alpha-\omega+\beta)t]$$

For convenience in manipulation, the useful part of E_p may be rewritten as:

$$E'_p=E_q \cos (\alpha-\omega+\beta)t$$

Referring to Fig. 3, three transmission lines 77, 79 and 81 are connected between the beat oscillator 75 and the modulator 73. The purpose is to provide a 90° phase shift over any band of frequencies through which the oscillator 75 is adjusted. Each line is terminated by a resistor equal to the characteristic impedance. The three lines are cut to different lengths. The line 79 is longer than the line 77, and shorter than the line 81 by the same amount, or $L_3-L_2=L_2-L_1$. The outputs of the lines 77 and 81 are applied in phase opposition to the attenuator 91. Since the output of the line 77 leads that of the line 79 and the output of the line 81 lags that of the line 79 by the same amount, the resultant input to the attenuator 91 is 90° out of phase with the output of the line 79, independent of the frequency.

The output of the beat oscillator 75 is:

$$E_r=E_s \sin (\alpha t+t)$$

Neglecting attenuation, the potential applied to the input circuit of the tube 85 is:

$$E_t=E_s \sin \alpha t$$

Using E as the reference potential, the potential applied to the tube 83 is

$$E_u=E_s \sin [\alpha t+2\pi/\lambda(L_2-L_1)]$$

and the potential applied to the tube 87_1, since $L_3-L_2=L_2-L_1$, $E_v=E_s[\sin \alpha t-2\pi/\lambda(L_2-L_1)]$.

The voltages E_u and E_v are combined in phase opposition and applied to the attenuator 91. The output of the attenuator 91 is

$$E_w=k_3(E_u-E_v)=k_3c_4[\sin 2\pi/\lambda(L_2-L_1) \cos \alpha t$$

Since E_w is a cosine function of t and E_t is a sine function of t, the two voltages differ in phase by 90°. To avoid large variations in amplitude of the resultant input to the attenuator 91, the differences in the lengths of the lines should be made considerably less than a quarter wave length at the highest frequency of operation of the oscillator 75. The attenuator 91 is variable and is ganged to the tuning control of the oscillator 75 as indicated by the dashed line 90 to compensate the remaining variations of amplitude with frequency.

Referring to Fig. 11, the circuit of the modulator 73 is similar to that of the modulator 65. Corresponding elements are designated by the same reference numerals as in Fig. 12. The operation of the modulator 73 is identical with that of the modulator 65 except for the differences in the frequencies involved. The single side band output of the modulator 65 is applied directly to the modulator 93, 93' and through the 90° phase shifter 99 to the modulator 95, 95'. The beat oscillator frequency voltages from the attenuators 99 and 91 are applied to the modulators 93, 93' and 95, 95' respectively. The output of the modulator 73 comprises a single potential differing from the received carrier frequency by the modulation frequency.

The operation of the circuit of Fig. 3 is as follows:

The output of the modulator 73 is radiated by the antenna C, and picked up together with the arriving signals by the antennas N, E, S and W.

If the antennas were in action continuously, the field at antennas N and S would produce potentials:

$$E_a\left[1+m \sin \left(\omega t-\frac{2\pi d \cos \theta \cos \psi}{\lambda}\right)+ m_1 \sin (\omega+\beta)t+\phi\right]$$

and

$$E_a\left[1+m \sin \left(\omega t+\frac{2\pi d \cos \theta \cos \psi}{\lambda}\right)+ m_1 \sin (\omega+\beta)t+\phi\right]$$

respectively, where E_a is the signal amplitude, m and m_1 are modulation factors, $\omega/2\pi$ is the signal carrier frequency, ds the spacing between the antennas N and S, θ is the azimuth of wave arrival with respect to the line between the antennas N and S, ψ is the elevation of wave arrival, λ is the wave length of the arriving wave, and ϕ is a constant.

The modulator 73 provides a multiplying voltage E_b $(1+m_2 \sin \alpha t)$. The output voltage of the I.-F. amplifier of the receiver 49, when the antenna N is operative, will be

$$E_d = m\frac{m_2}{2}E_a E_b\left[\cos(\alpha-\omega)t+\frac{2\pi d\cos\theta\cos\psi}{\lambda}+\right.$$

$$\left.\cos(\alpha-\omega-\beta)t-\phi\right]$$

The second detector of the receiver 53 will produce, when the antenna S is operative, a voltage

$$E_f = cE_aE_b\cos\left(\beta t-\frac{2\pi d\,\theta\cos\psi+\phi}{\lambda}\right)$$

Thus the combined signals are mixed by the action of the second detectors of the receivers 49, 51, 53 and 55, providing output waves of the form illustrated in Fig. 5. The filters 19, 21, 23 and 25 are tuned to accept the power frequency components of frequency $\beta/2\pi$, as described above. The outputs of the filters thus comprise sinusoidal waves bearing the same phase relations with respect to each other as the R.-F. voltages induced in the corresponding antennas bear to each other. The phases of the outputs of the filters 19 and 23 are compared in the input circuit of the amplifier 22 to provide an A.-C. voltage proportional in magnitude to the sine of the bearing. The outputs of the filters 21 and 25 are similarly combined in the amplifier 24 to provide a second voltage of the same frequency proportional in amplitude to the cosine of the bearing. The outputs of the amplifiers 22 and 24 are in time phase. The cathode ray beam of the tube 31 is therefore deflected to produce a linear trace at an angle equal to the bearing angle. In order to remove the reciprocal bearing indication, the trace is blacked out or defocused over one-half its length by applying the output of the receiver 57 to the intensity control electrode.

The injection antenna C of the system of Fig. 3 may be removed from its central location and placed at some outside location as shown in Fig. 13, provided that phase shifters corresponding to the altered geometry are placed in the channels of the receivers 49, 51, 53 and 55. The path C'N is the shortest and for convenience is used as a reference. If a phase advance equal to $2\pi/\lambda$ times the differences in the lengths of the paths C'—N and C'—E is introduced in the channel of the receiver 49, a phase advance of $2\pi/\lambda$ time the difference between the paths C' S and C' E introduced in the channel of receiver 53, and a phase advance of $2\pi/\lambda$ times the difference between the path C'W and C'E in the channel of the receiver 55, the operation will be the same as in the above described system. The central antenna may be replaced by two antennas C'' and C''' as illustrated in Fig. 14, located equidistant from the center point O, and on a line which passes through the point O. The mean phase of the pair will be the same as the phase O.

Mean phase voltage for eliminating reciprocal bearing indications may be obtained without the use of a central sense antenna by modifying the antenna switching sequence to include periods wherein two or more antennas operate simultaneously. The filter output during these periods will be mean phase voltage. The relation between the commutation frequency and the modulation frequency must be changed to conform to the new switching sequence. For example, if the switching sequence is N, N—S, E, E—W, S, N—S, W, E—W, the modulation frequency must be

$n\beta/2\pi$ where the commutation frequency is $\beta/4\pi$ and n is any real integral number The sense period may be repeated once for each complete commutation cycle, rather than four times. Thus the switching sequence may be N, E, S, W, N—S. In this case if the commutation frequency is $\beta/4\pi$ the modulation frequency must be $5n\beta/8\pi$. In each of the above cases, the sense voltage may be derived from either diagonal pair or from all of the antennas connected simultaneously. The receivers 49, 51, 53 and 55 may be replaced by a single receiver with switches connected in its input and output circuits and operated in synchronism with the antenna switching, as illustrated in Fig. 16.

Thus the invention has been described as a method of direction finding in which erroneous indication due to abnormally polarized or steeply incident radiation is avoided by preventing response to any other than vertical electric field components. This is accomplished by use of antenna structures which may be cyclically commutated to change their electrical characteristic from those of a vertical conductor to those of a plurality of relatively short isolated conductors. The antennas are commutated successively, so that only one antenna at a time is operative, the other antennas being effective and removed from the field. This prevents response to horizontally polarized field components which would otherwise occur as a result of antenna proximity effects.

I claim as my invention:

1. A radio direction finder including a directive antenna array, a radiation injection antenna, radio receiver means connected to said directive array, a limiter connected to an intermediate frequency circuit of said receiver means so as to provide intermediate frequency voltage with modulation removed therefrom, a local source of low frequency voltage, a balanced modulator connected directly to said limiter and to said low frequency source, a second balanced modulator connected through 90° phase shifters to said limiter and to said low frequency source, a third balanced modulator connected directly to the output circuits of said first two balanced modulators, a fourth balanced modulator connected through a 90° phase shifter to the output circuits of said first two balanced modulators, a beat oscillator connected through a phase shifting network to said third and fourth balanced modulators so as to provide voltages to said balanced modulators which are in quadrature phase with respect to each other, and connections from the output circuits of said third and fourth balanced modulators to said injection antenna whereby said injection antenna radiates energy at a frequency differing from that of an arriving wave by a predetermined amount.

2. The invention as set forth in claim 1 wherein said phase shifting network between said beat oscillator and said third and fourth balanced modulators comprises transmission line means providing three delay periods, the shortest delay and the longest delay each differing from the intermediate delay by the same amount, and means for combining in phase opposition the voltage delayed by said shortest amount and that delayed by said longest amount.

3. A radio direction finder comprising a plurality of spaced antenna structures each including a series of isolated conductive segments of relatively short length compared to the wave length of the highest frequency at which the system is to operate, commutator means ar-

ranged to connect said segments to form a single vertical conductor, means for operating said commutators successively whereby said vertical conductors are sequentially set up at spaced points, receiver means connected to said antenna structures, a radiation injection antenna, an auxiliary antenna, an auxiliary receiver connected to said auxiliary antenna, a limiter connected to an intermediate frequency circuit of said auxiliary receiver means so as to provide intermediate frequency voltage with modulation removed therefrom, a local source of low frequency voltage, a balanced modulator connected to said limiter and to said low frequency source, a second balanced modulator connected through 90° phase shifters to said limiter and to said low frequency source, a third balanced modulator connected to the output circuit of said first two balanced modulators, a fourth balanced modulator connected through a 90° phase shifter to the output circuits of said first two balanced modulators, a beat oscillator connected through a phase shifting network to said third and fourth balanced modulators so as to provide voltages to

said balanced modulators which are in quadrature phase with respect to each other, and connections from the output circuits of said third and fourth balanced modulators to said injection antenna whereby said injection antenna radiates energy at a frequency differing from that of an arriving wave by a predetermined amount.

4. The invention as claimed in claim 3, including filters connected to said receiver means, a cathode ray tube provided with deflection circuits connected to said filters, and an intensity control electrode connected to the output of said auxiliary receiver.

LOWELL E. NORTON.

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The following references are of record in the file of this patent:

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